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

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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 Emissior

1. A2-HCA0-v1 (1980-2007)
   Compiled from a technology based inventory from D. Streets, aircraft emissions from NASA's AEAP project, and ship emissi based on work from V. Eyring

2. A2-HCA0-v2 (1980-2005)
   SO2 emissions replaced with emissions from EDGAR 4.1 to fix overestimate in HCA0-v1over Europe.

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

4. A2-ACCMIP (1980-2010)
   ACCMIP is a technology based inventory which was created Lamarque et al. for IPCC AR5 experiments in 10 year increme from 1850 to 2000; years after 2000 derived from RCP8.5; line interpolation applied for years in between (MACCity).

General Features

	A2-HCA0-v1	A2-HCA0-v2	China/India	A2-ACCMIP
Spatial Resolution	1x1	1x1	0.1x0.1	0.5x0.5
Temporal Resolution	Yearly	Yearly	Monthly	Yearly
Period	1980-2007	1980-2005	1996-2010	1980-2010

China/India: Residential sector with monthly variation per provin
Aircraft emissions: 1x1, monthly, 1976-2010

Land-based Anthropogenic Emissions

Wide variation of emission rates for different types of processes and control technolo
In rapidly developing countries (China, India) new technologies cause significant cha
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:

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

EF is the net emission factor and is given b

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

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

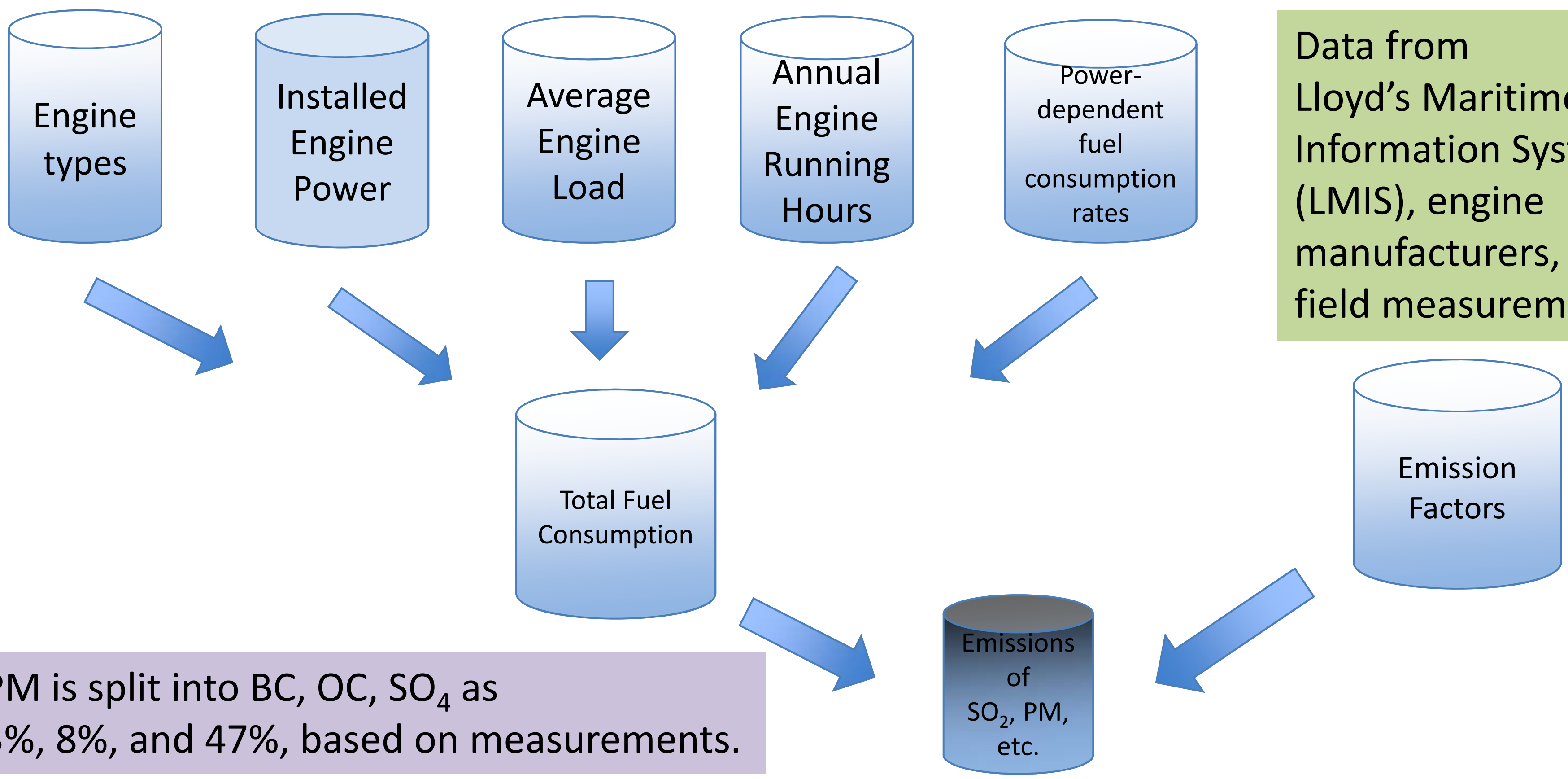
$A_{i,l,m}$: activity rates (fuel consumption rates)
$X_{i,l,m,n}$: fraction of fuel (product) that is
consumed by a specific technology.
EF_{PM}: bulk particulate emission factor
$F_{1.0}$: fraction with d < 1 μm
F_{BC} (F_{OC}): fraction of BC (OC)
$F_{control}$: unfiltered fraction of PM
η_k: removal efficiency of technology k
S and S_R: 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

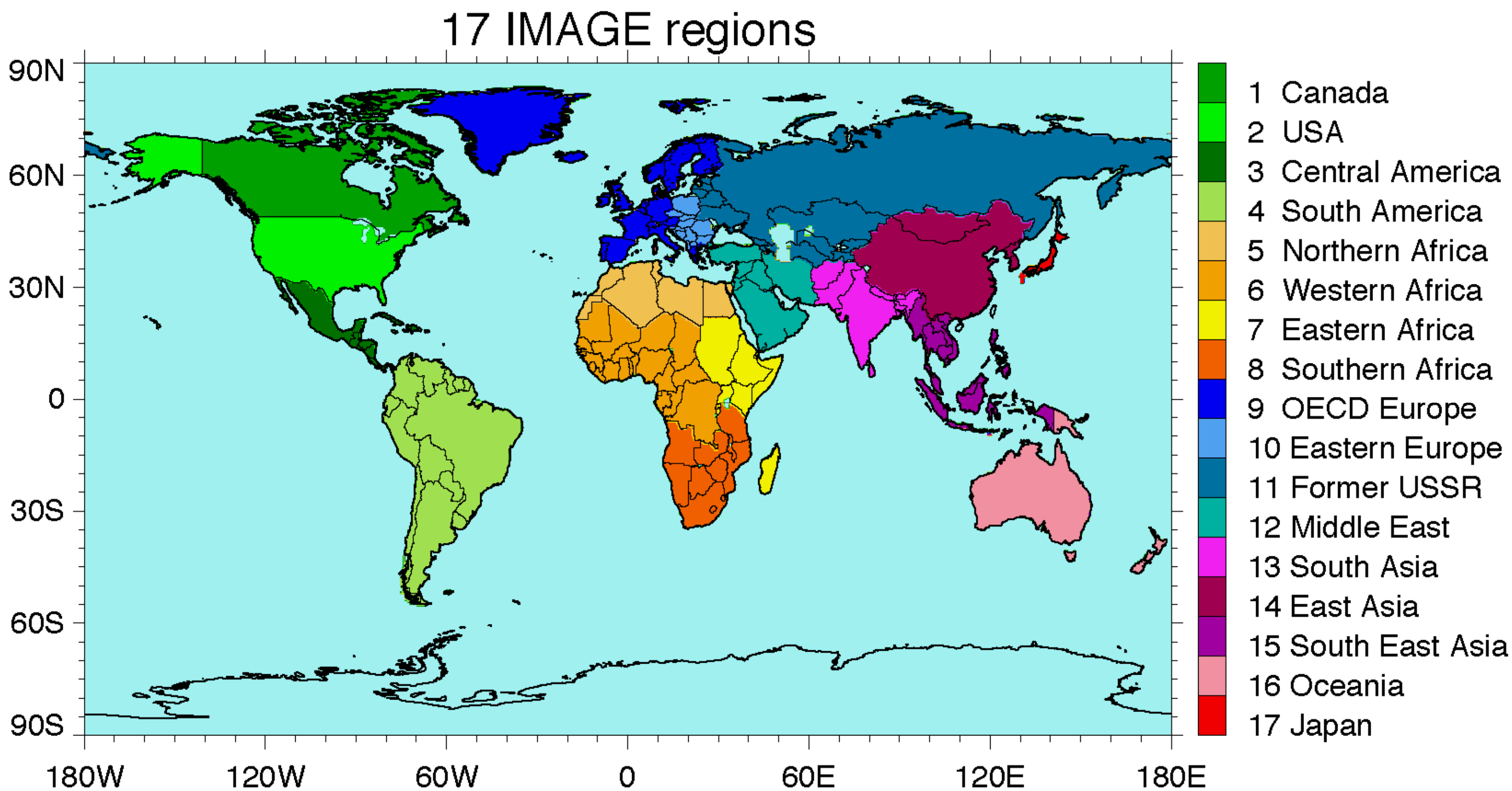


Data from Lloyd's Maritime Information System (LMIS), engine manufacturers, and field measurements.

PM is split into BC, OC, SO_4 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.:

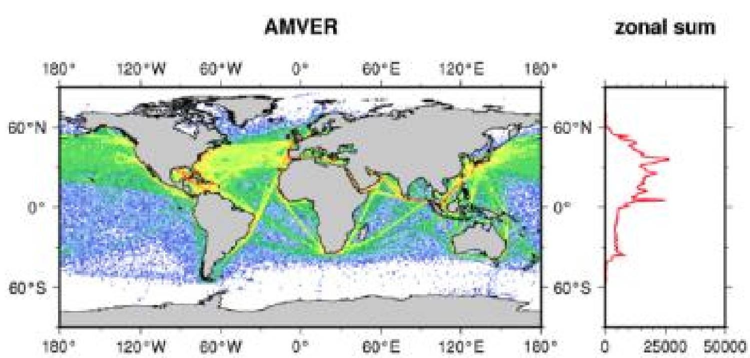
Population distribution from LandScan Global Population Dataset (ORNL)

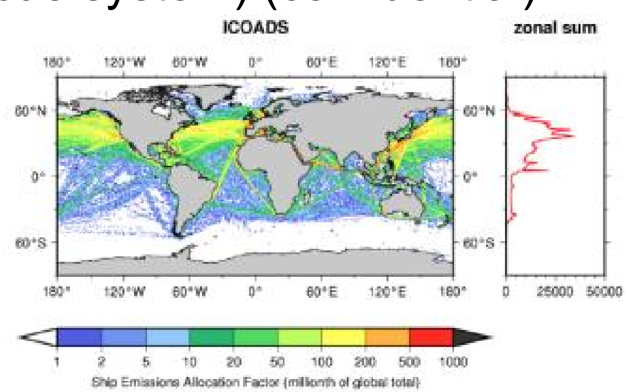
Urban and rural population data from the Global Rural-Urban Mapping Project (GRUMP (CIESIN, Columbia University)

Road networks from the Defense Mapping Agency (DMA)

Point Source information for power plants in some cases

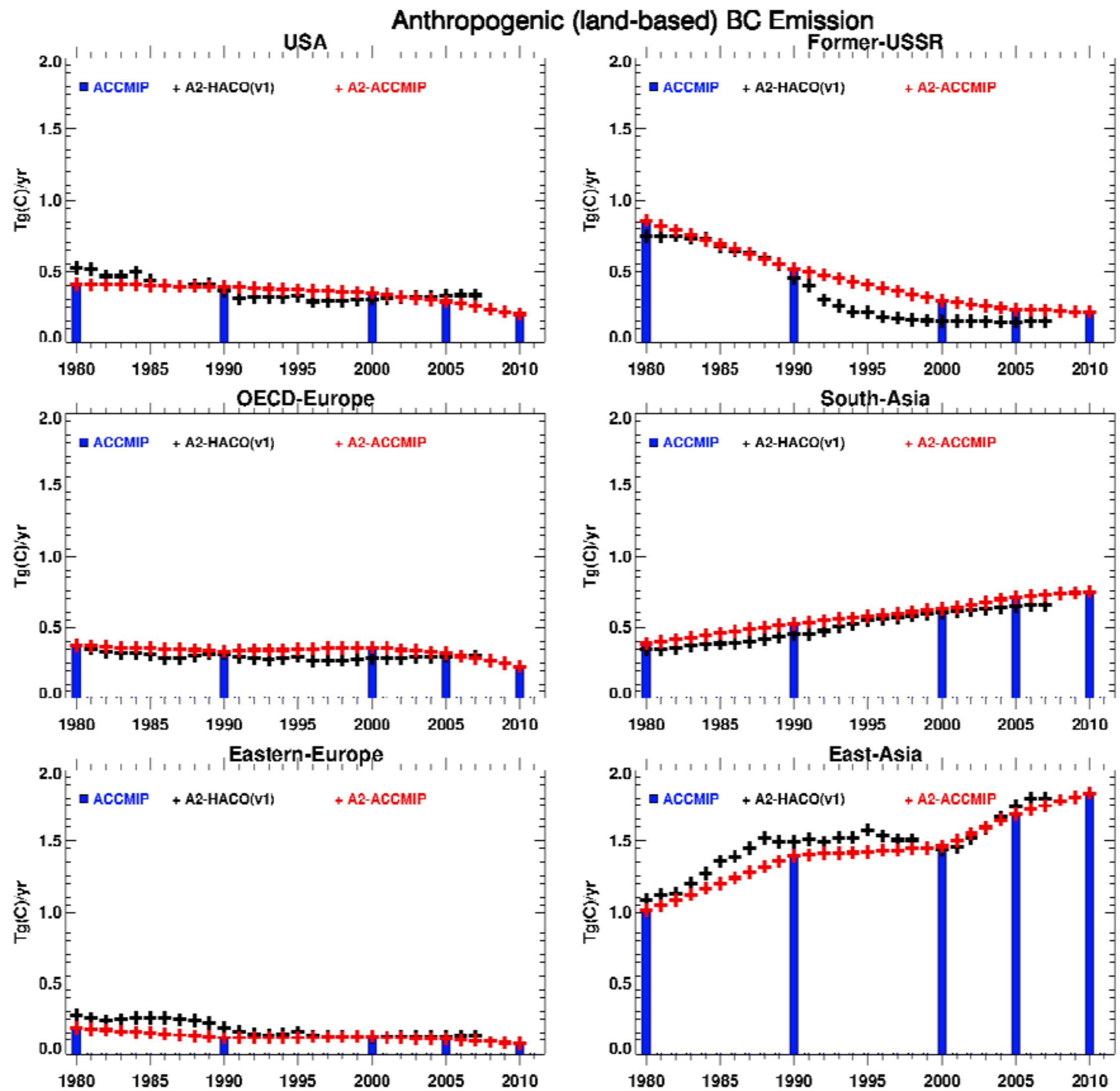
Shipping routes:
International Comprehensive Ocean-Atmosphere Data Set (ICOADS) (freely available)
AMVER (Automated Mutual-assistance Vessel Rescue system) (confidential)



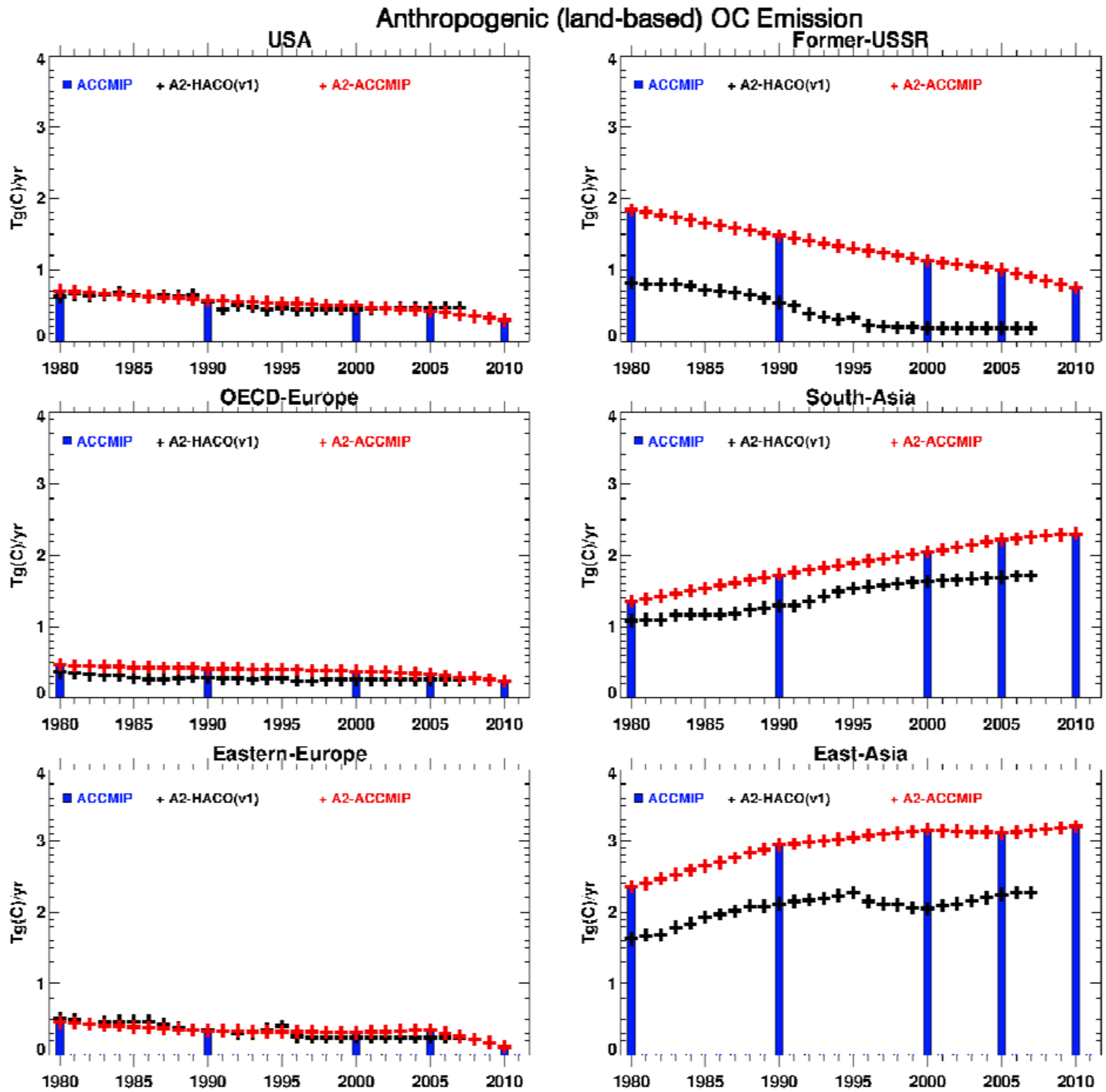


BC Land-based Emissions

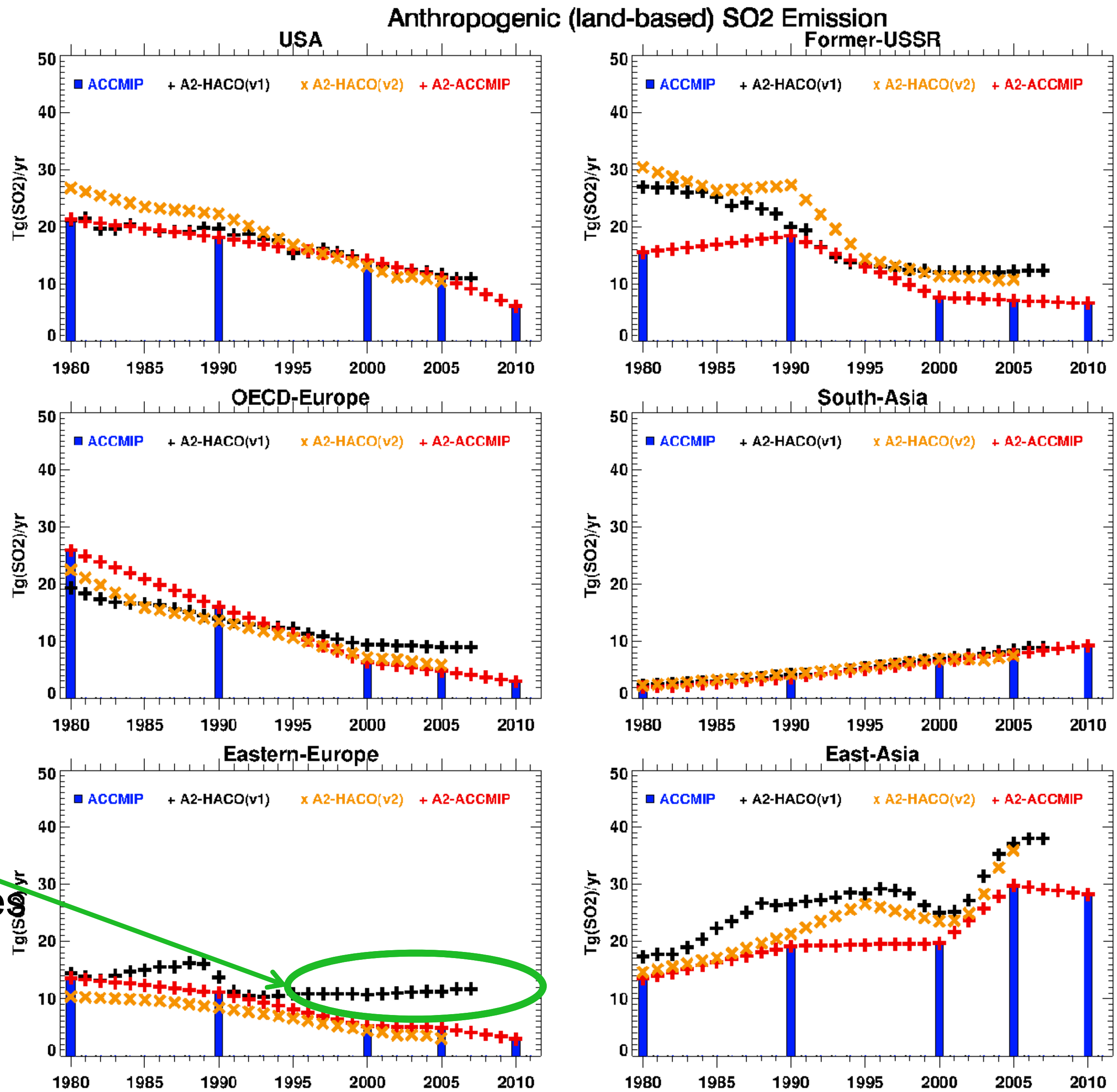
Decline in residential fuel use and transport sector from 1995 to 1996 in U.S.



OC Land-based Emissions

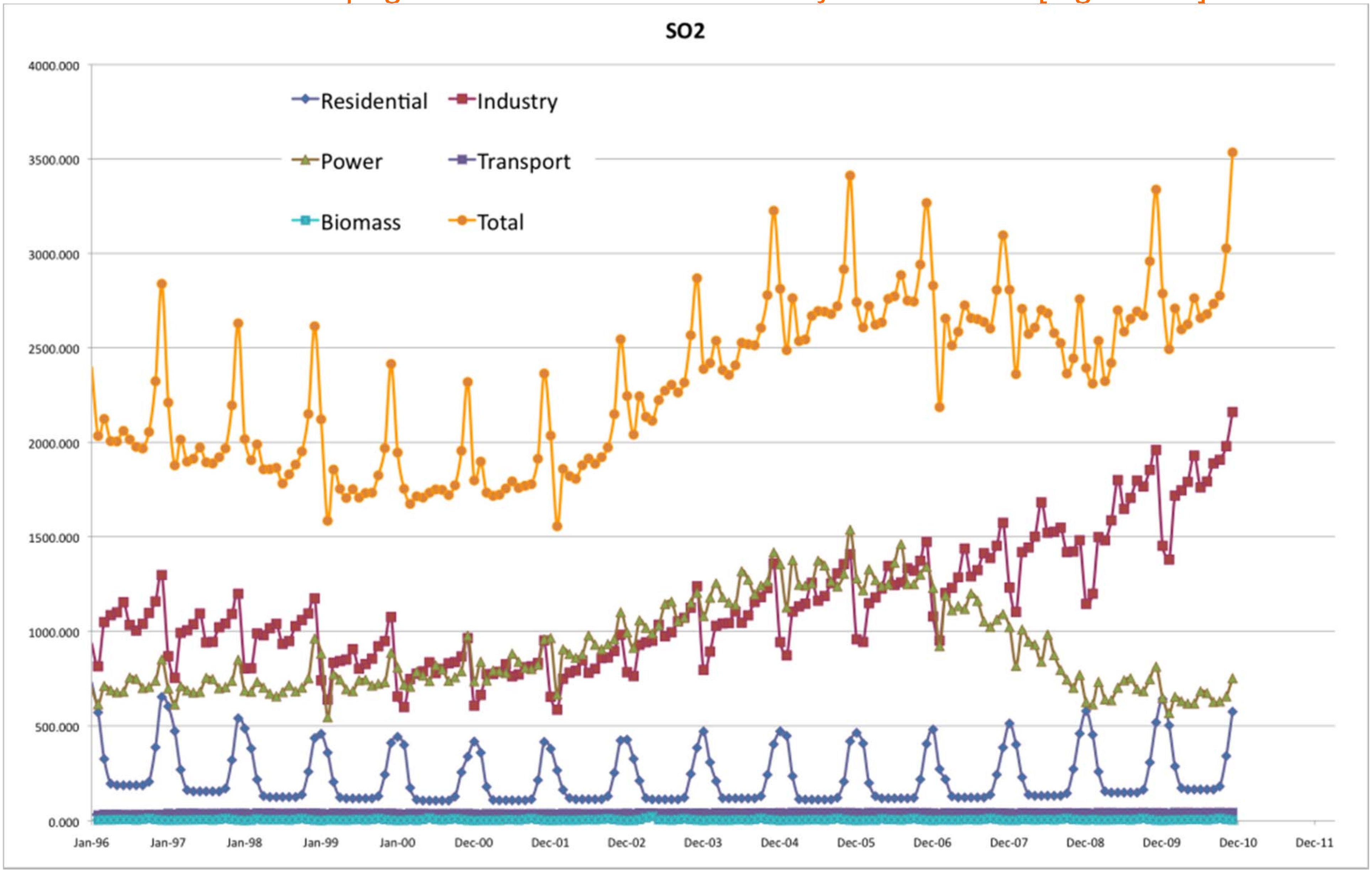


SO2 Land-based Emissions

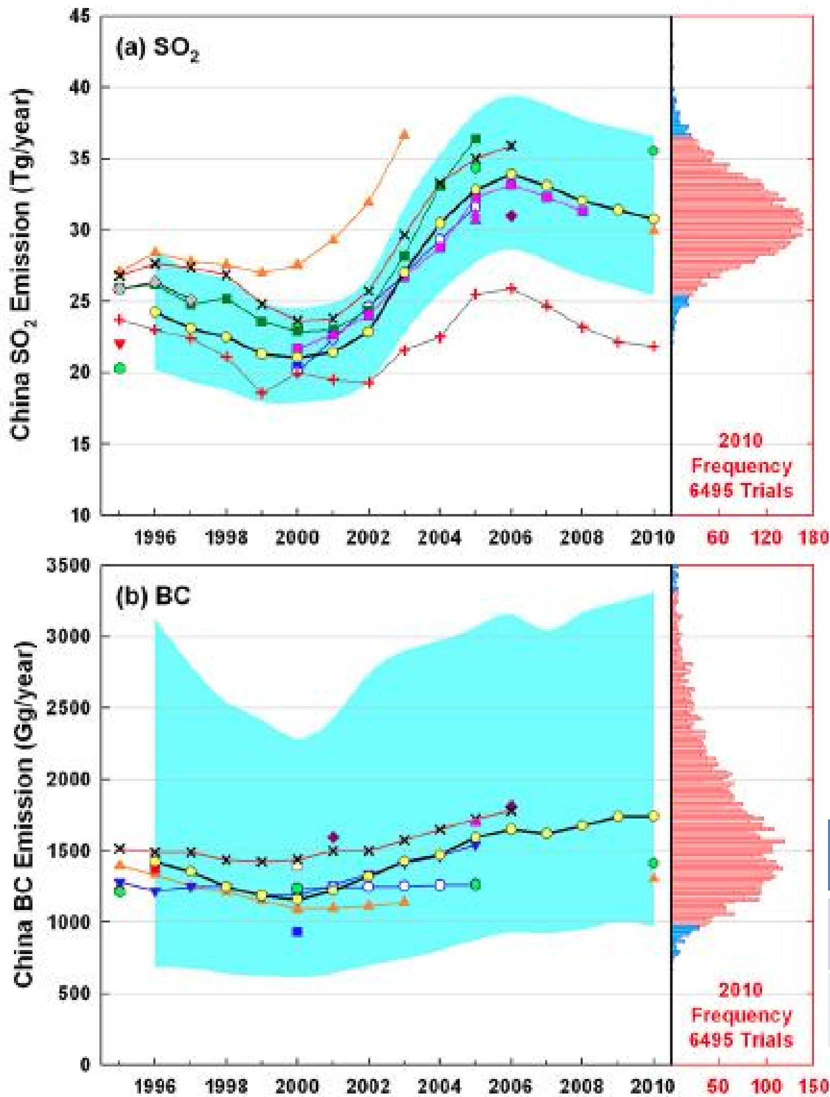


V1 trend probably overestimated;
SO2 reduction measures not accurate

Total Anthropogenic Emission over China by Sector: SO2 [Gg/month]



Uncertainty Estimates for China/India



Lu et al., 2011

Determine probability distribution for each input parameter.
Run ≈6000 Monte Carlo simulations to generate 95% CIs.

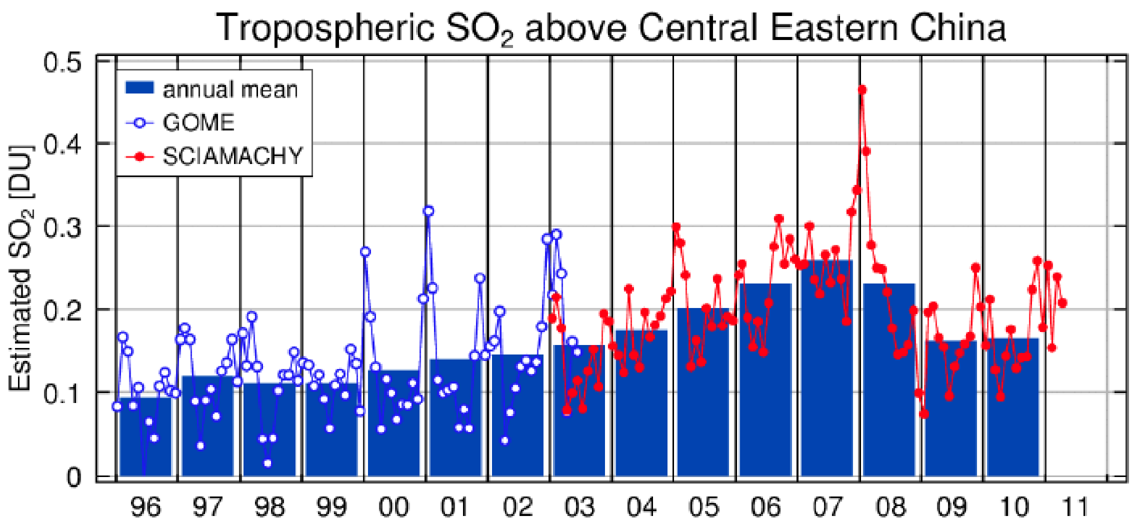
SO2 parameters: mostly normal distribution
BC/OC emission factors: lognormal

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

	SO2	BC	OC
China	-16% to 17%	-43% to 93%	-43% to 80%
India	-15% to 16%	-41% to 87%	-44% to 92%

BC uncertainty in China decreases over time:
decreasing share of residential and industry sect

SCIAMACHY/GOME Observations

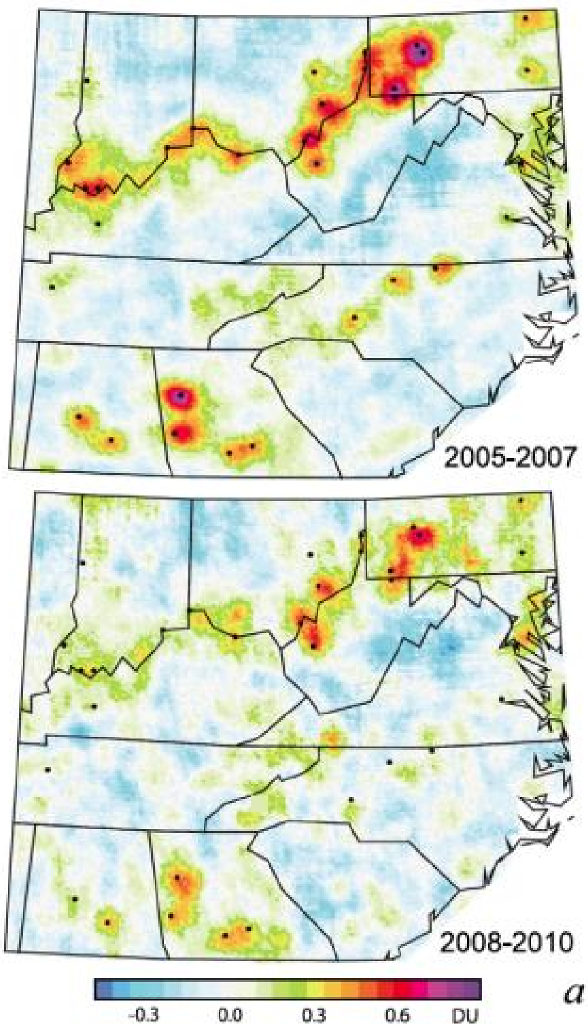


After 2007 drop due to FGD

But: slight increase in 2010
Non-power sources dominant

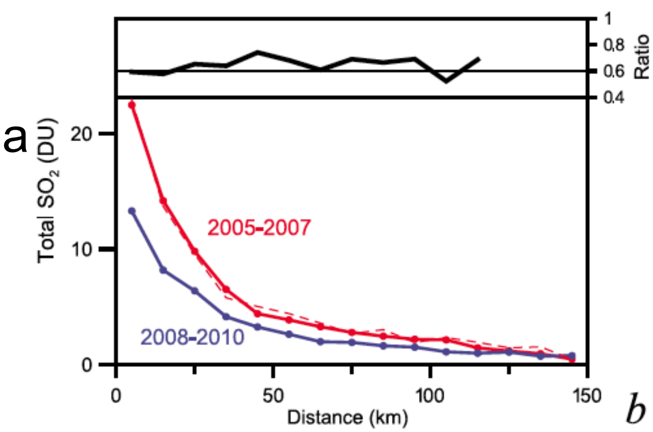
Richter (2011)

OMI SO2 observations



Mean OMI observations over Eastern US 2005-2007 v
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%.



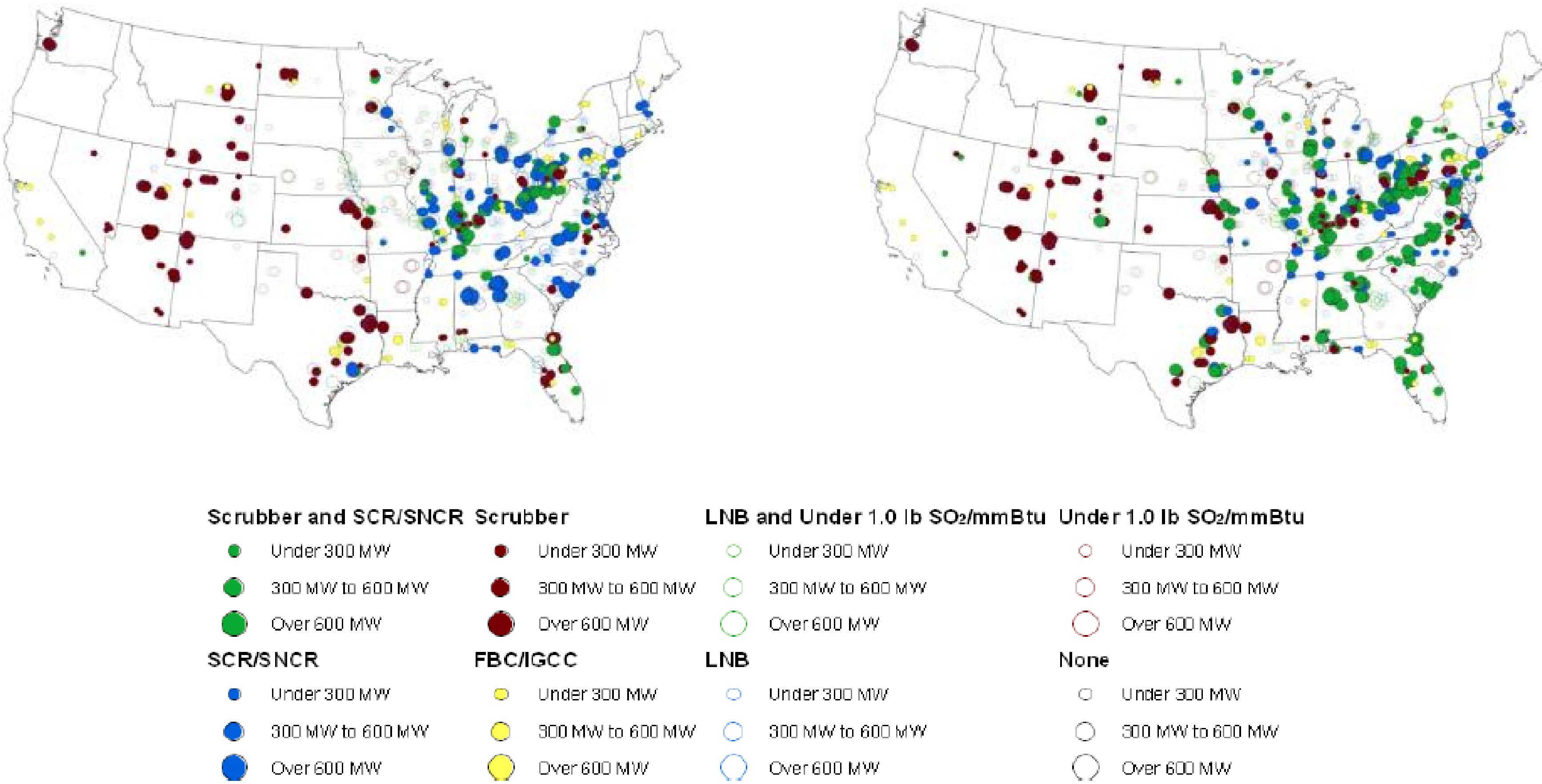
Fioletov et al., 2011

EPA Coal Controls for SO2 (and NOX)

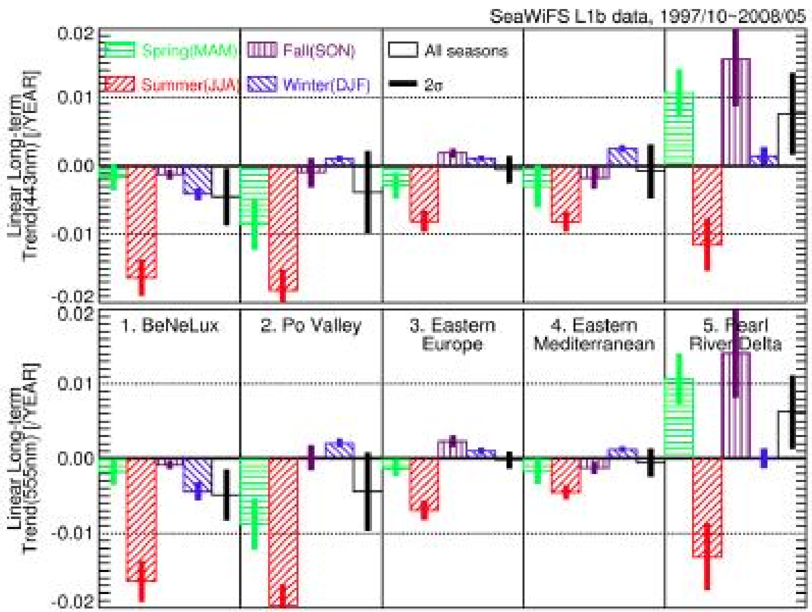
Mostly “tall” stacks (> 500 ft)

2005

2010



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



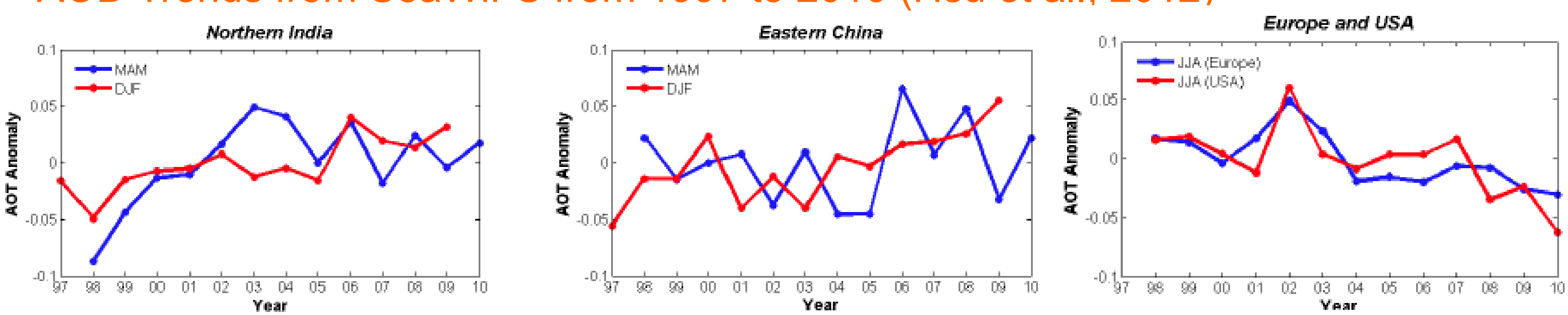
Benelux and Po-Valley spring and summer:
Mostly anthrop., downward trend

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

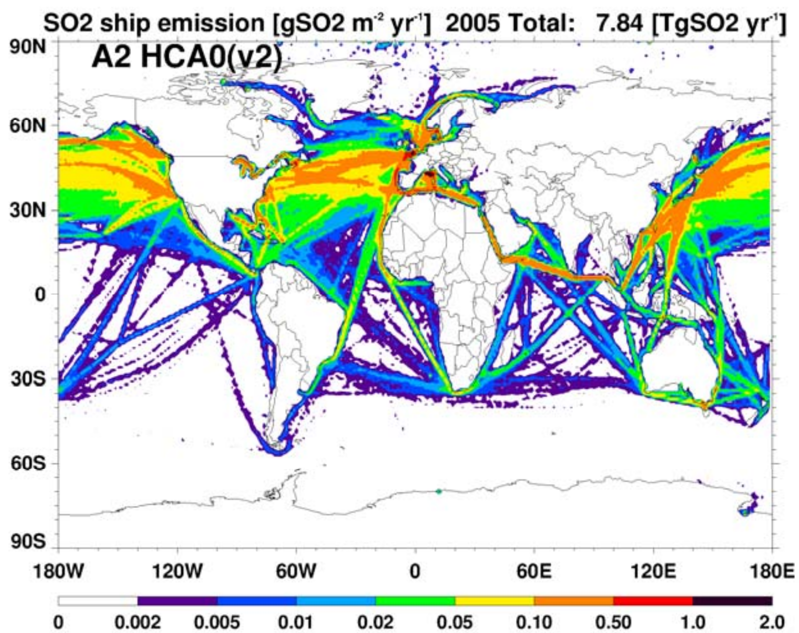
Winter: Cloud contamination; drier conditions?

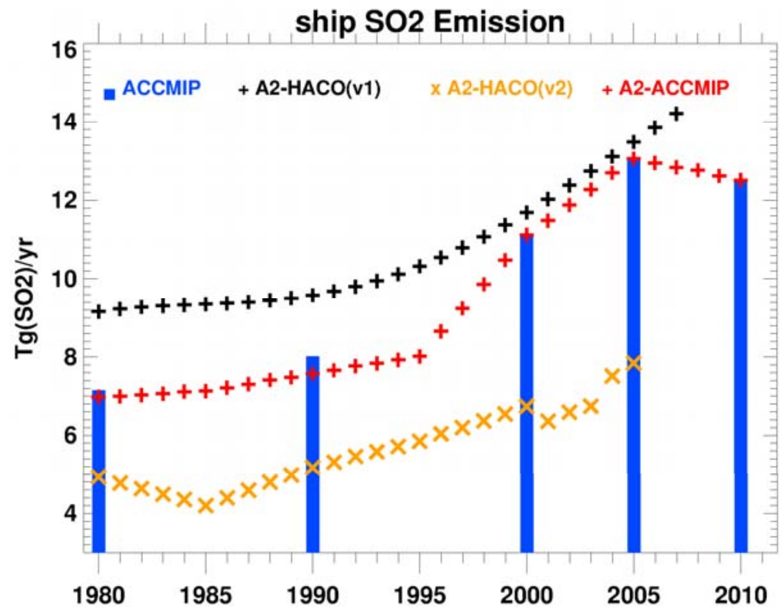
Pearl River Delta:
Upward trend (except summer)
Summer: cloud contaminated; misclassification
of aerosols and clouds?

AOD Trends from SeaWiFS from 1997 to 2010 (Hsu et al., 2012)

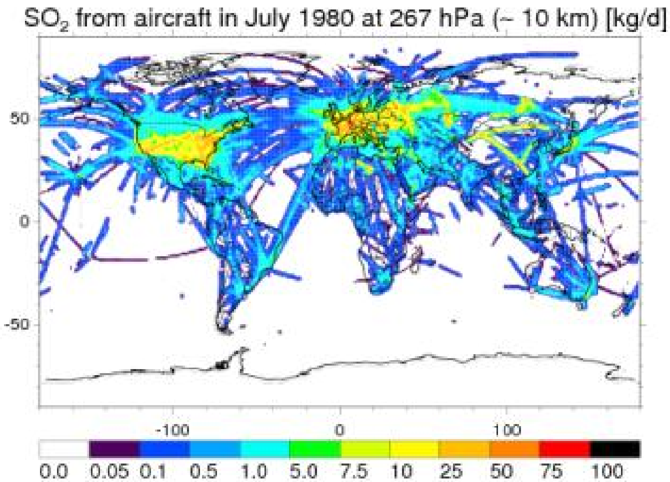


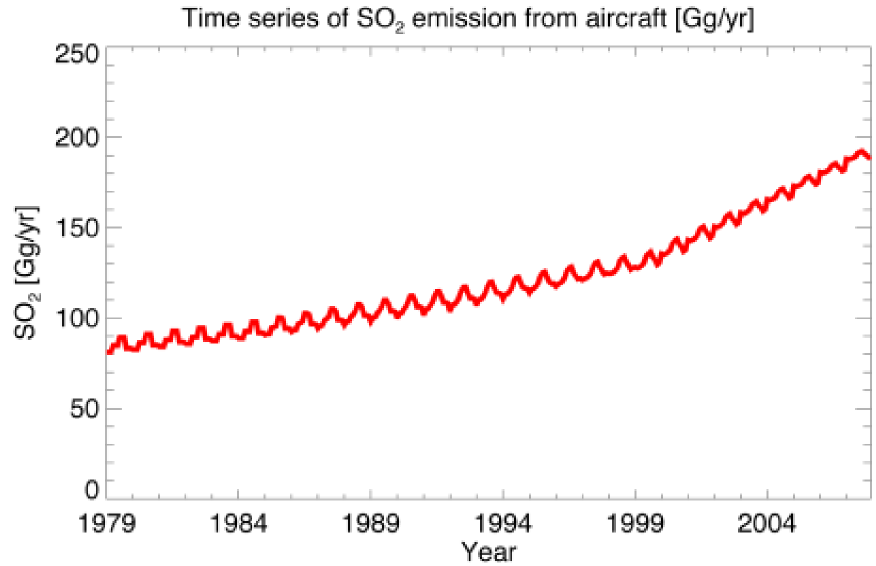
Ship Trends

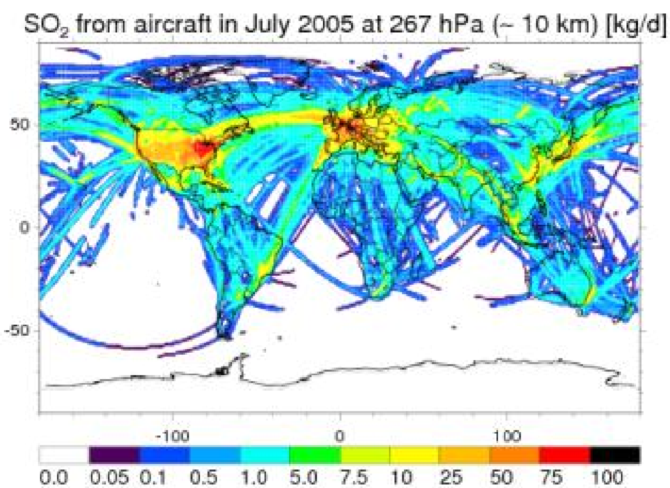

SO2 ship emission [gSO2 m-2 yr-1] 2005 Total: 7.84 [TgSO2 yr-1]
A2 HCA0(v2)
90N
60N
30N
0
30S
60S
90S
180W
120W
60W
0
60E
120E
180E
0
0.002
0.005
0.01
0.02
0.05
0.10
0.50
1.0
2.0


ship SO2 Emission
ACCMIP
A2-HACO(v1)
A2-HACO(v2)
A2-ACCMIP
Tg(SO2)/yr
16
14
12
10
8
6
4
1980
1985
1990
1995
2000
2005
2010

Aircraft Emissions



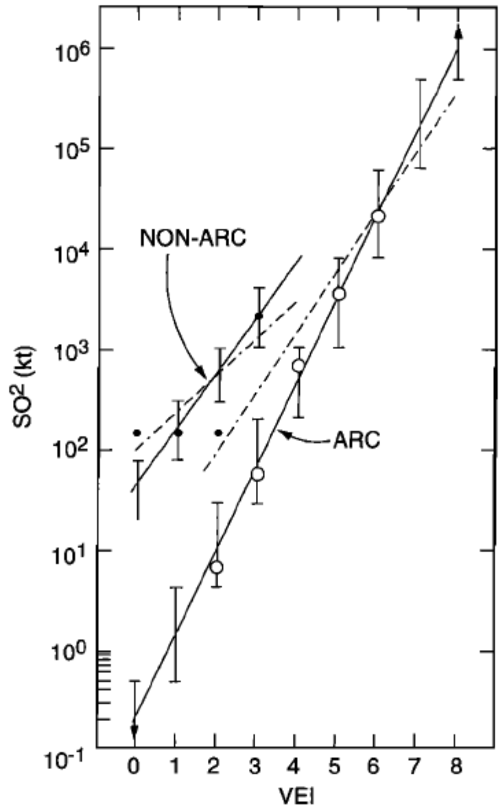




- Based on gridded burnt fuel files from AEAP project for 1976, 1984, 1992, 1999, and a projection for 2015
- Emission index (EI) of 0.8 - 0.4 for SO_2; height dependent EI for BC (≈0.04)
- OC=1/3 BC; all hydrophilic

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



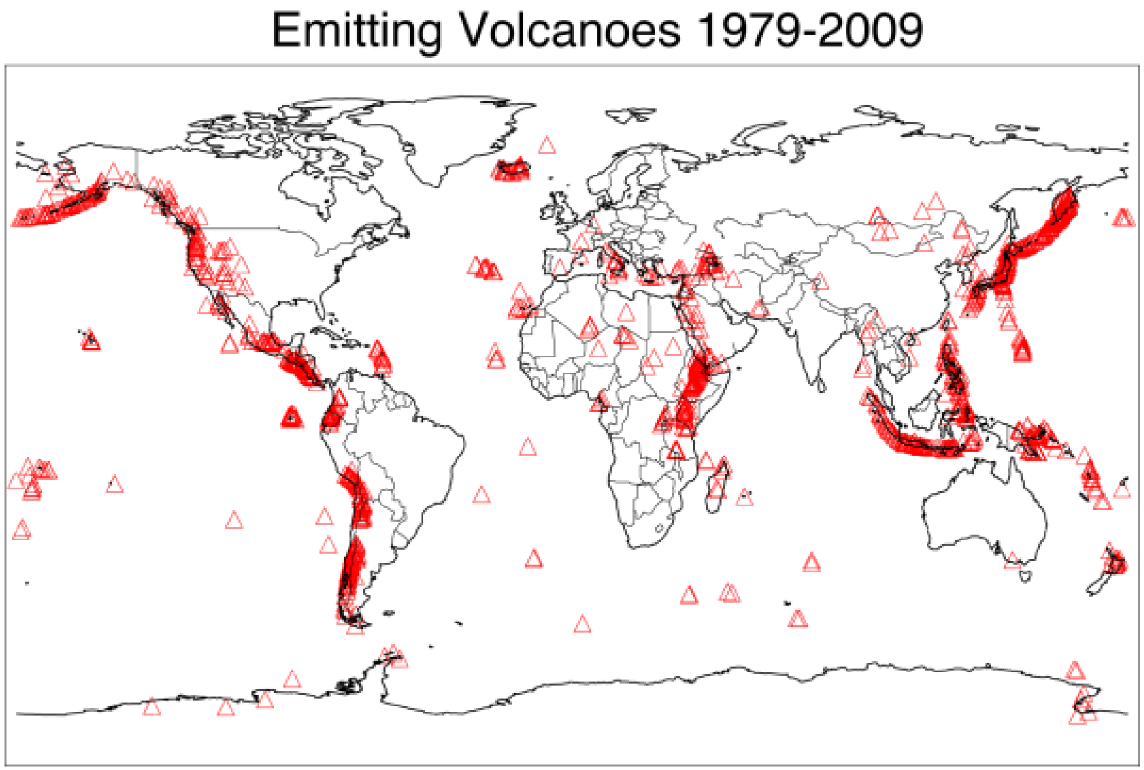
VEI/VSI classification

- 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 1. Volcanic SO_2 Index (VSI), Compared With the VEI Scale of Newhall and Self

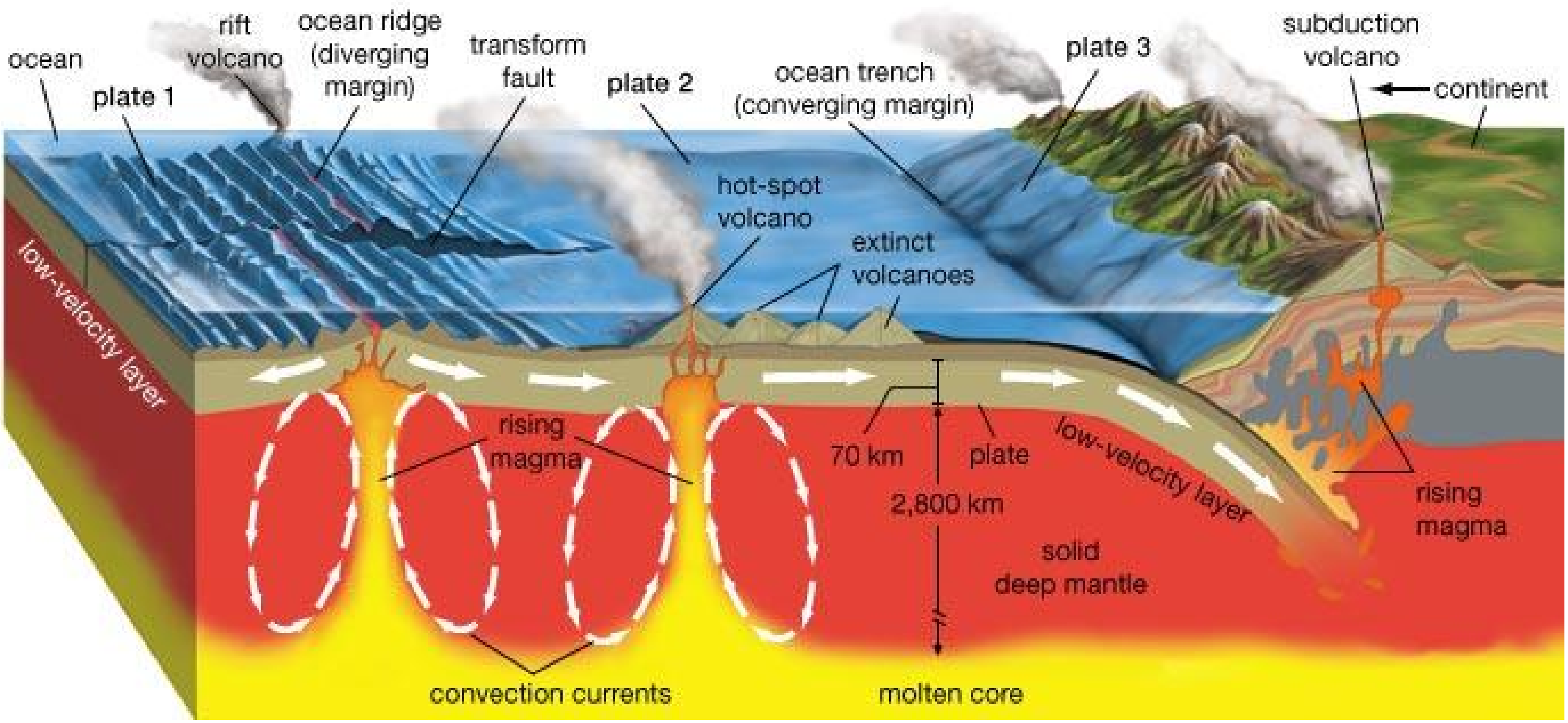
	VSI								
	0	1	2	3	4	5	6	7	8
Arc volcano SO_2, kt	<0.5	0.5–4	4–30	30–200	$0.2–1 \times 10^3$	$1–8 \times 10^3$	$0.8–6 \times 10^4$	$0.6–5 \times 10^5$	$>5 \times 10^5$
Nonarc volcano SO_2, kt	<80	80–300	$0.3–1 \times 10^3$	$1–4 \times 10^3$					
	VEI								
	0	1	2	3	4	5	6	7	8
General description	nonexplosive	small	moderate	moderate large	large	very large	very large	very large	very large
Cloud column height, km	<0.1	0.1–1	1–5	3–15	10–25	>25	>25	>25	>25
Volume of tephra, m^3 (arc only)	$<10^4$	$10^4–10^6$	$10^6–10^7$	$10^7–10^8$	$10^8–10^9$	$10^9–10^{10}$	$10^{10}–10^{11}$	$10^{11}–10^{12}$	$>10^{12}$

Distribution of



- 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

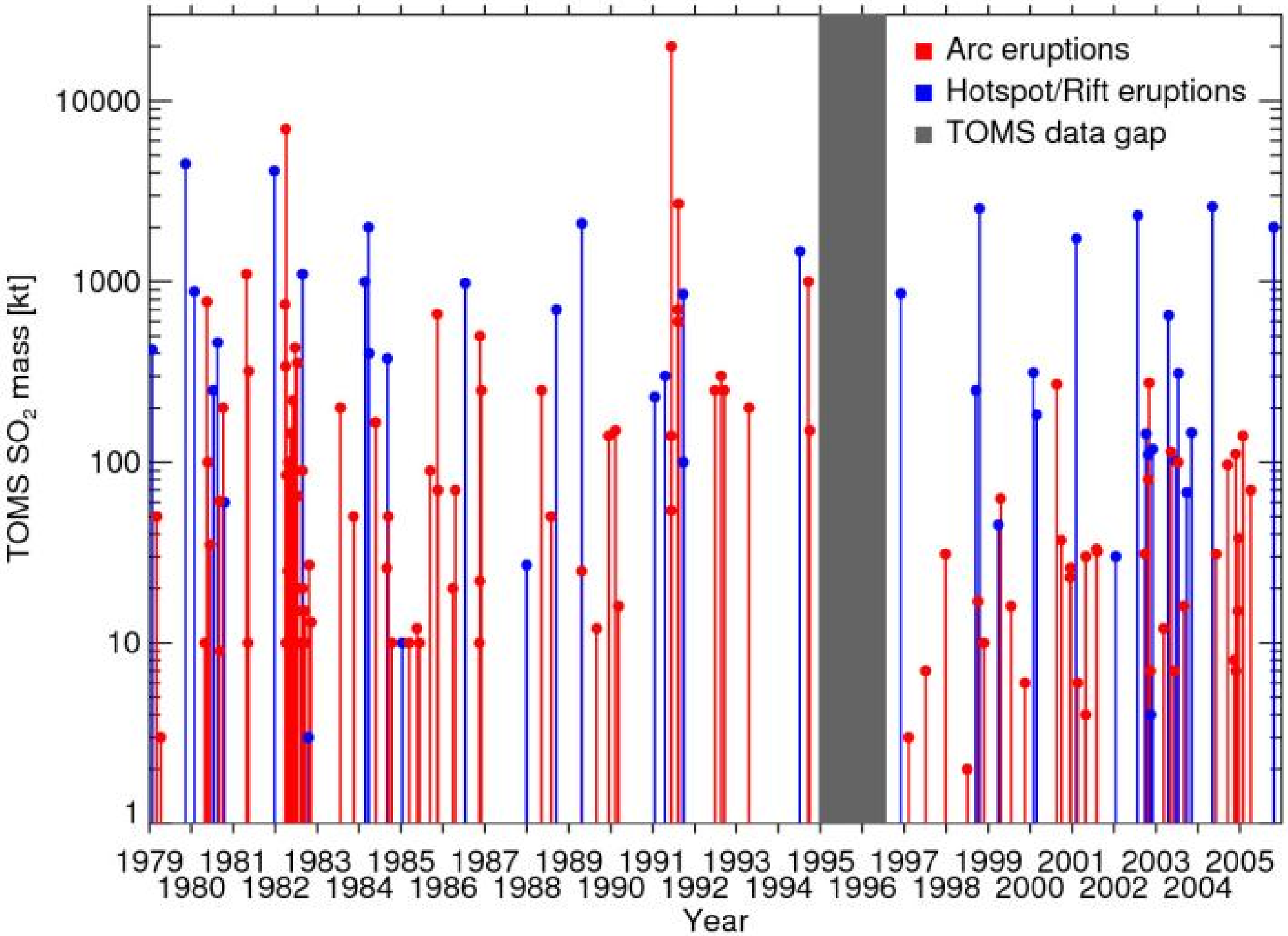
Volcano Settings



Methodology

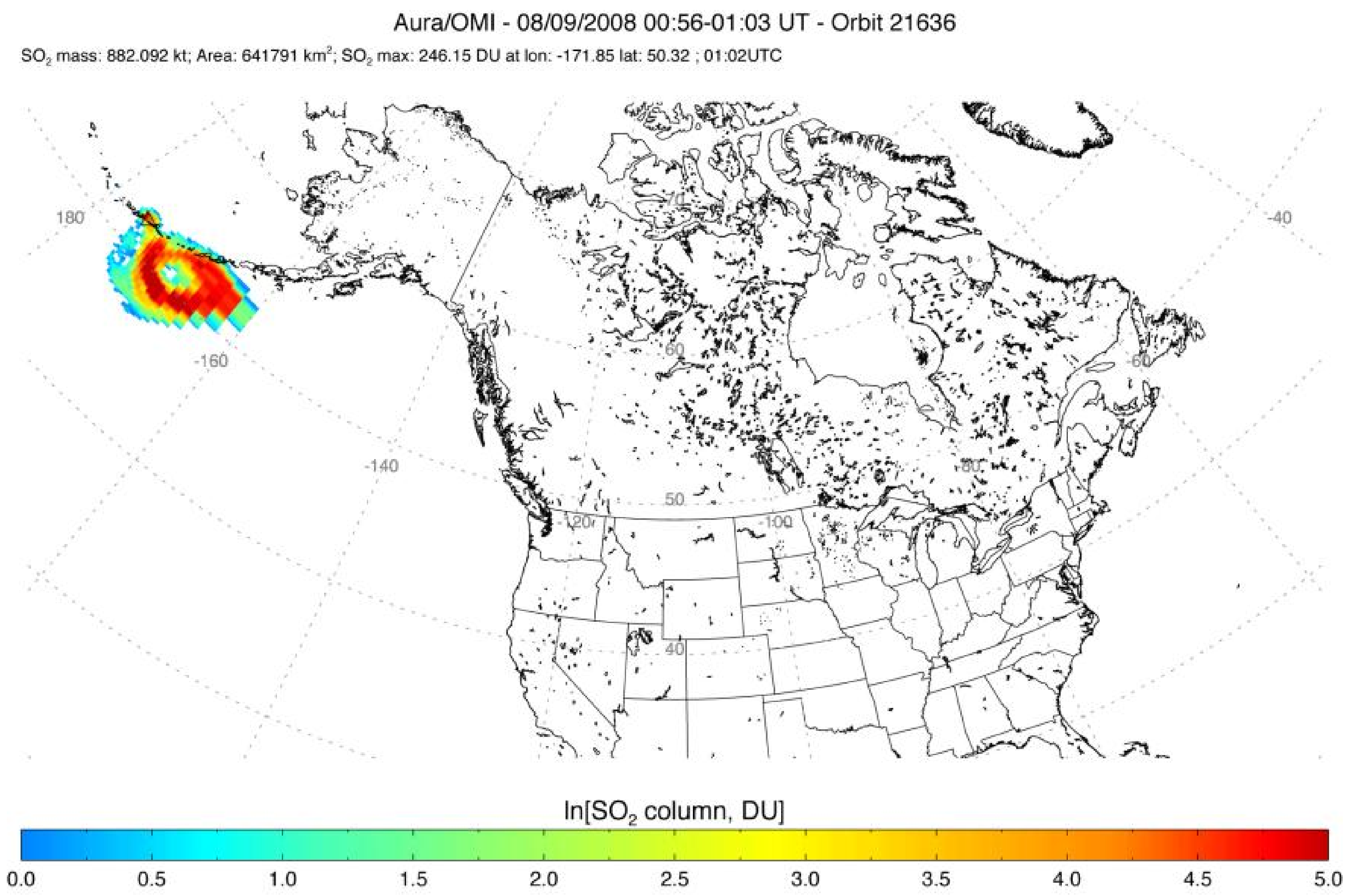
- SO_2 amount iteratively refined for individual eruptions by satellite (e.g. TOMS, OMI) and COSPEC (Correlation Spectrometer) observations, and more detailed analyses from publications
- For some eruptions with known Lava and/or Tephra volumes, the SO_2 is estimated from these amounts
- Data for quasi-continuously 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)

TOMS SO2



Currently re-processed with retrieval algorithm used for OMI

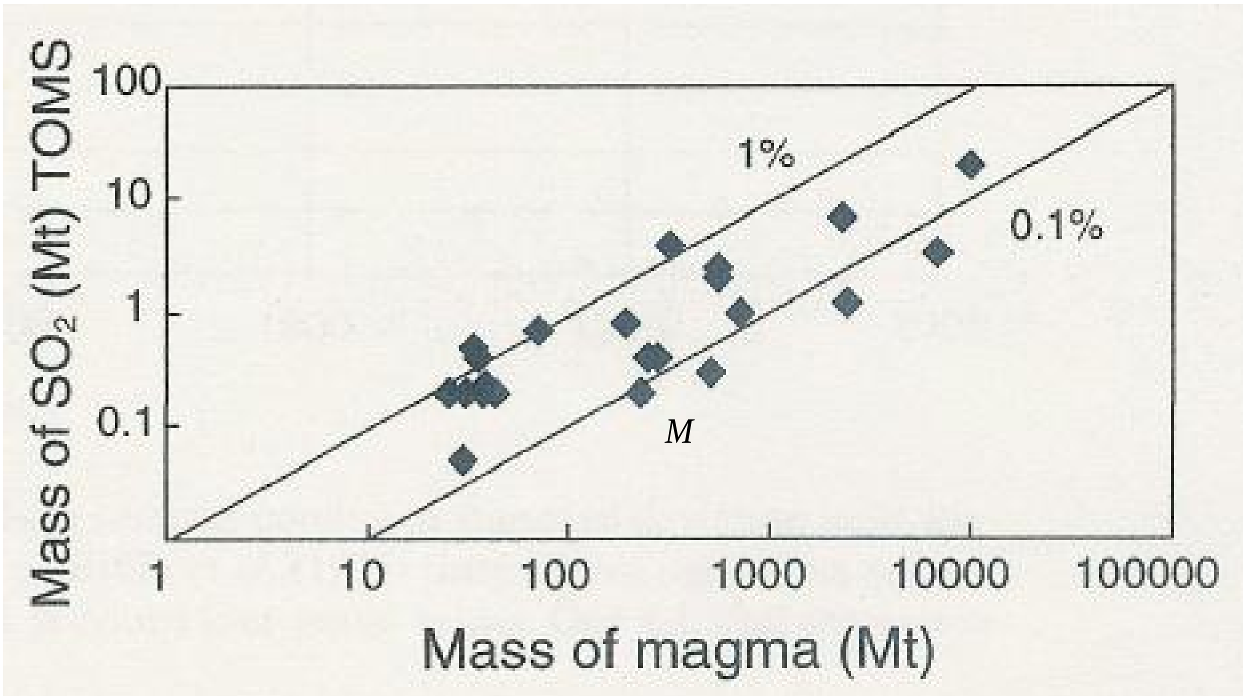
Example from OMI - Kasatochi



Volcanic SO2 Measurement Aspects

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

SO_2 related to ejected magma



Correlation of TOMS SO_2 data with erupted magma yields:

M_{SO2}(in Mt) = 1.77 (M_{magma} (in Gt))$^{0.64}$ (r^2=0.67) (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 Etı reported errors are about 20%.

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

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

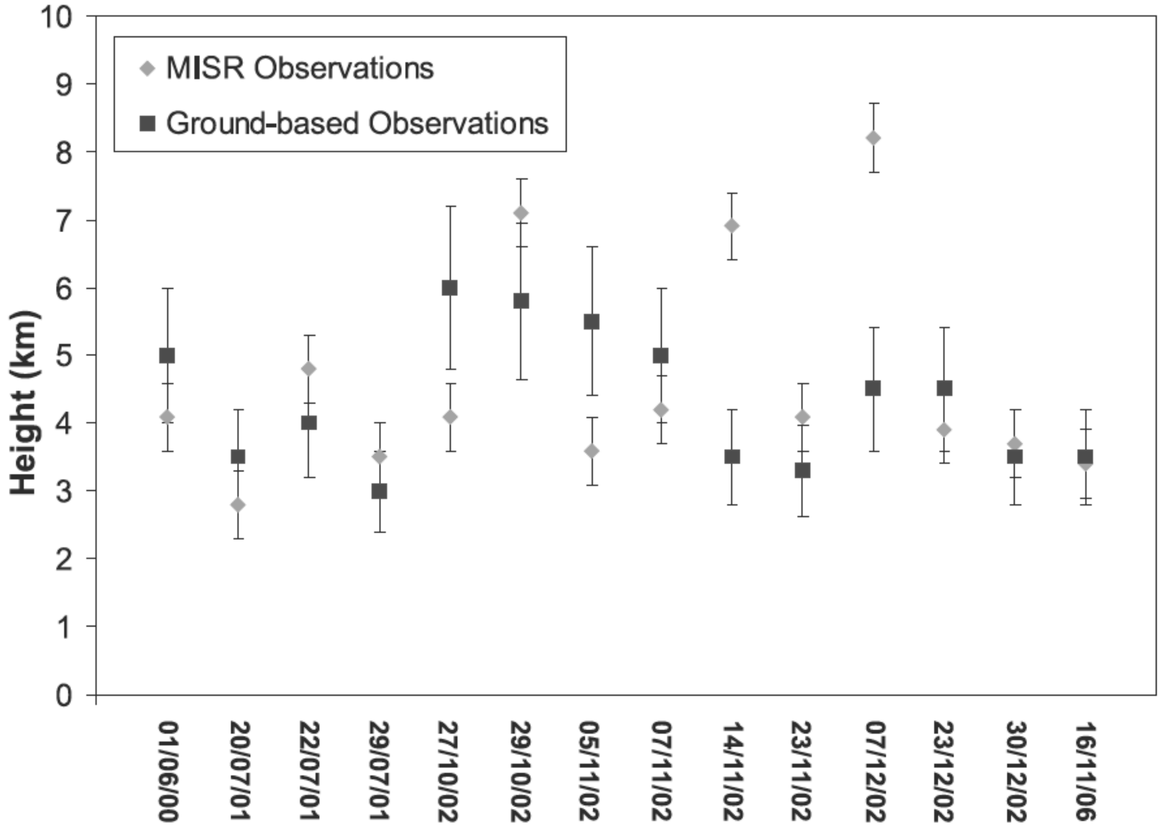
Plume Height Estimation in AeroCom

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.

SO_2 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 altitude of Etna eruption 2002-10-2

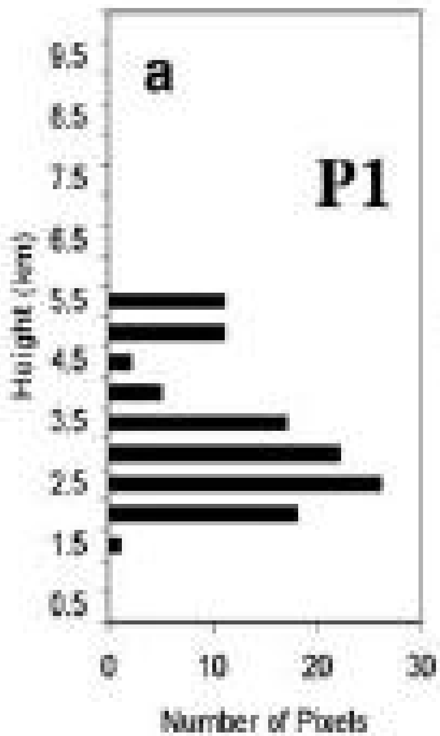


MISR provides multispectral and multiangle measurements.

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

Mean uncertainty of height: ± 0.5 km

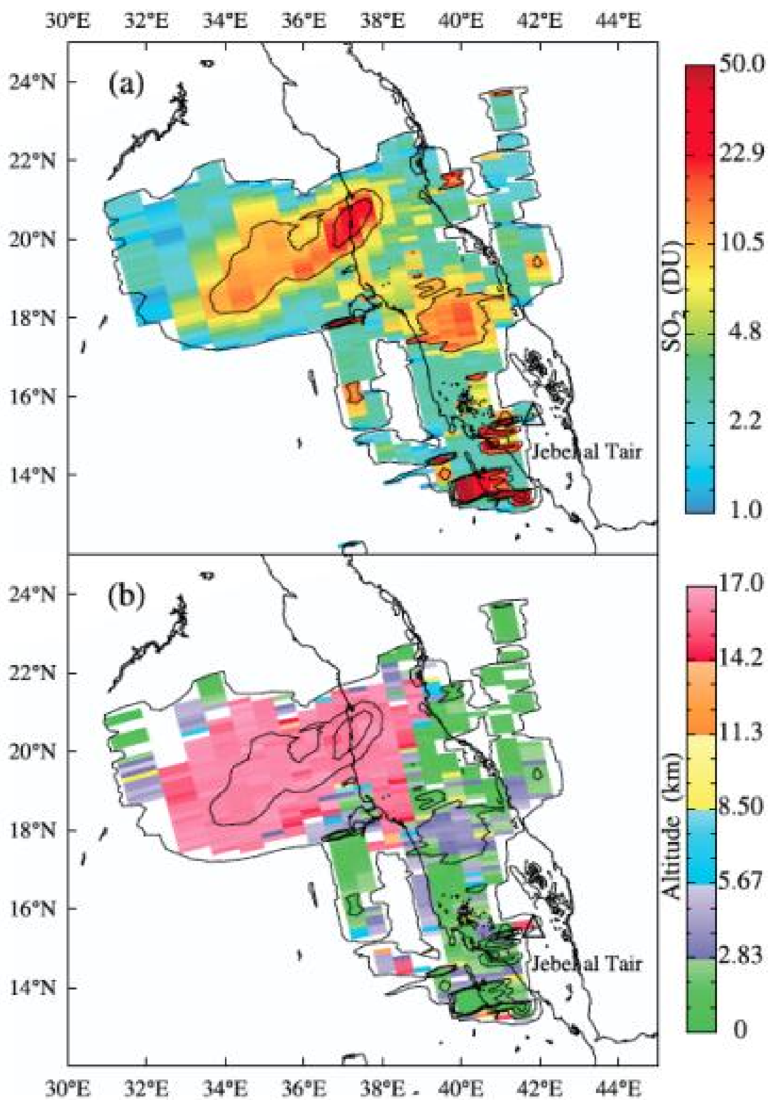
MISR: Vertical Distribution of Plume



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

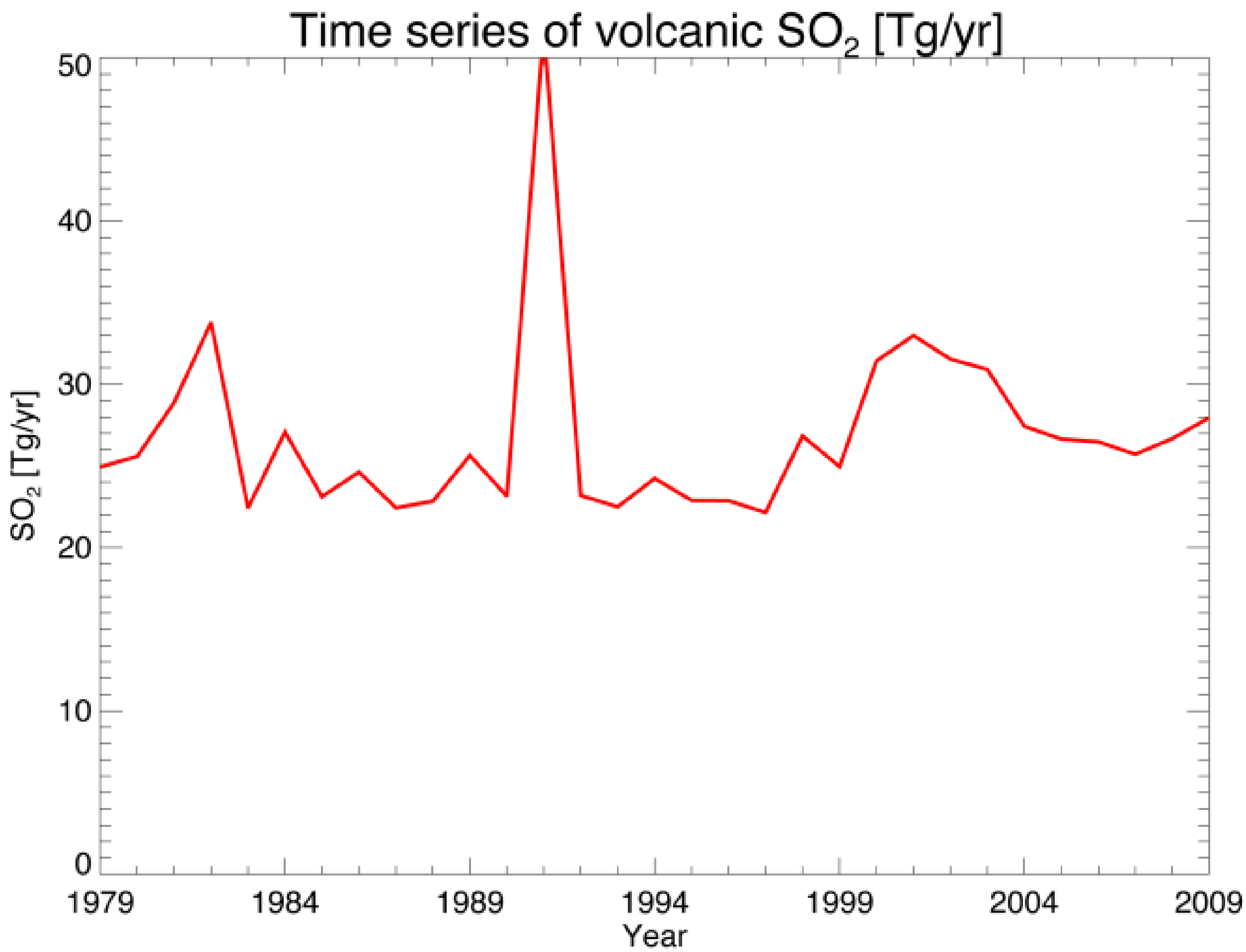
Histogram of MISR Stereo product plume heigh
the site of the volcano. In this case the aerosol
are not uniformly distributed within the column
(Kahn et al.).

Plume Altitude from OMI UV measurements



Yang et al. have estimated SO2 plume heights from the eruption of Jebel al Tair (Yemen) on Septembe 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.

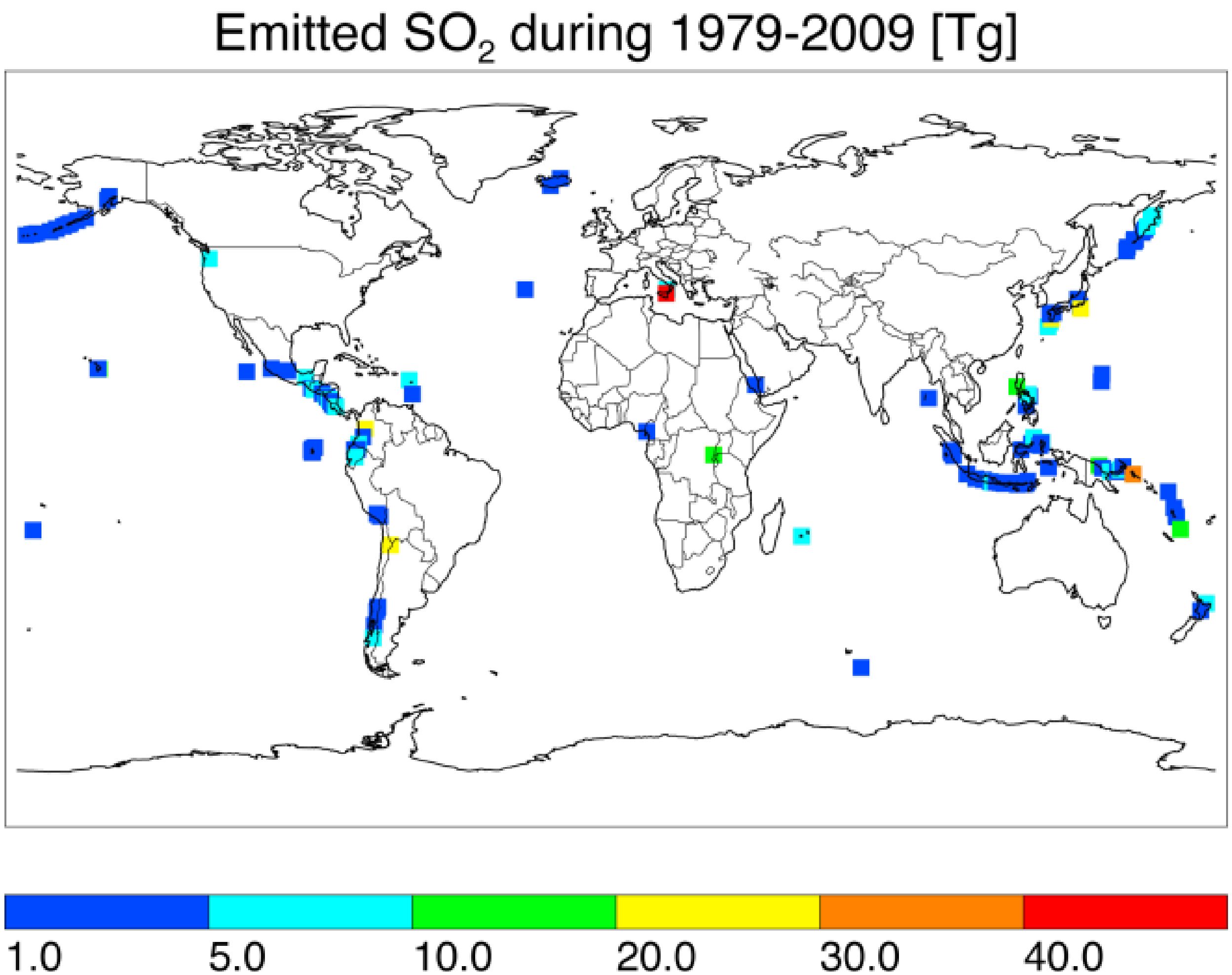
Total SO_2 per Year



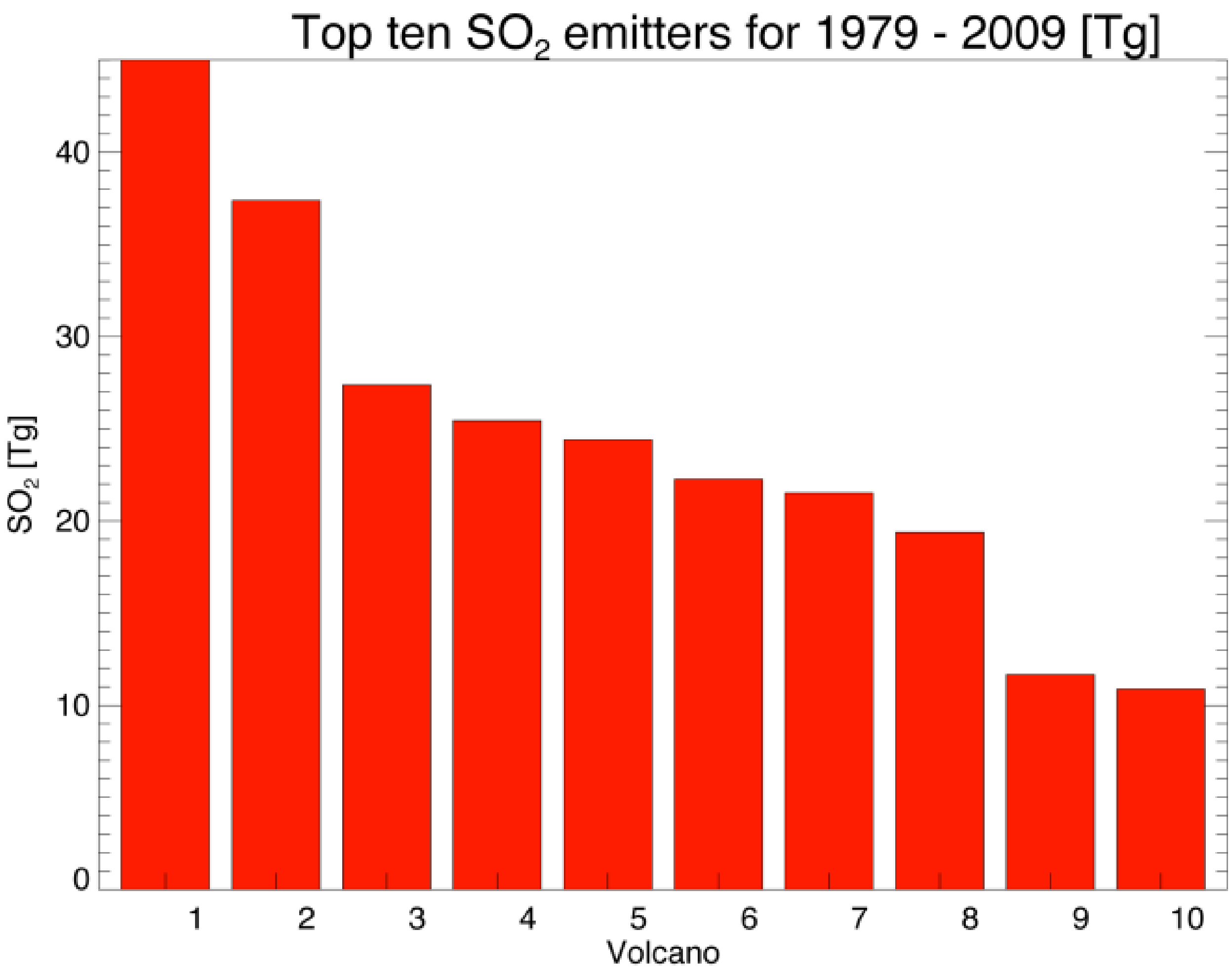
	Minimum	Maximum	Average	Median
Total SO_2/year	22 Tg	52 Tg	27 Tg	26 Tg

About 11-13 Tg/year from silent degassing included

Total SO_2 per Volcano

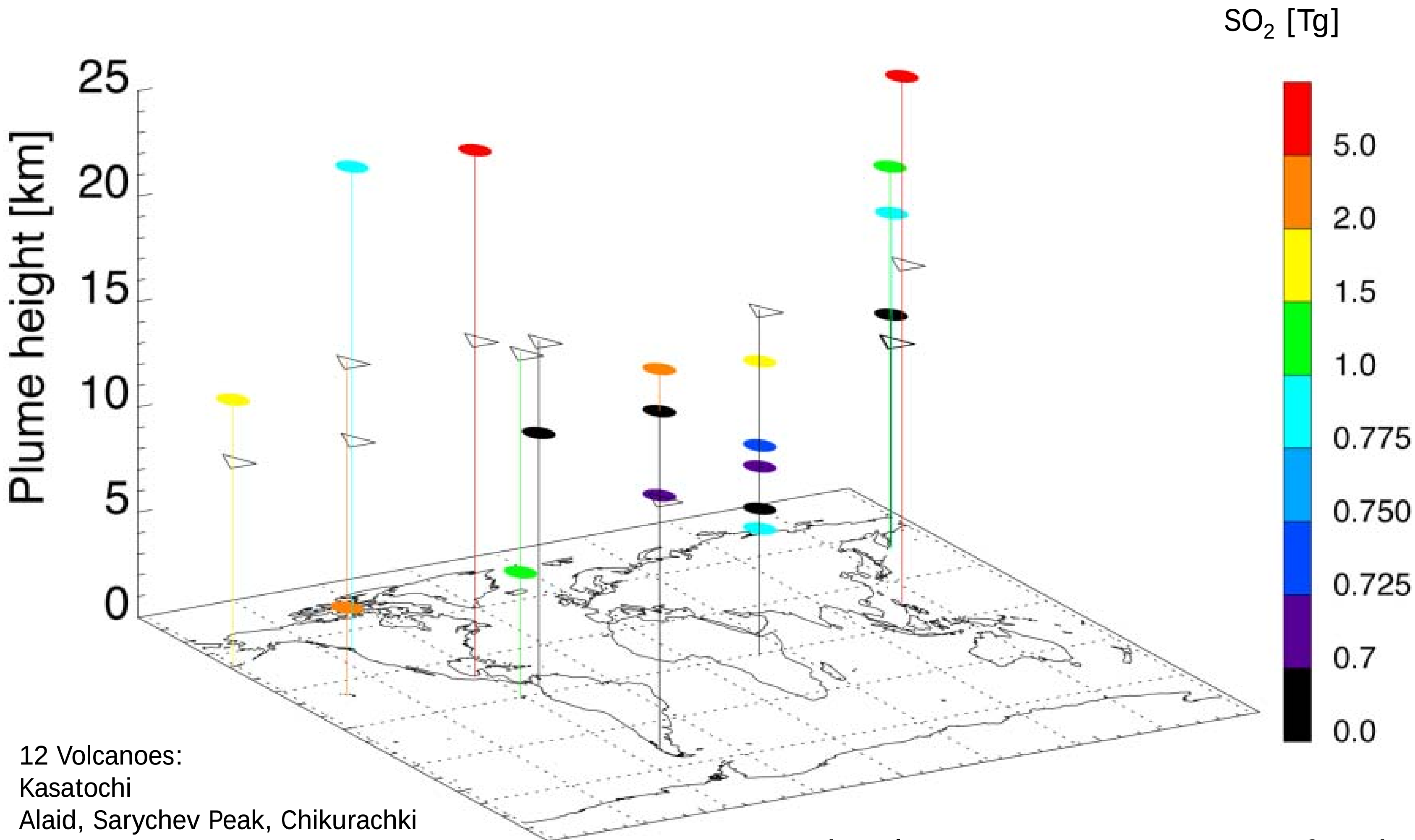


Strongest Emitters



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

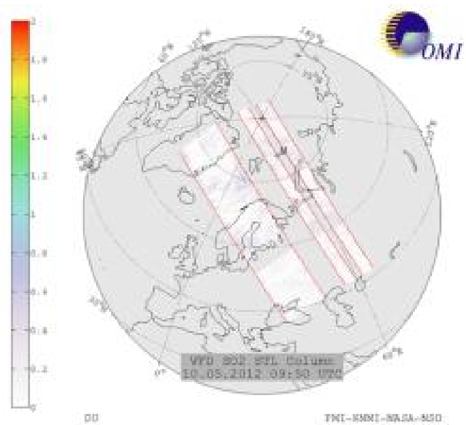
Largest 20 Explosive Eruptions

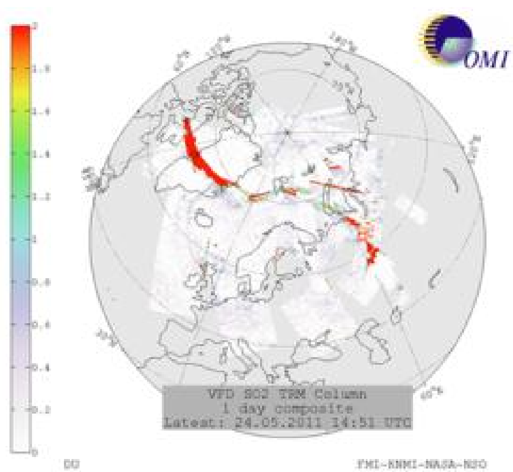


12 Volcanoes:
Kasatochi
Alaid, Sarychev Peak, Chikurachki
St. Helens
Mauna Loa, El Chichon, Sierre Negra, Nevado del Ruiz
Nyamuragira, Pinatubo
Cerro Hudson

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 emissi
  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-consumi manual analysis and is typically not possible in NRT.

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