Direct effects of aerosols on climate: What do we know?

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IPCC Expert Meeting on Aerosols

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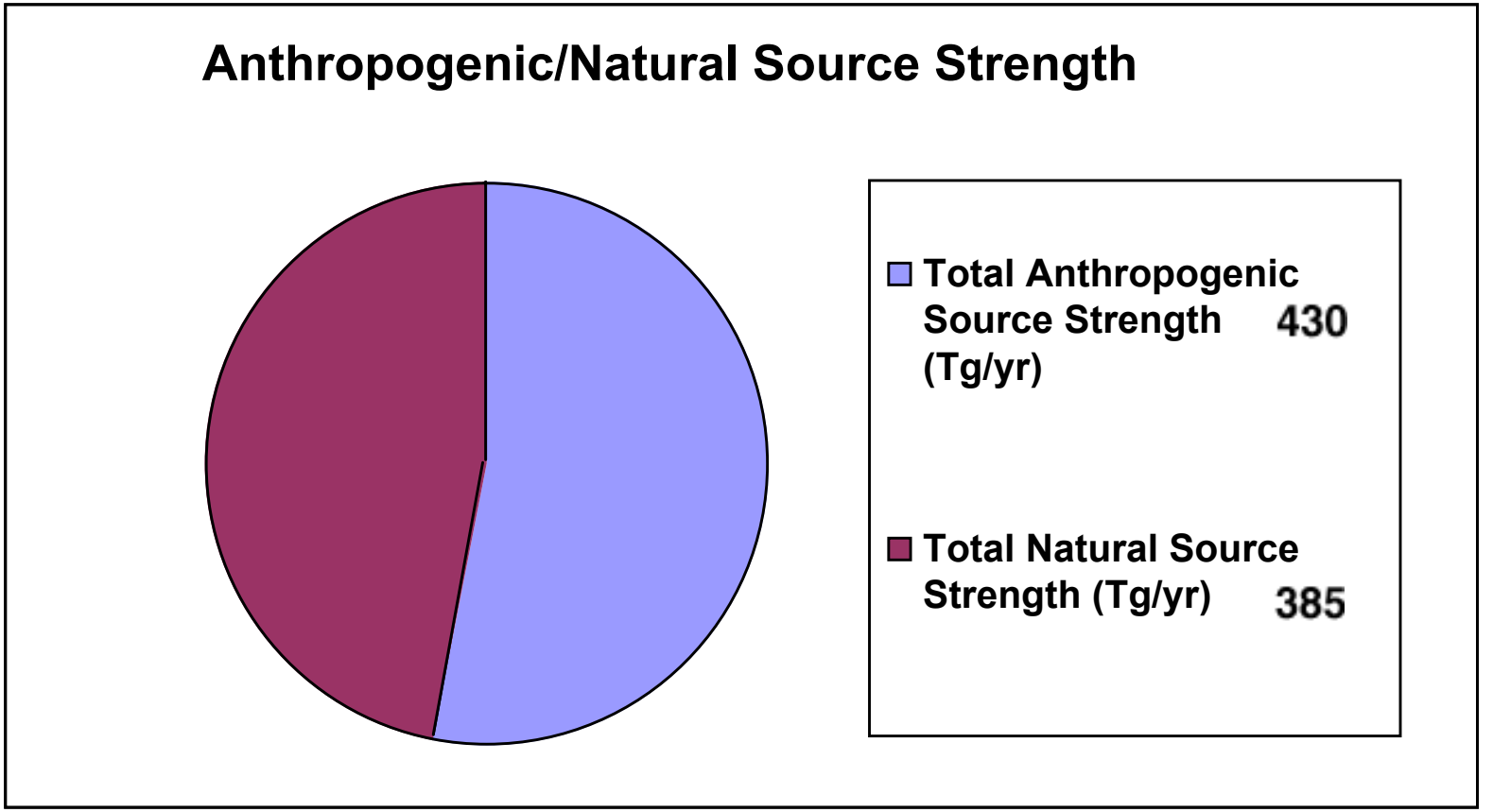
Outline

- Sources and processes determining direct forcing estimates
- Intercomparison of model results for surface concentrations, aerosol optical depth, aerosol extinction profile
- Inverse methods for improving aerosol sources
- Uncertainty in direct aerosol forcing

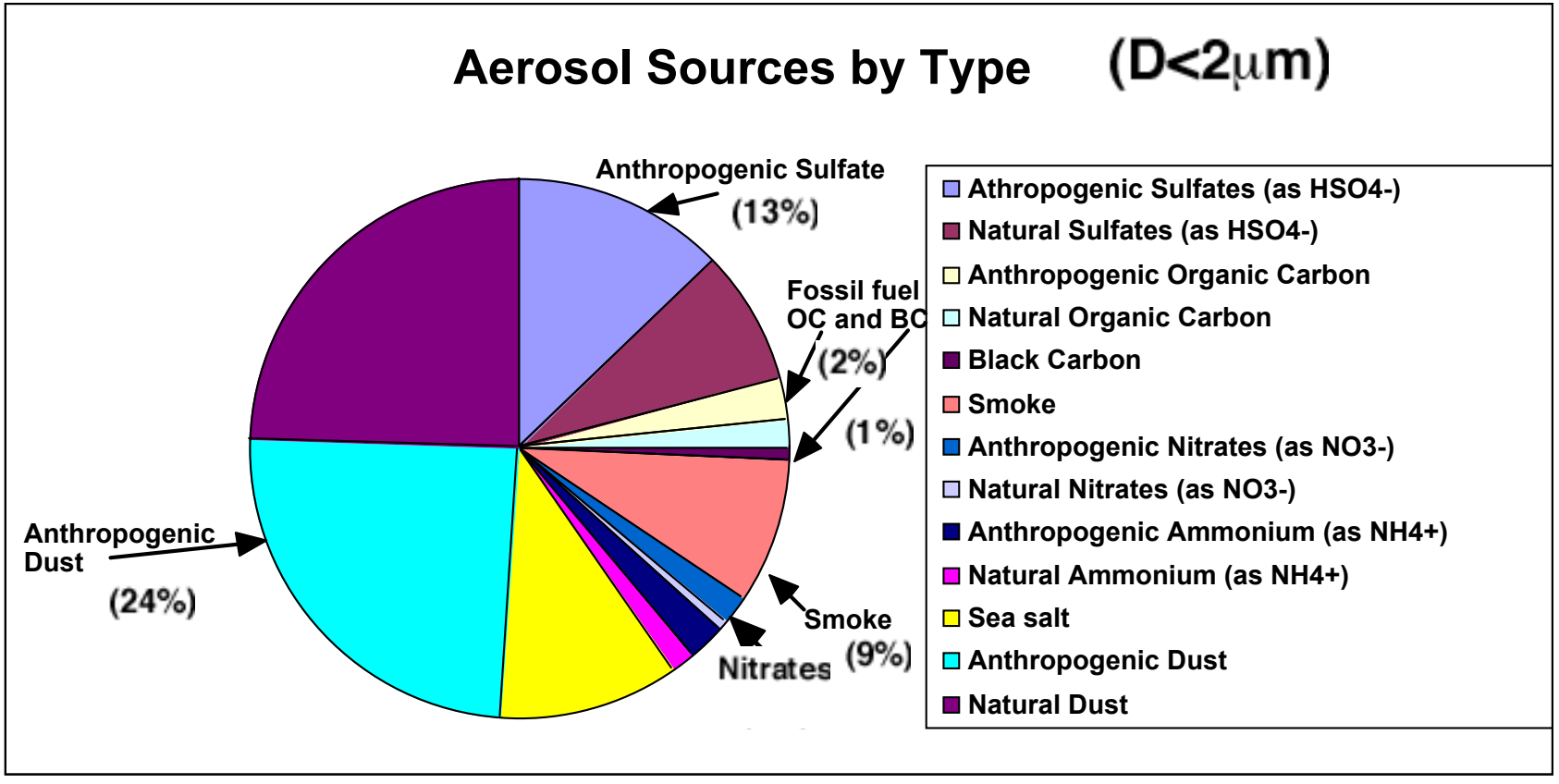
About half of the total aerosol source for D<2 μm is anthropogenic:



Aerosol direct effects: Anthropogenic Aerosols

- Fossil fuel sulfate and associated ammonium
- Organic carbon and black carbon from fossil fuels
- Smoke from biomass burning
- Mineral dust
- Fossil fuel nitrate and associated ammonium

The major anthropogenic source types are sulfates, nitrates, organic and black carbon, smoke, and dust



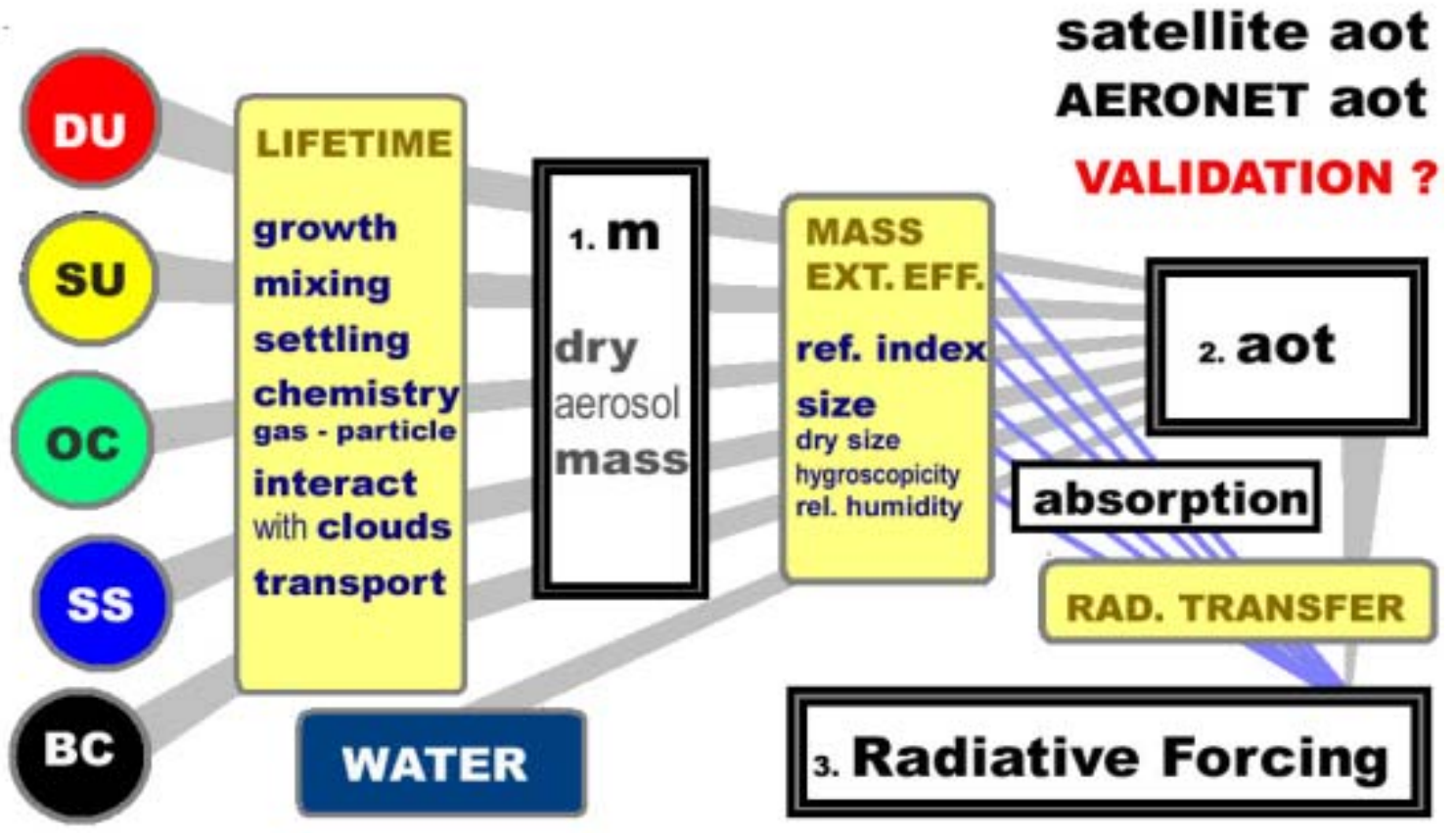
There are major uncertainties in emissions (Chapter 5, Penner et al., 2001 IPCC)

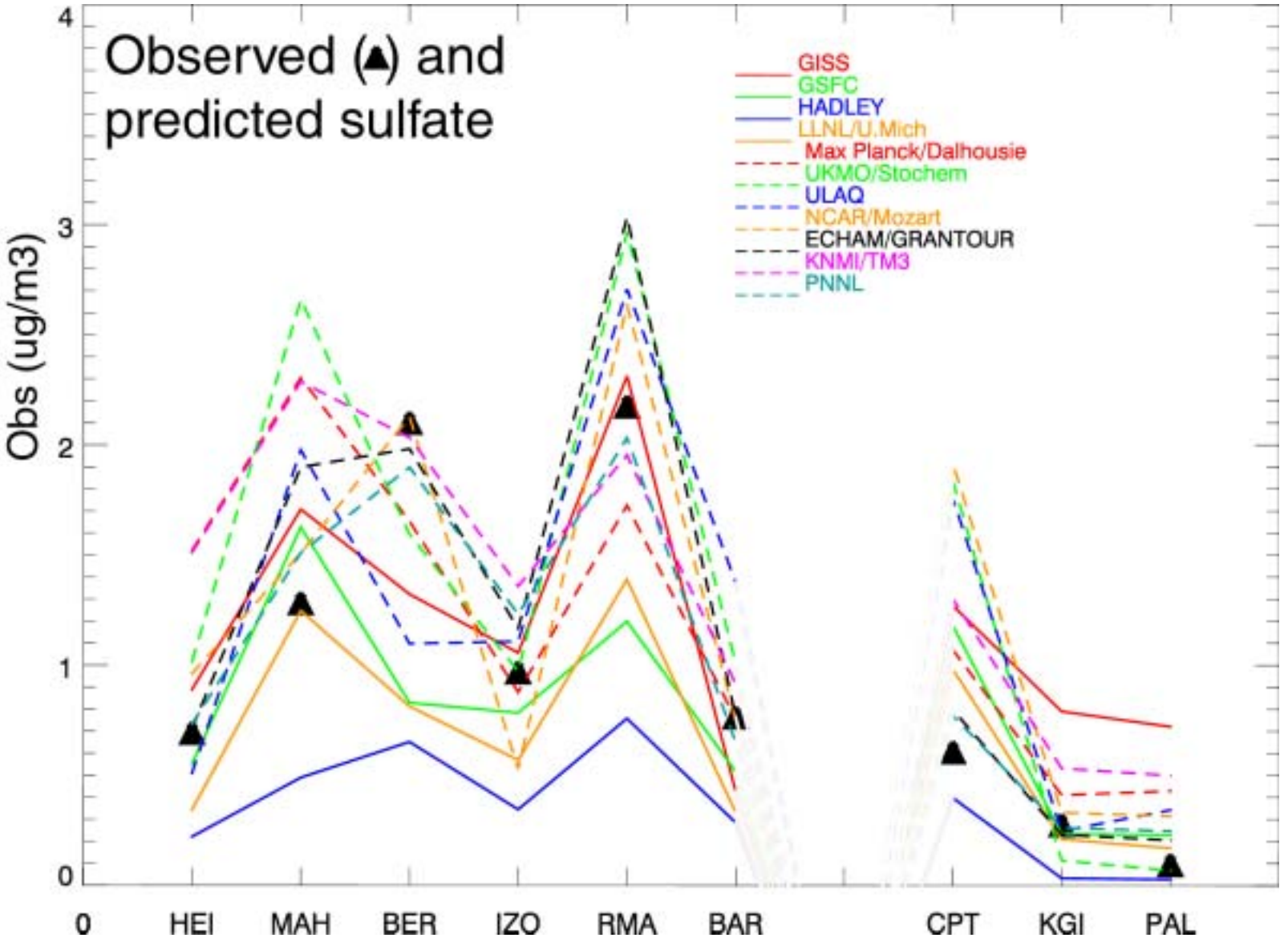
In assessing models, the emissions should account for differences between the year of the emissions and year of observations

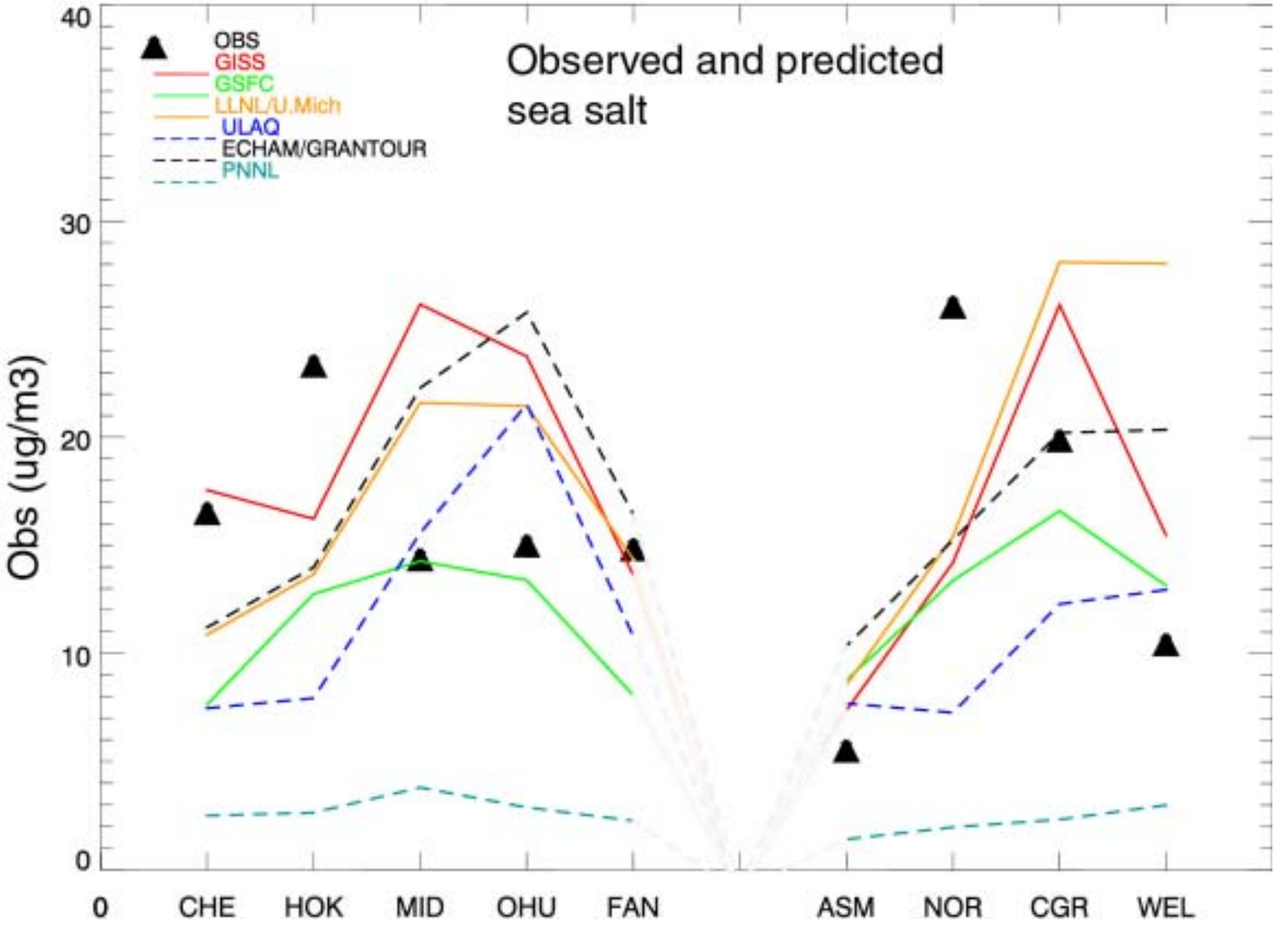
The quality of the simulation should be judged in light of uncertainties in emissions

	Anthropogenic		Natural	
Aerosol type	Source strength ($Tg\ yr^{-1}$)	Range	Source strength ($Tg\ yr^{-1}$)	Range
Sulfates (as HSO_4-)	104	(59-182)	67	(32-142)
Organic Carbon	20	(10-30)	14	(8-40)
Black Carbon	7	(4-11)		
Smoke	70	(50-90)	?	
Nitrates (as NO_3^-)	14	(10-20)	4	(2-8)
Ammonium (as NH_4^+)	19	(11-34)	12	(6-26)
Sea salt			88	(30-165)
Dust r<1 um	200	(100-300)	200	(100-300)

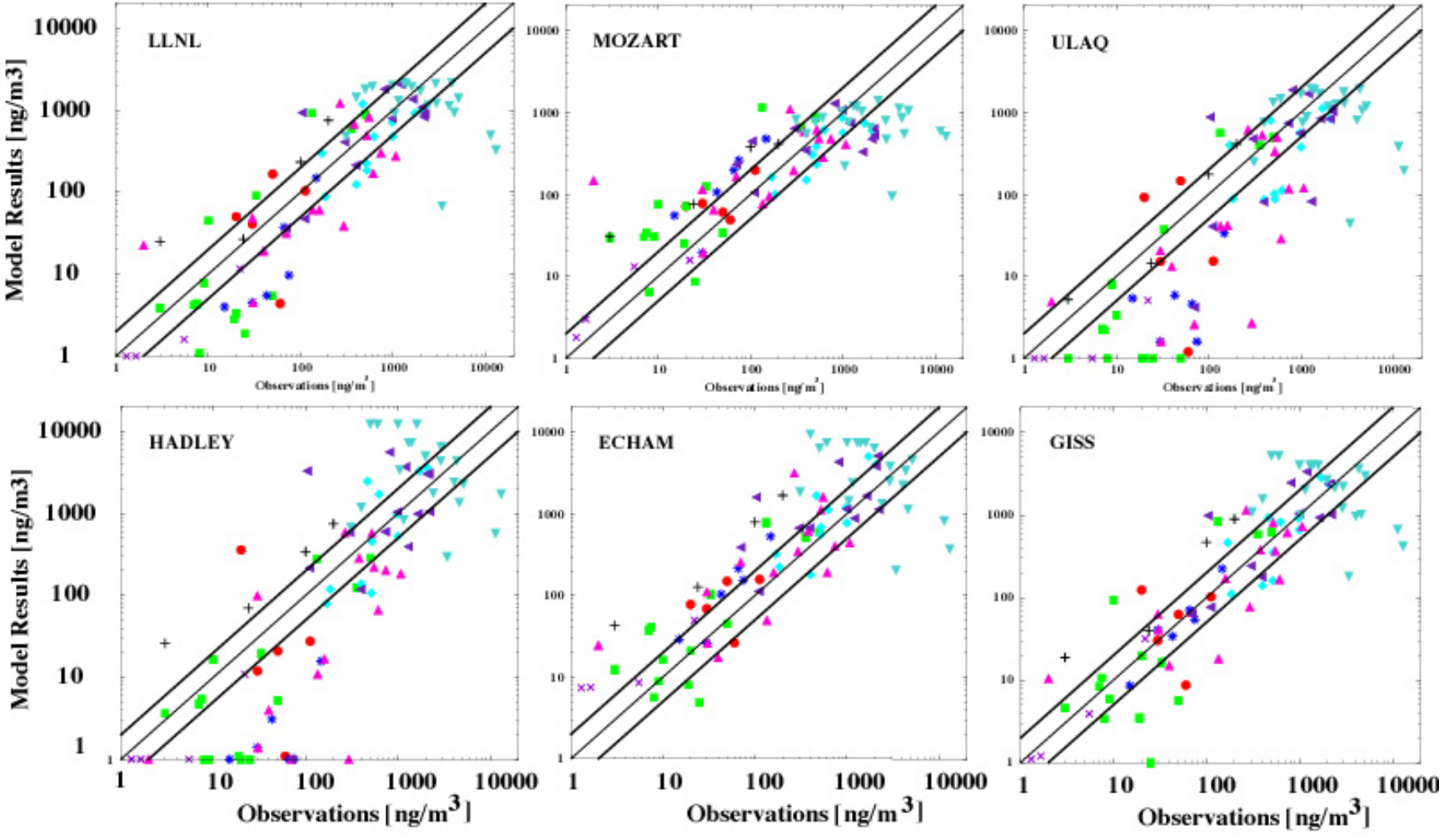
Uncertainties in direct aerosol forcing are associated with every step in the modeling process




Observed (▲) and predicted sulfate
GISS
GSFC
HADLEY
LLNL/U.Mich
Max Planck/Dalhousie
UKMO/Stochem
ULAQ
NCAR/Mozart
ECHAM/GRANTOUR
KNMI/TM3
PNNL
Obs (ug/m3)
0
1
2
3
4
0
HEI
MAH
BER
IZO
RMA
BAR
CPT
KGI
PAL


Observed and predicted
sea salt
OBS
GISS
GSFC
LLNL/U.Mich
ULAQ
ECHAM/GRANTOUR
PNNL
Obs (ug/m3)
40
30
20
10
0
0
CHE
HOK
MID
OHU
FAN
ASM
NOR
CGR
WEL

Observed and predicted black carbon

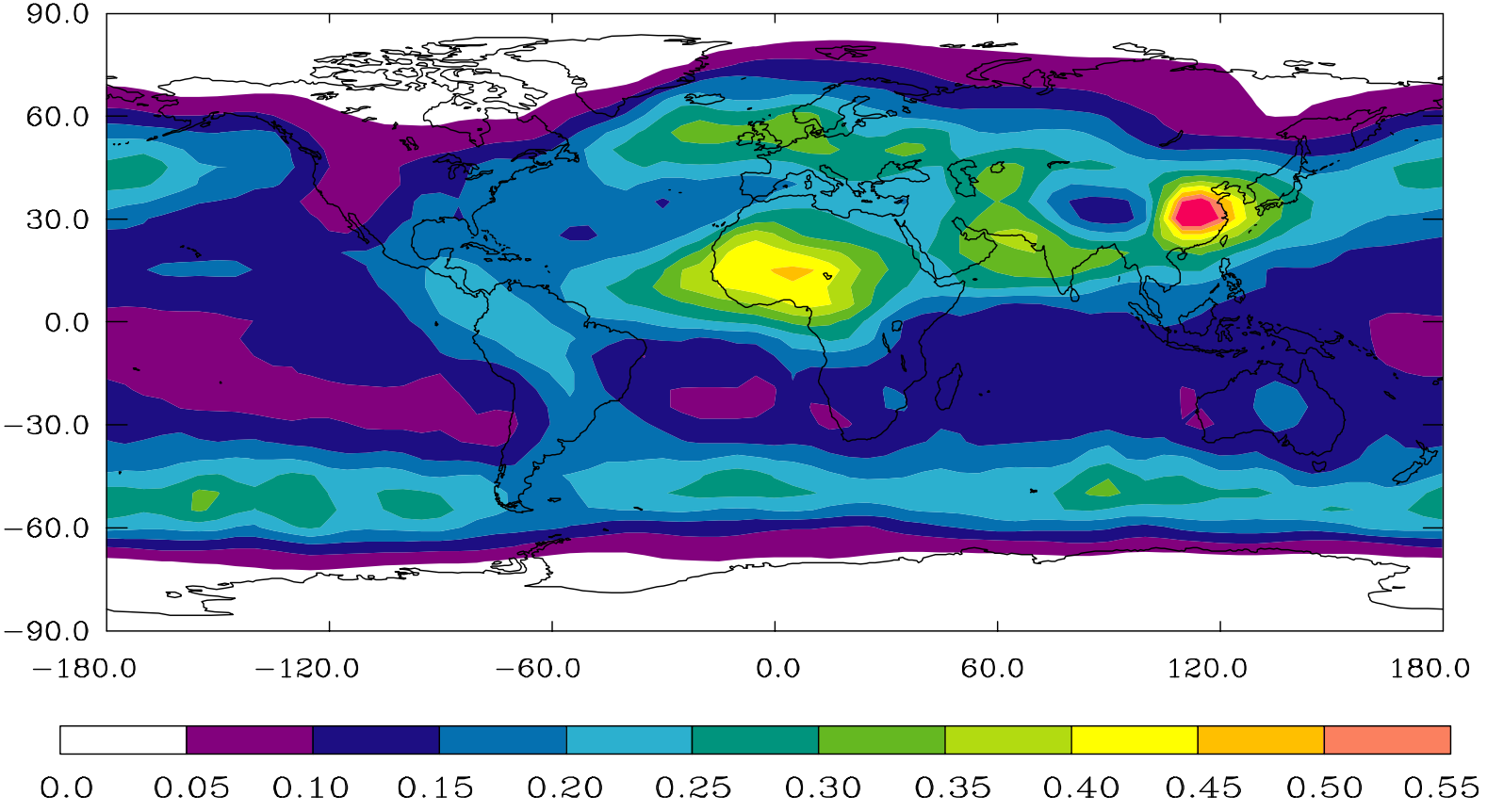


Average absolute error between models and observations of aerosol species at selected surface locations (%).

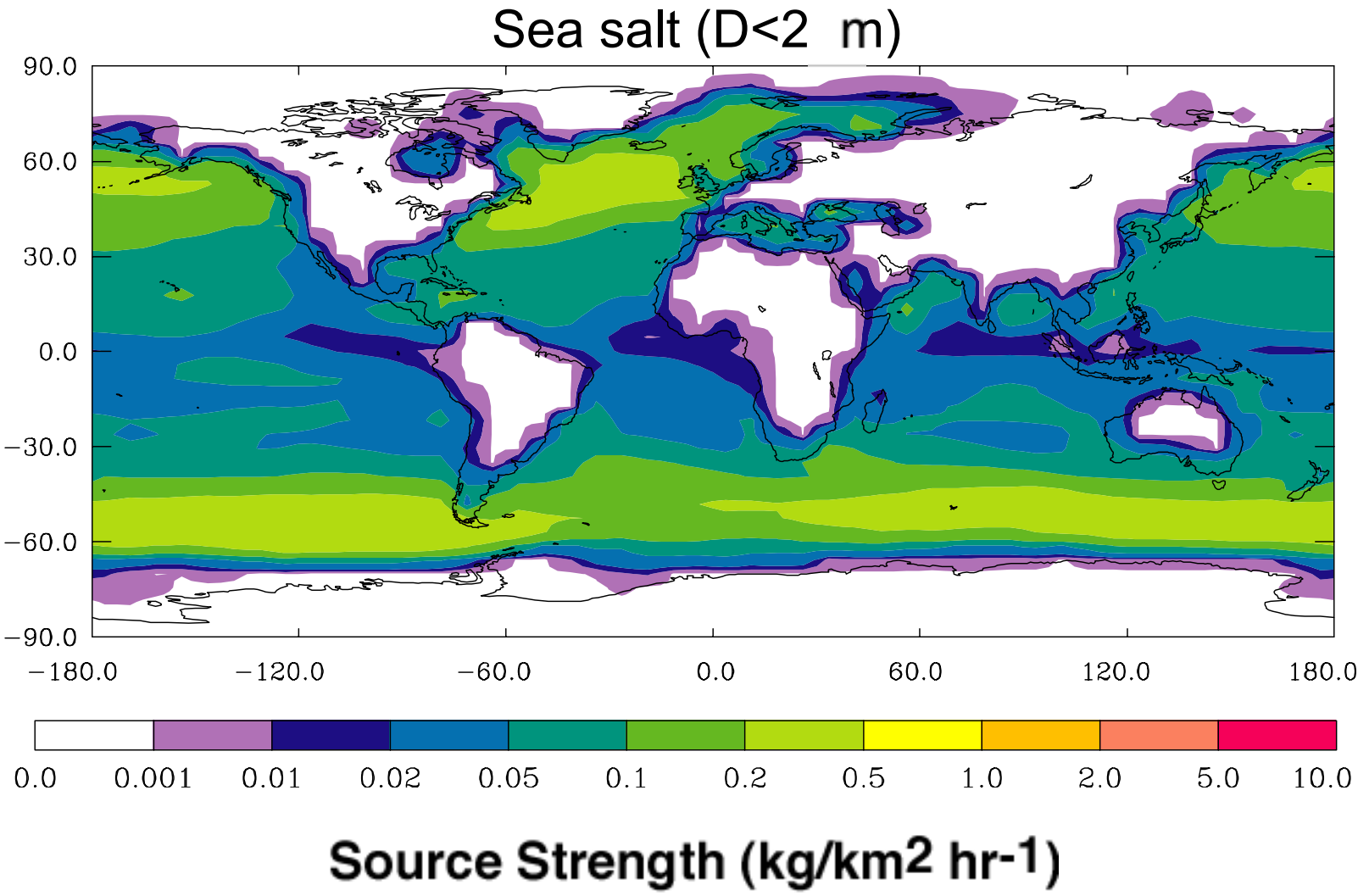
Model	Sulfate	Black Carbon	Organic Carbon	Dust	Sea Salt
GISS	63	127	121	178	40
GSFC	53	219	134	92	30
Hadley	32	220			
CCM/Grantour	48	111	85	157	68
ECHAM	98	276	285		
Stochem	63				
ULAQ	43	84	100	95	88
Mozart	46	211			
ECHAM/Grantour	41	230	135	122	33
TM3	96				
PNNL	49	133	220		16
Average of all models	57	179	154	129	46

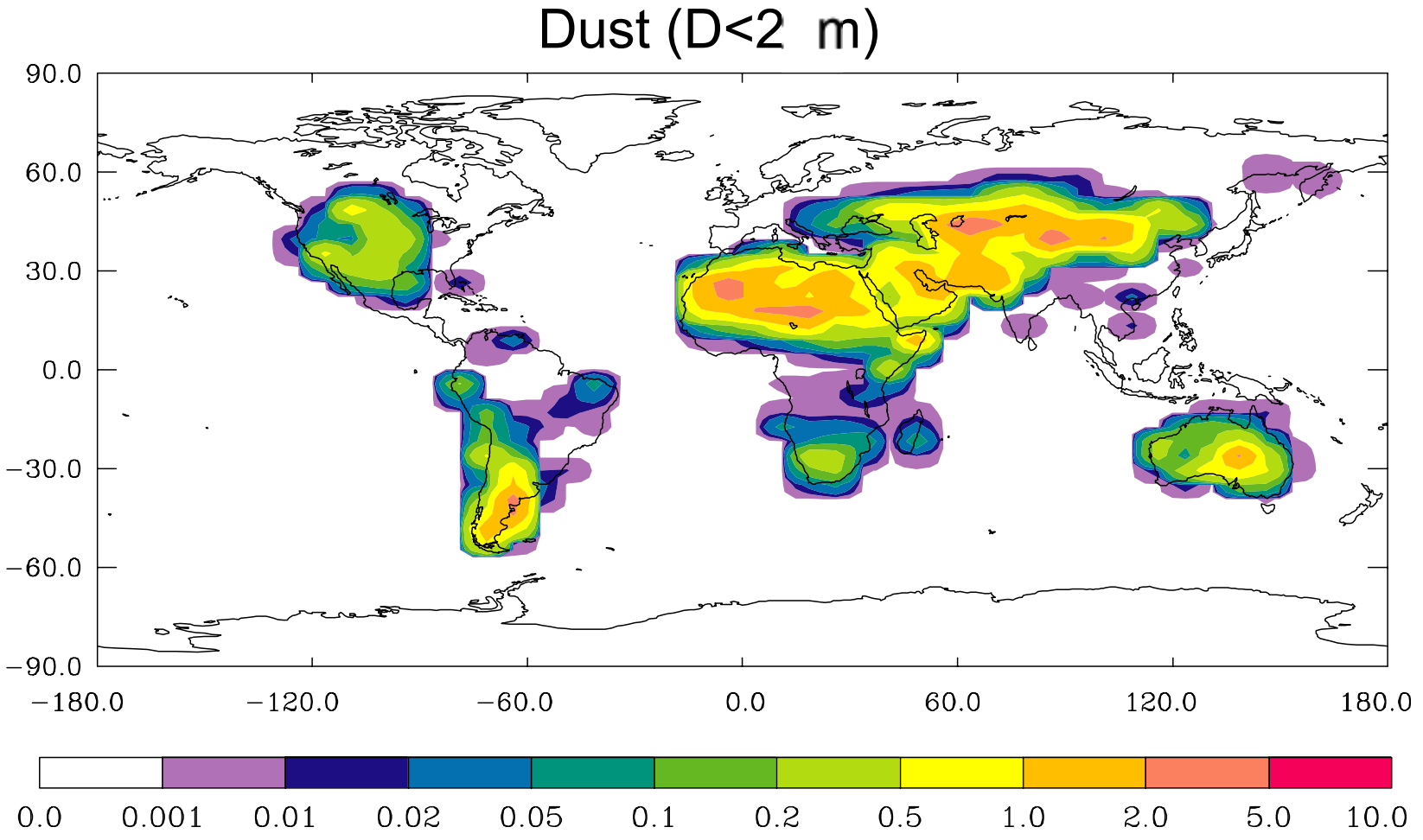
Zhang, Penner et al., 2004, submitted

Total optical depth

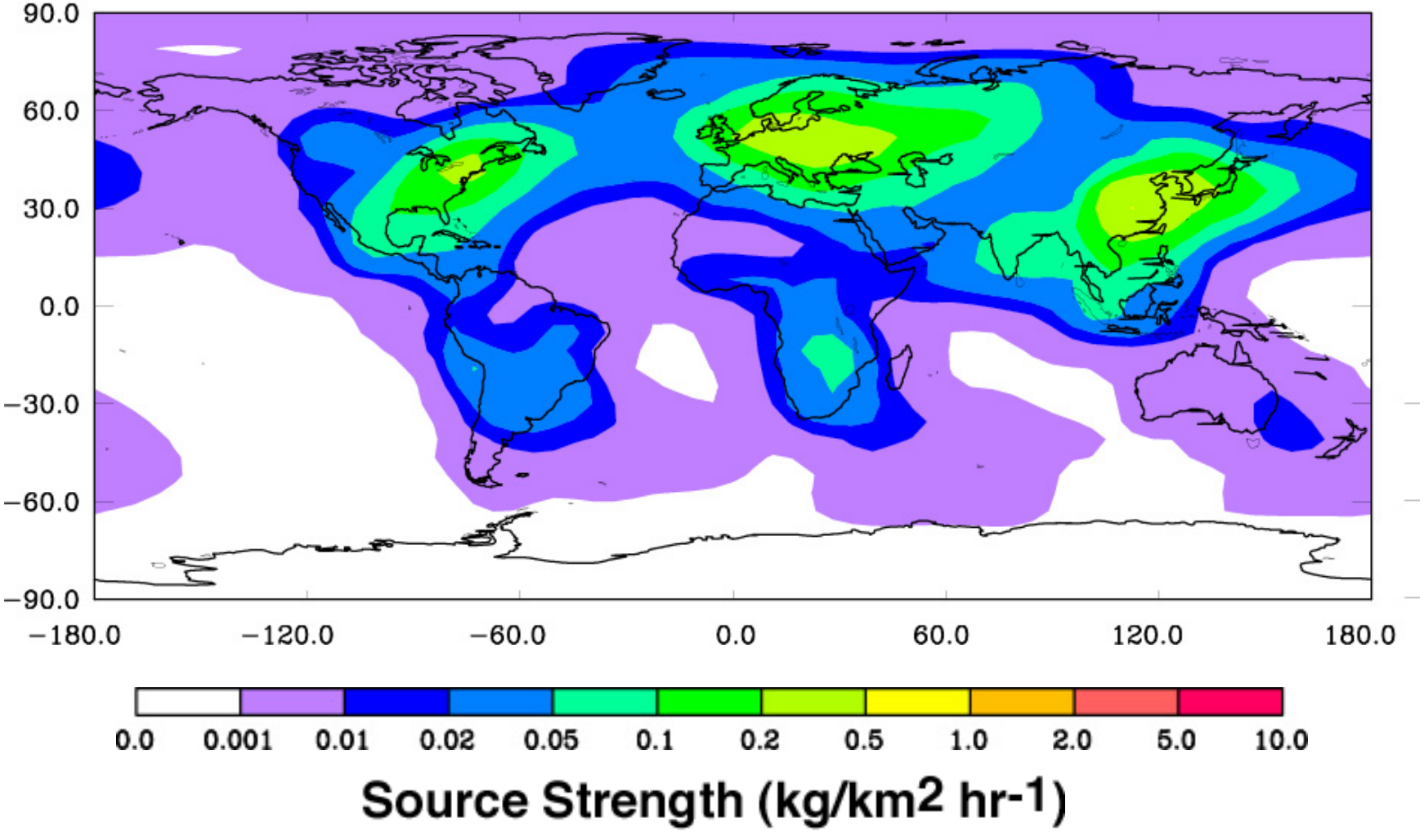


Aerosol optical depth is determined by the sum of all aerosol types

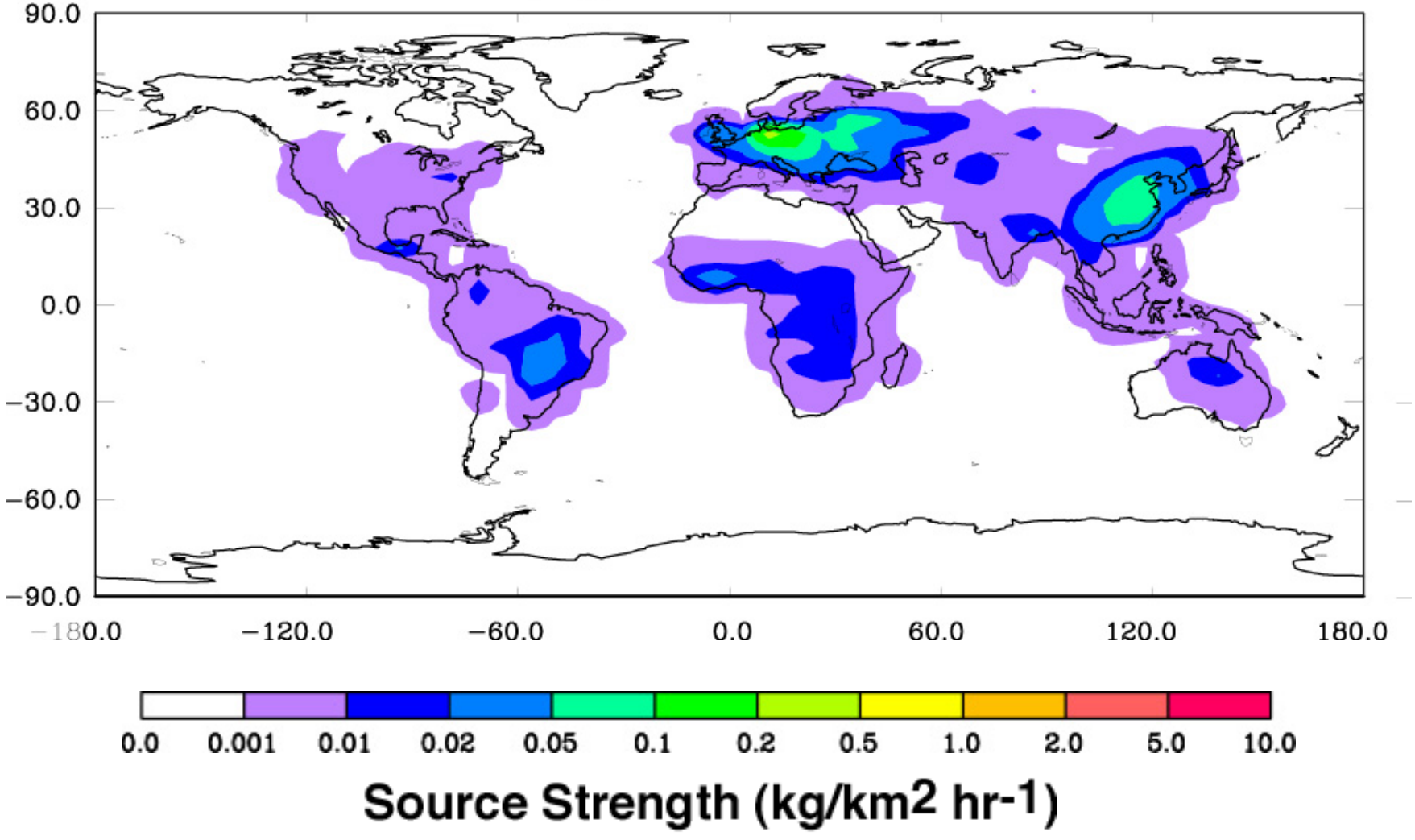

Sea salt (D<2 m)
90.0
60.0
30.0
0.0
−30.0
−60.0
−90.0
−180.0
−120.0
−60.0
0.0
60.0
120.0
180.0
0.0
0.001
0.01
0.02
0.05
0.1
0.2
0.5
1.0
2.0
5.0
10.0
Source Strength (kg/km2 hr-1)

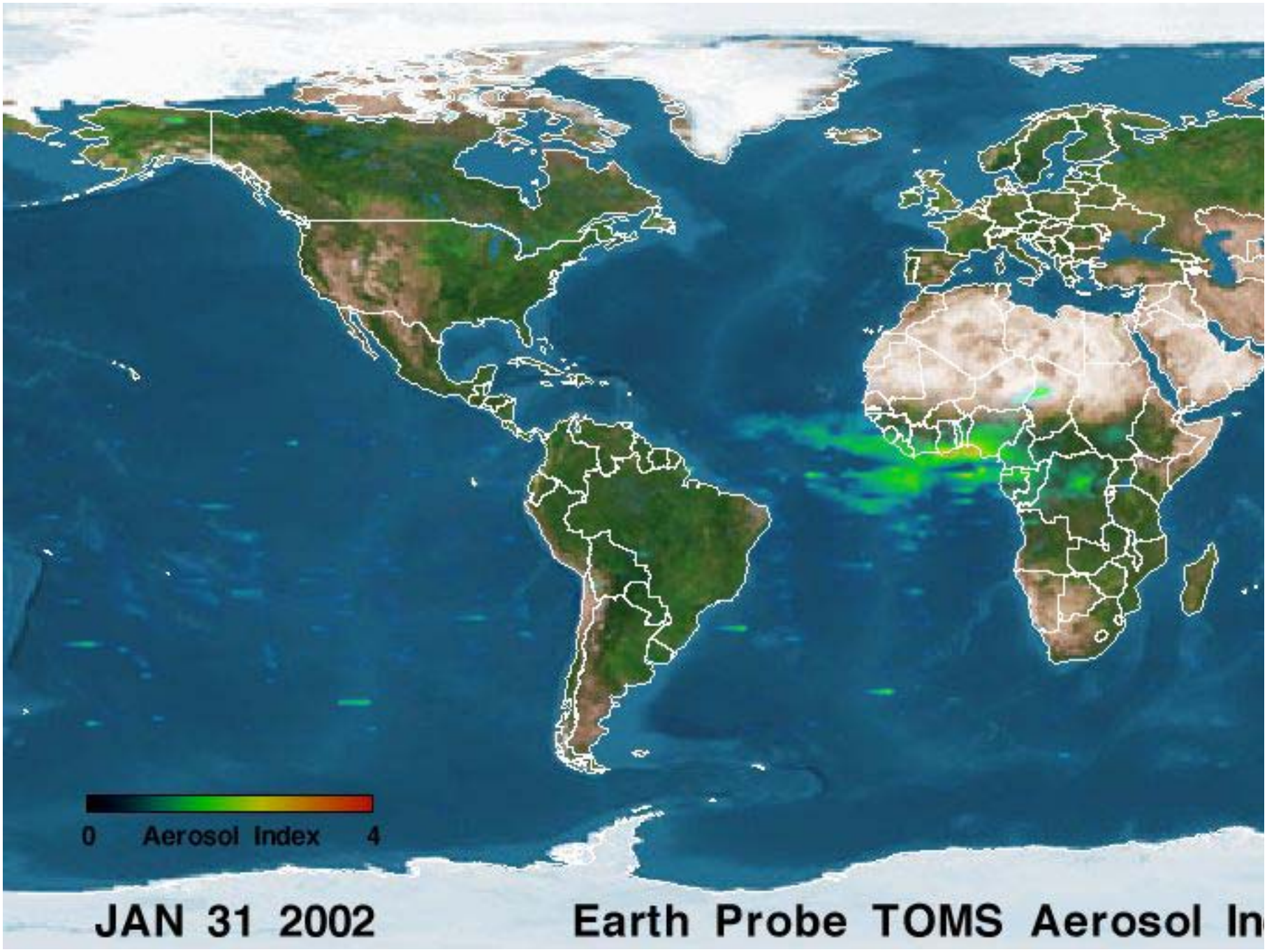

Dust (D<2 m)
90.0
60.0
30.0
0.0
−30.0
−60.0
−90.0
−180.0
−120.0
−60.0
0.0
60.0
120.0
180.0
0.0
0.001
0.01
0.02
0.05
0.1
0.2
0.5
1.0
2.0
5.0
10.0
Source Strength (kg/km2 hr-1)

Anthropogenic sulfate production rate

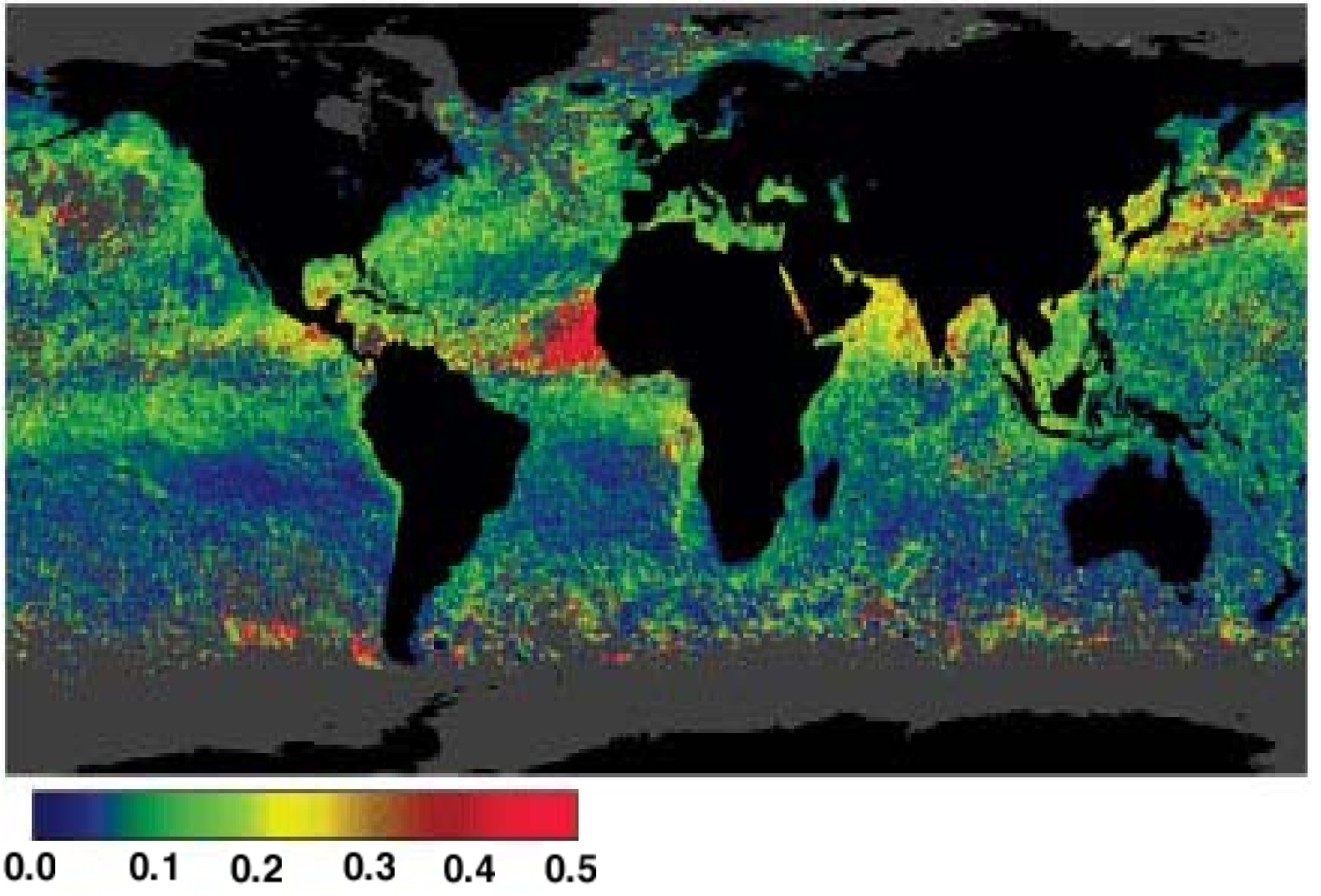


Anthropogenic black carbon

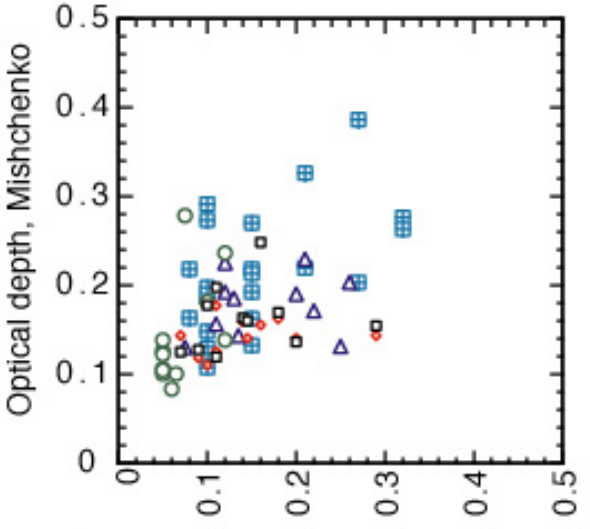


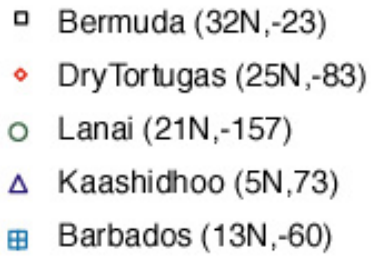

0 Aerosol Index 4
JAN 31 2002
Earth Probe TOMS Aerosol In

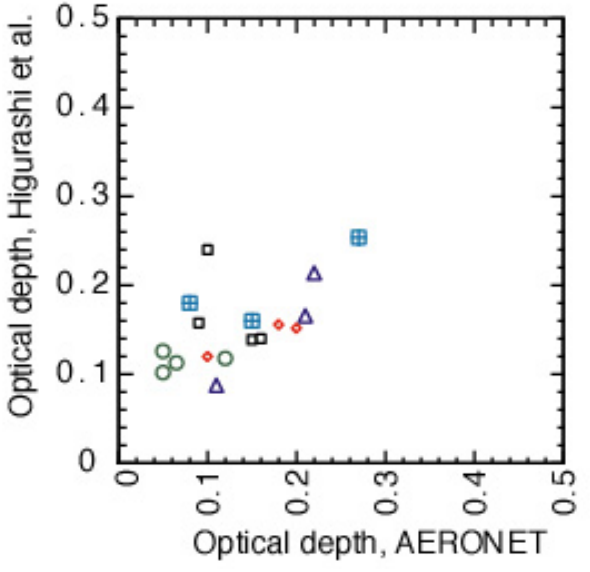
Aerosol optical depth at 865 nm in May 1997

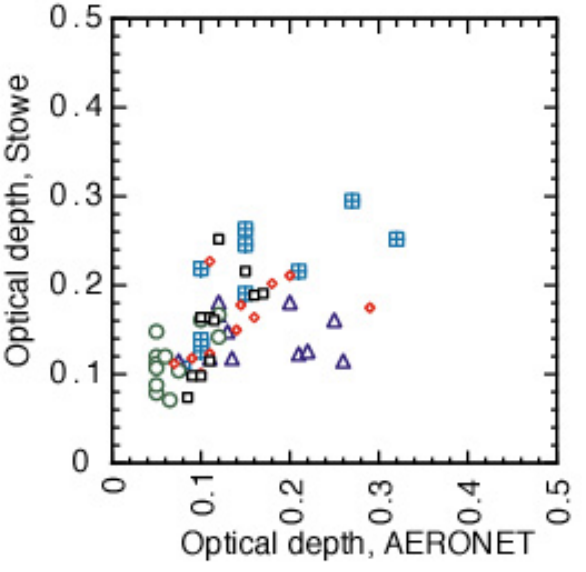


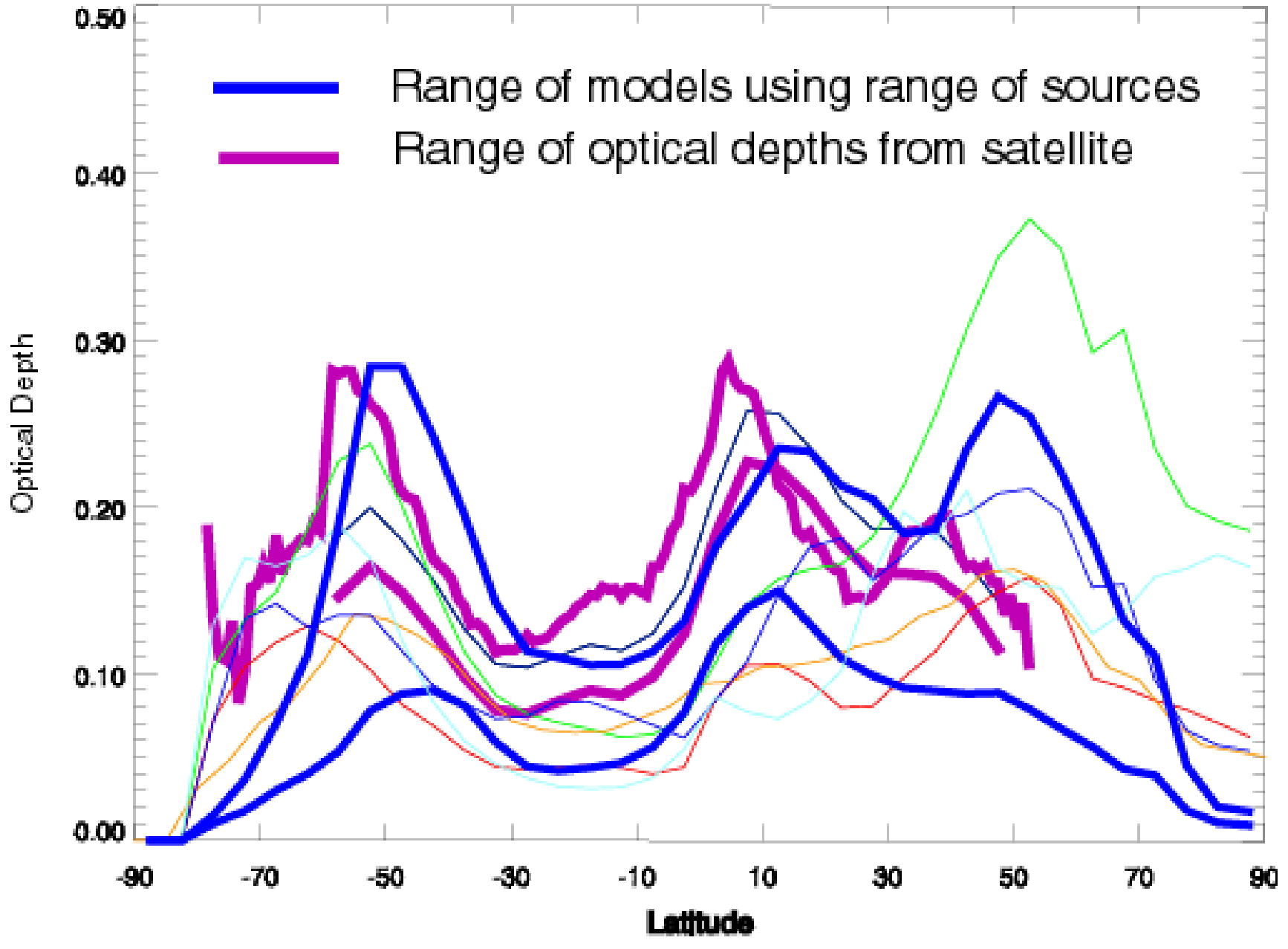
Comparison of AERONET and AVHRR satellite optical depth









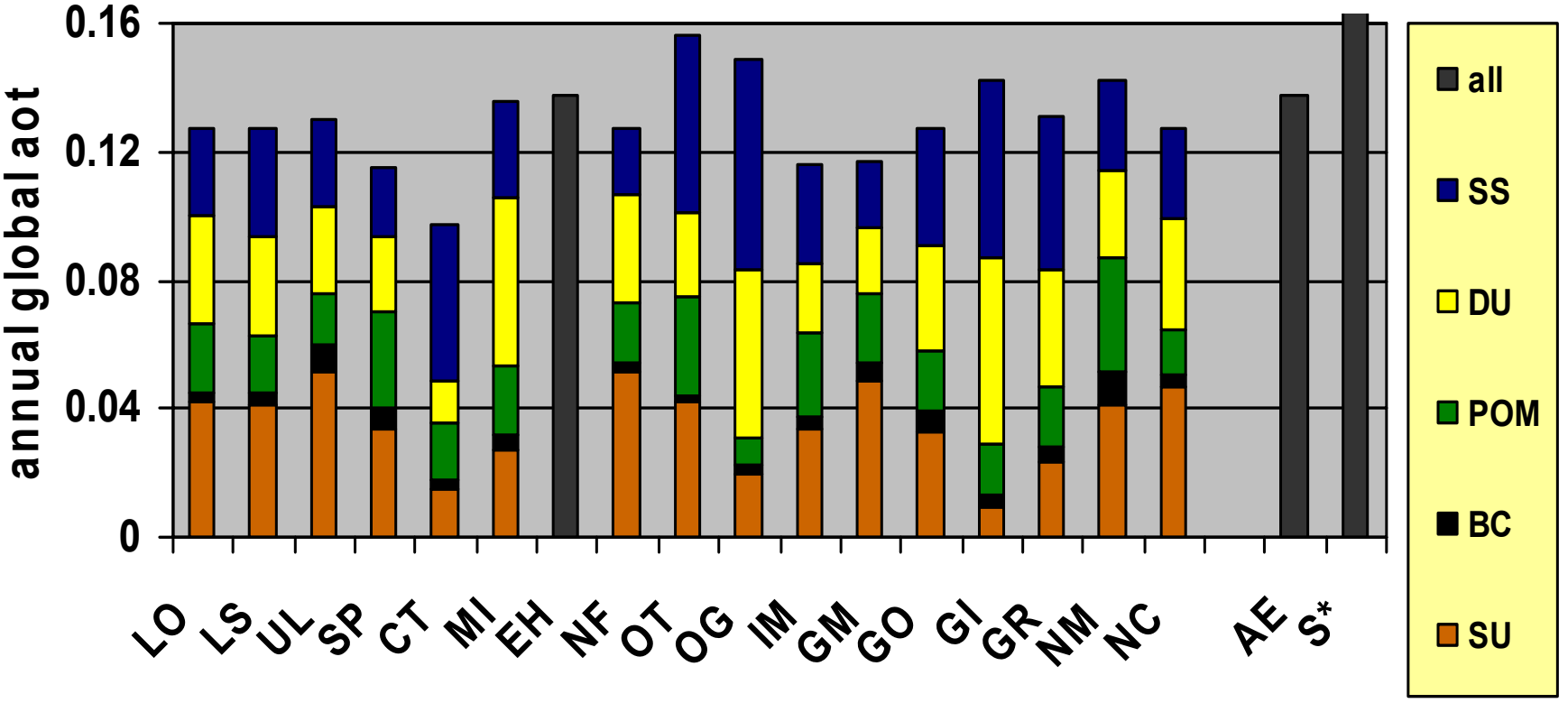

Range of models using range of sources
Range of optical depths from satellite
Optical Depth
0.50
0.40
0.30
0.20
0.10
0.00
-90
-70
-50
-30
-10
10
30
50
70
90
Latitude

Difference between model-derived optical depth and that for each satellite-retrieved optical depth

4-Month Average	Nakajima	Michchenko	Stowe
CCM1/GRANTOUR	-0.04	-0.06	-0.01
ULAQ	-0.02	-0.04	0.00
MPI/Dalhousie	-0.06	-0.08	-0.03
GISS	-0.05	-0.07	-0.03
ECHAM/GRANTOUR	-0.06	-0.08	-0.03
GOCART	0.01	-0.01	0.04
Model Mean	-0.04	-0.06	-0.01

Penner et al., 2002

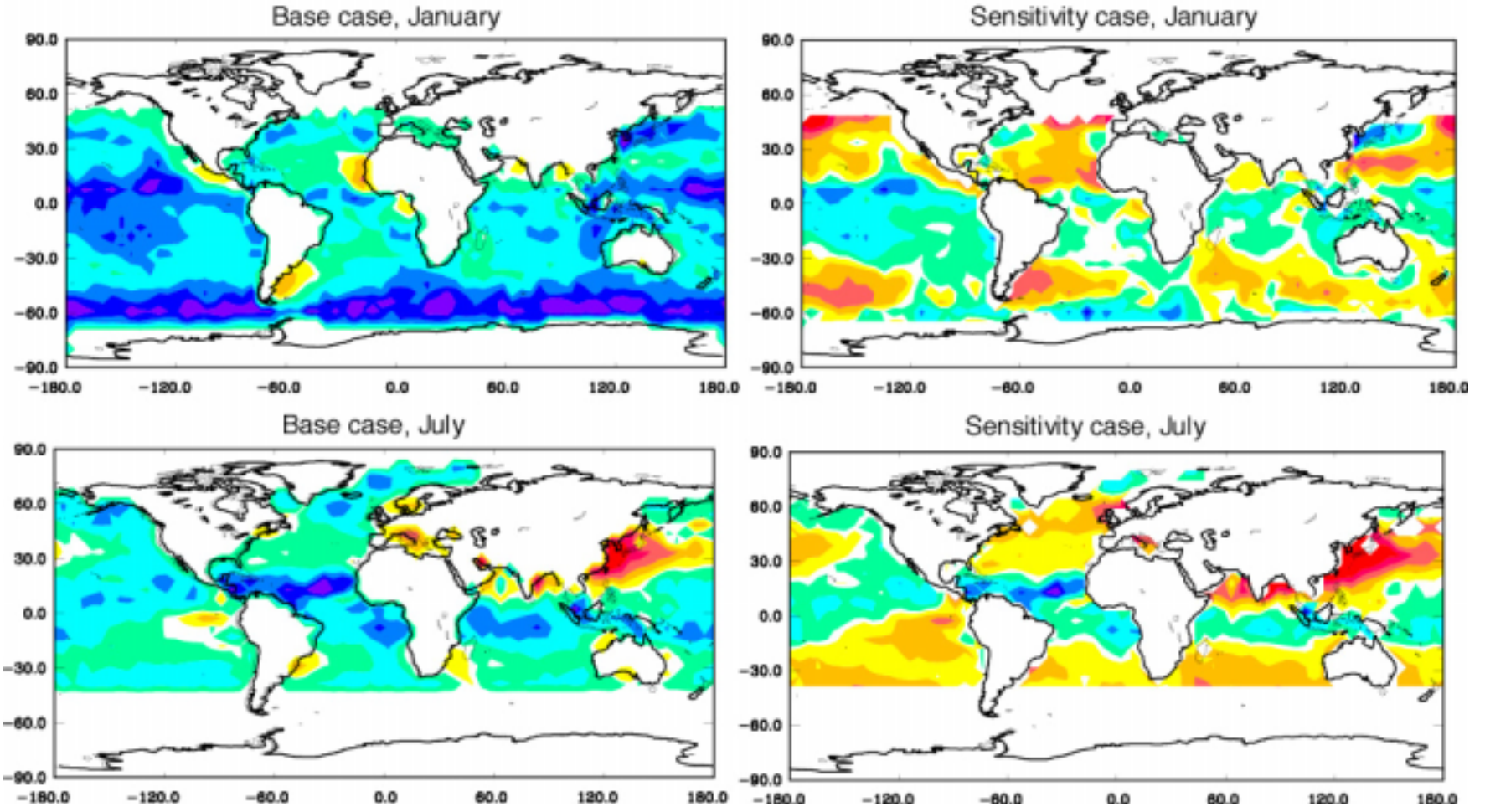
Are current models doing better? (AEROCOM, Kinne et al., 2005)



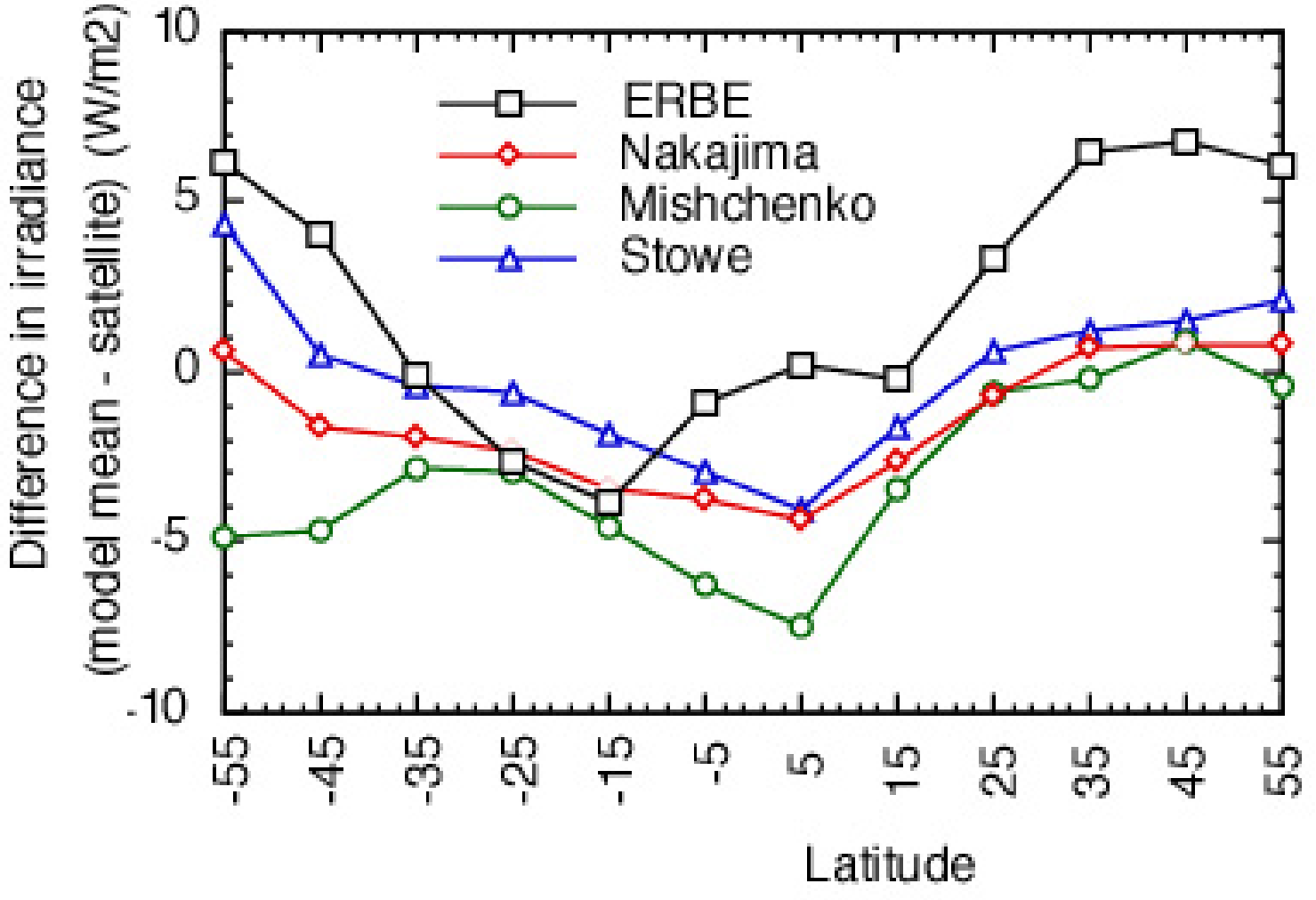
Difference between model-derived aerosol forcing and that for each satellite-retrieved forcing (W/m^2)

4-Month Average	Nakajima	Michchenko	Stowe
CCM1/GRANTOUR	-2.34	-3.76	-0.84
ULAQ	0.86	-2.00	0.47
MPI/Dalhousie	-2.84	-4.64	-1.40
GISS	-2.82	-4.32	-1.35
ECHAM/GRANTOUR	-3.20	-4.64	-2.04
GOCART	1.04	-0.75	2.19
Model Mean	-1.80	-3.32	-0.47

Difference between satellite optical depth and modeled optical depth



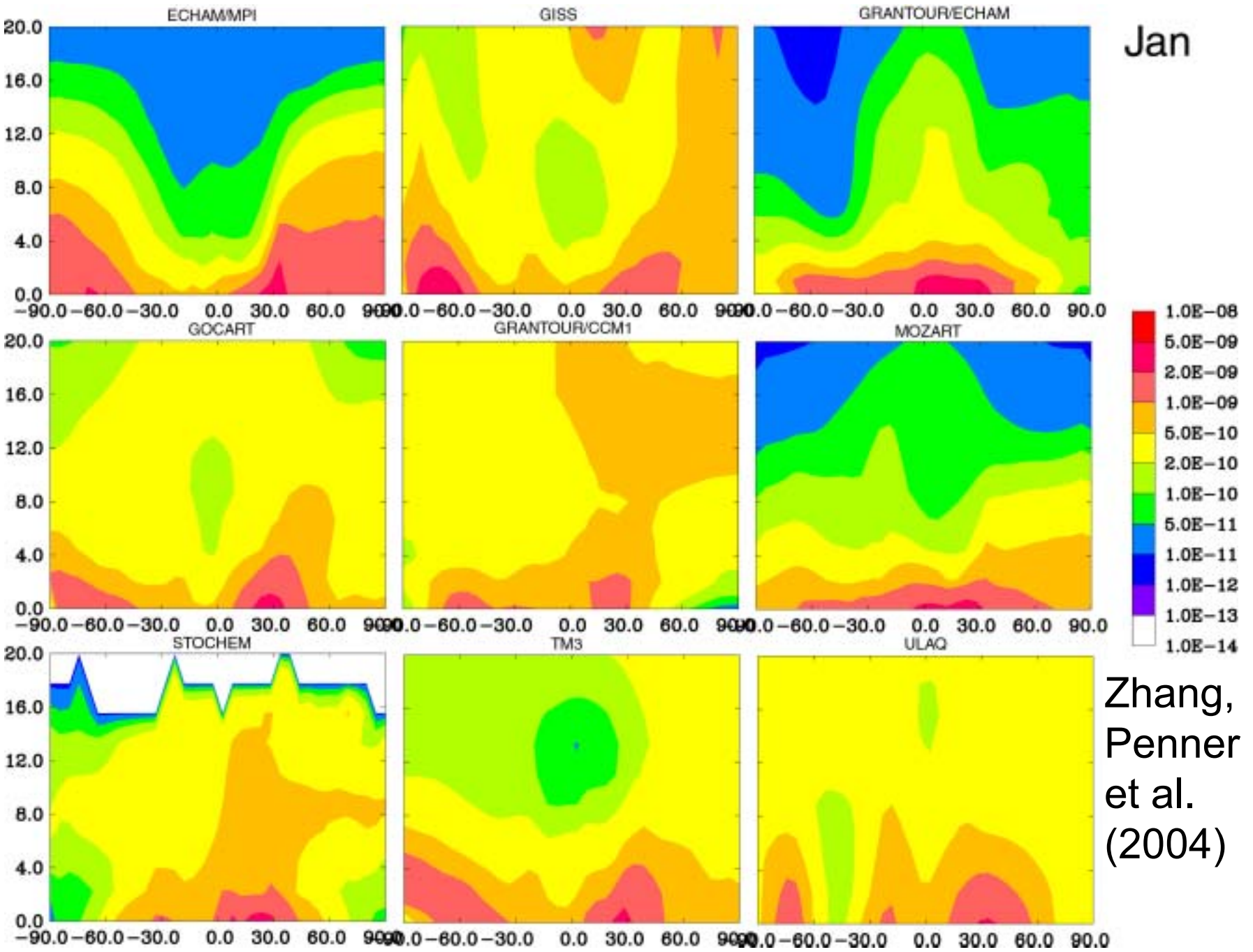
Comparison of satellite and modeled optical depth may indicate that forcing estimates from models are too low

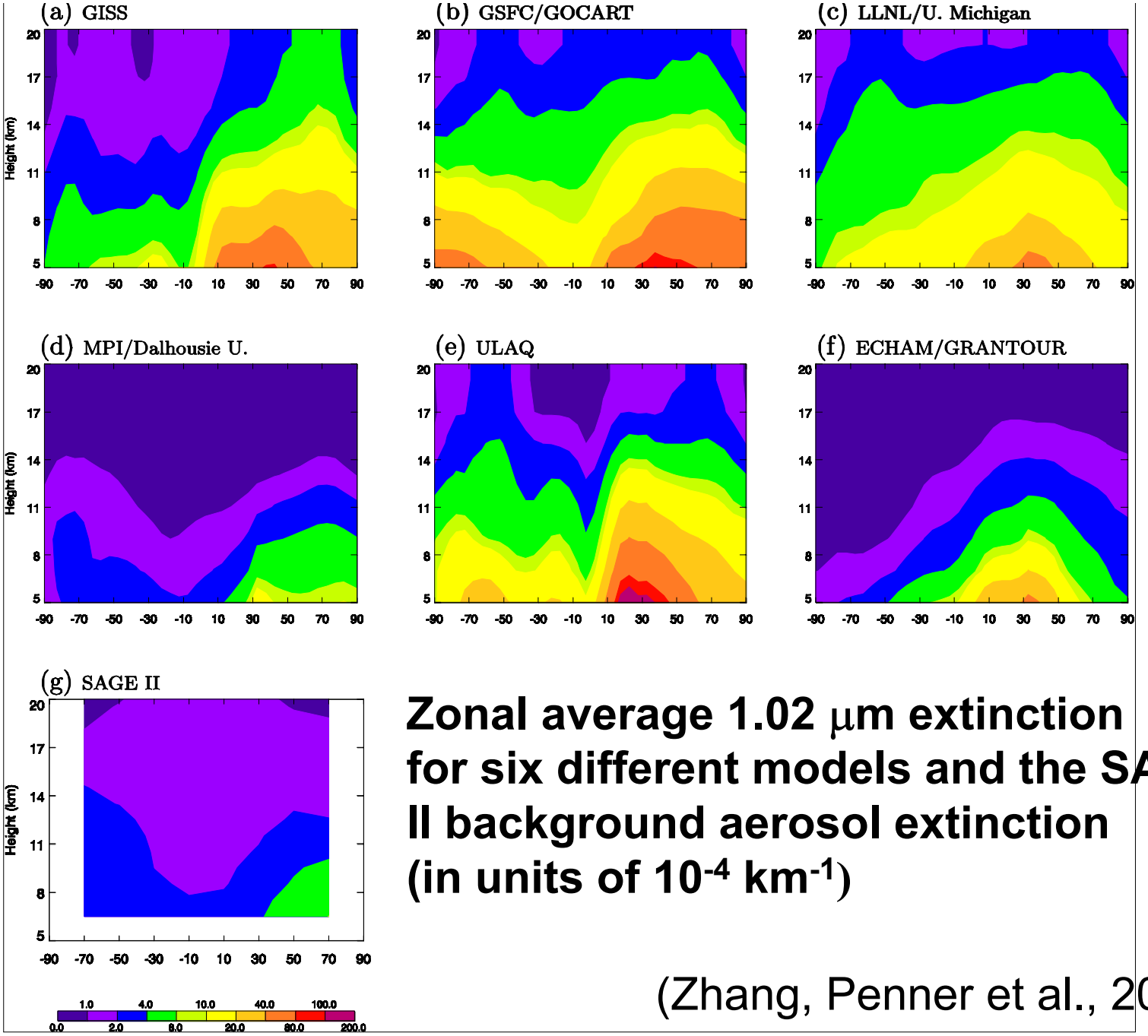


What about the vertical distribution of aerosols?

- Previously only limited analysis has been available from a few vertical profiles

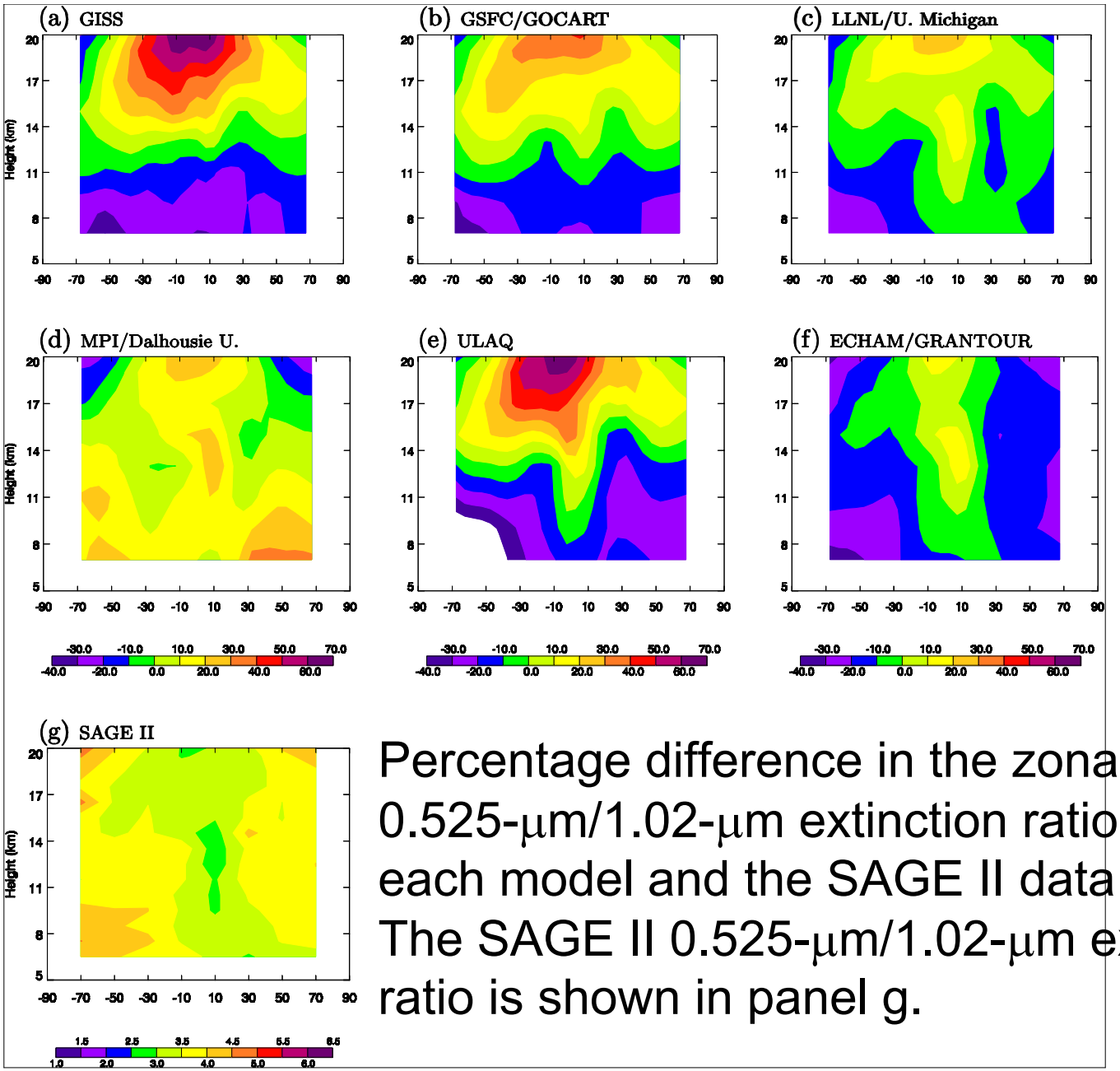
- Zhang, Penner et al. [2004] compared SAGE II extinction profiles with profiles determined from the 2001 IPCC models


ECHAM/MPI
GISS
GRANTOUR/ECHAM
GOCART
GRANTOUR/CCM1
MOZART
STOCHEM
TM3
ULAQ
20.0
16.0
12.0
8.0
4.0
0.0
−90.0 −60.0 −30.0 0.0 30.0 60.0 90.0
1.0E−08
5.0E−09
2.0E−09
1.0E−09
5.0E−10
2.0E−10
1.0E−10
5.0E−11
1.0E−11
1.0E−12
1.0E−13
1.0E−14
Jan
Zhang, Penner et al. (2004)



Zonal average 1.02 μm extinction for six different models and the SAGE II background aerosol extinction (in units of 10^{-4} km^{-1})

(Zhang, Penner et al., 2004)



Percentage difference in the zonal average 0.525-μm/1.02-μm extinction ratio between each model and the SAGE II data. The SAGE II 0.525-μm/1.02-μm extinction ratio is shown in panel g.

What do measured vertical profiles of organic aerosols tell us?

- Several field campaigns have identified significant amounts of organic aerosols in the upper troposphere:
  - TARFOX (Novakov et al., 1997)
  - Sonex
  - Ace Asia

- These large amounts cannot be explained by models: Implication is that there is a large secondary source of organic aerosols that is not represented in the models
  - Acid-catalyzed formation process??

Conclusions (direct forcing)

- Reduced uncertainty in aerosol direct forcing will require improvements in global models:
  - Aerosol sources
  - Processes determining aerosol lifetime and burden including formation of secondary organic aerosols
- The biggest uncertainties relate to determining:
  - BC, POM, and dust
  - Dust appears to be overestimated in the upper troposphere
  - Organic aerosols are underestimated in the upper troposphere

Can we improve our understanding of biomass aerosol sources? Biomass aerosol emission are generally considered uncertain to a factor of 2

- Several new bottom-up estimates of emissions from satellite estimates of burned area:
  - Ito, A., and J. E. Penner (JGR, 2004)
  - Hoelzemann et al. (JGR, 2004)
  - van der Werf et al. (Global Change Biol., 2003)

- Several new efforts based on inverse modeling for CO emissions using satellite observations:
  - Arellano et al. [GRL, 2004]
  - Petron et al. [GRL, 2004]

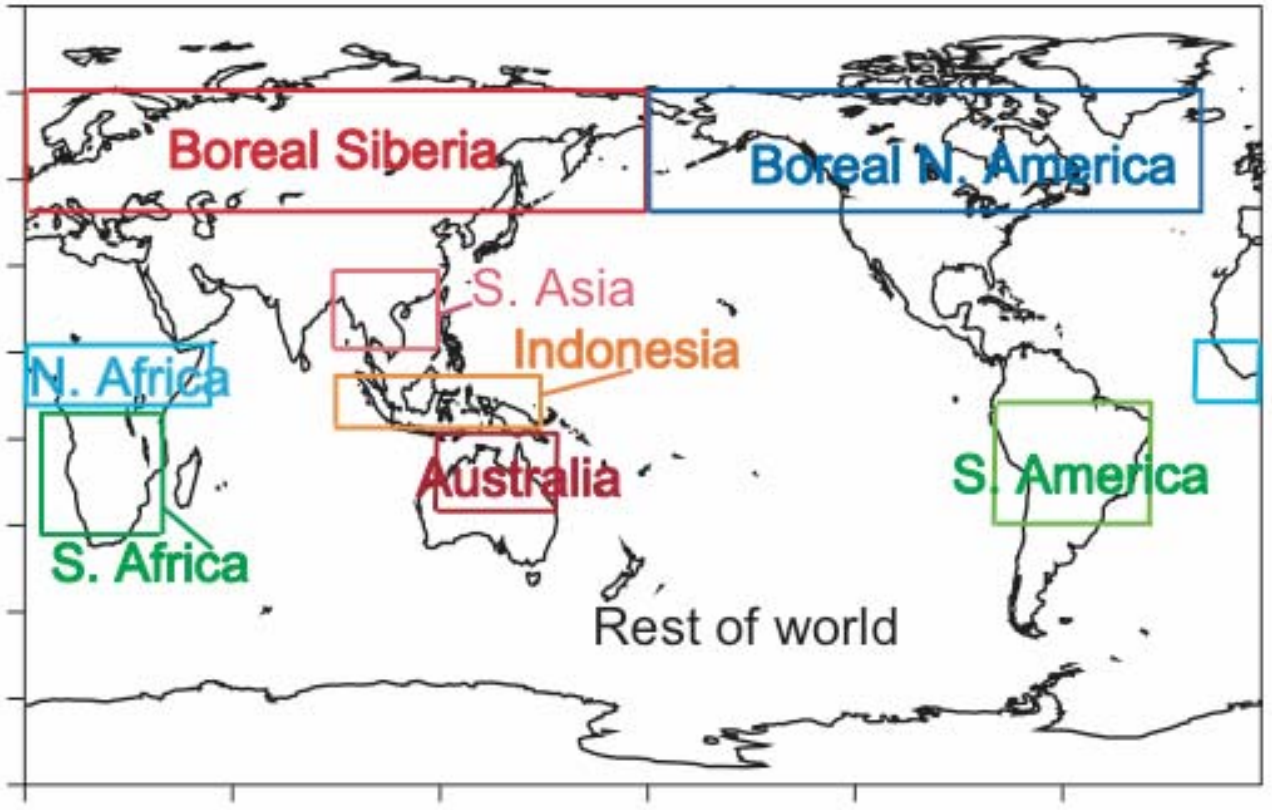
Use of TOMs AI is more direct than the use of CO in inverse studies (not as many competing sources):

- Use a Bayesian inverse technique designed to match satellite-retrieved aerosol index (AI) [Zhang, Penner, and Torres, submitted, 2004]

- A priori estimates based on 2 cases:
  - Bottom-up estimate of BC emissions developed from the GBA 2000 data set for burned areas [Ito and Penner, 2004a]
  - Inferred BC from scaling the results of an inverse study of CO emissions by Arellano et al. [2004] (spatial distribution within a region is the same as that in Ito and Penner [2004a] and temporal variation uses the TOMs AI)

- Uncertainty in a priori estimates based on 2 cases:
  - Assumed 50% everywhere
  - Estimated from the difference between the bottom up and top-down estimates (I.e. Ito and Penner vs Arellano et al.)

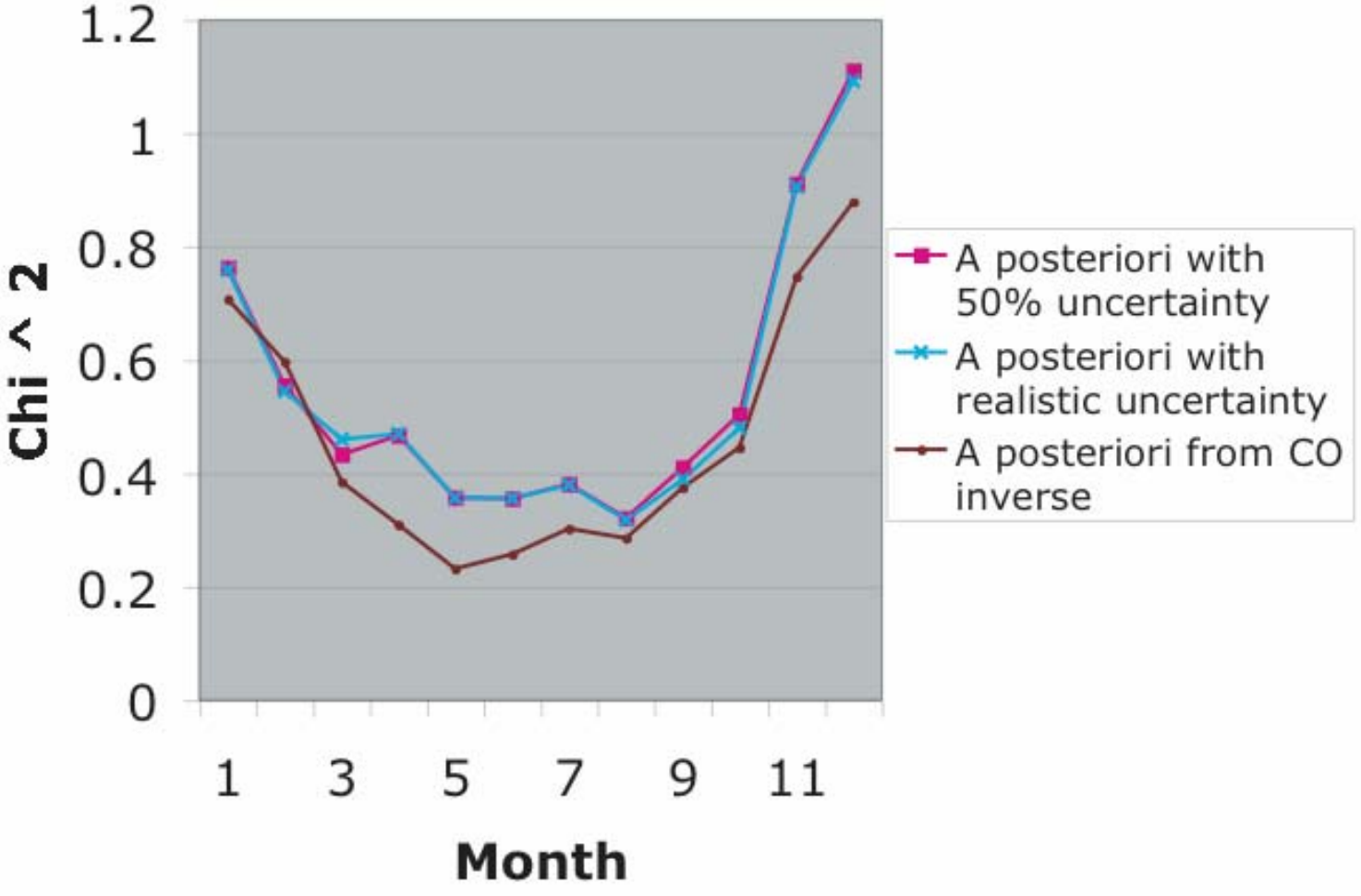
9 Regions considered in the analysis:



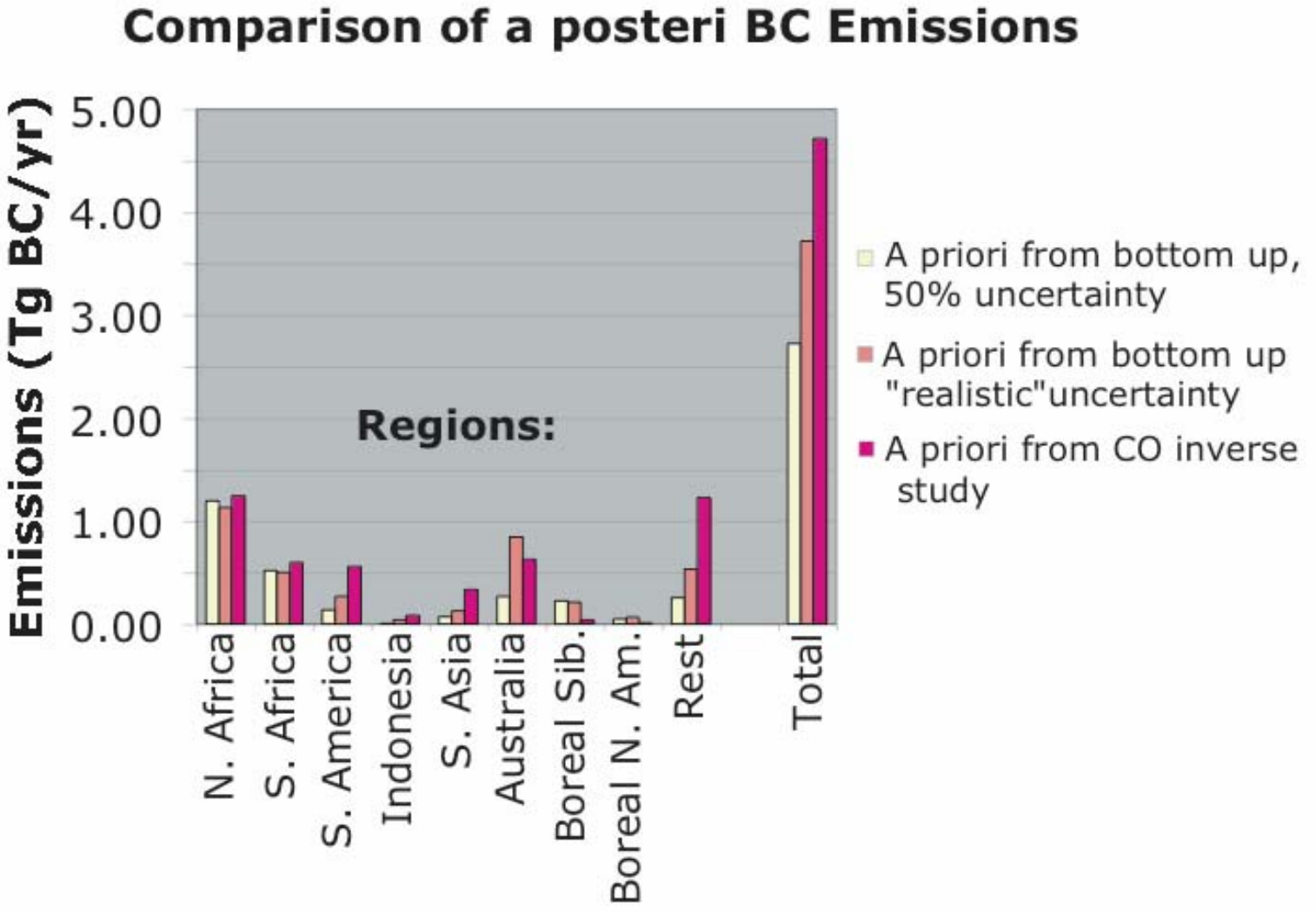
Uncertainties in apriori emissions determined from difference of 2 cases:

Region	Inversion based on CO	Bottom-up estimate	Difference
N. Africa	0.63	0.45	41%
S. Africa	0.35	0.49	28%
S. America	0.65	0.07	828%
Indonesia	0.08	0.01	685%
S. Asia	0.35	0.04	783%
Australia	0.27	0.08	243%
Boreal Sib.	0.04	0.20	-79%
Bor. N. Am.	0.01	0.03	-79%
Rest	1.23	0.25	394%
Total	3.62	1.62	124%

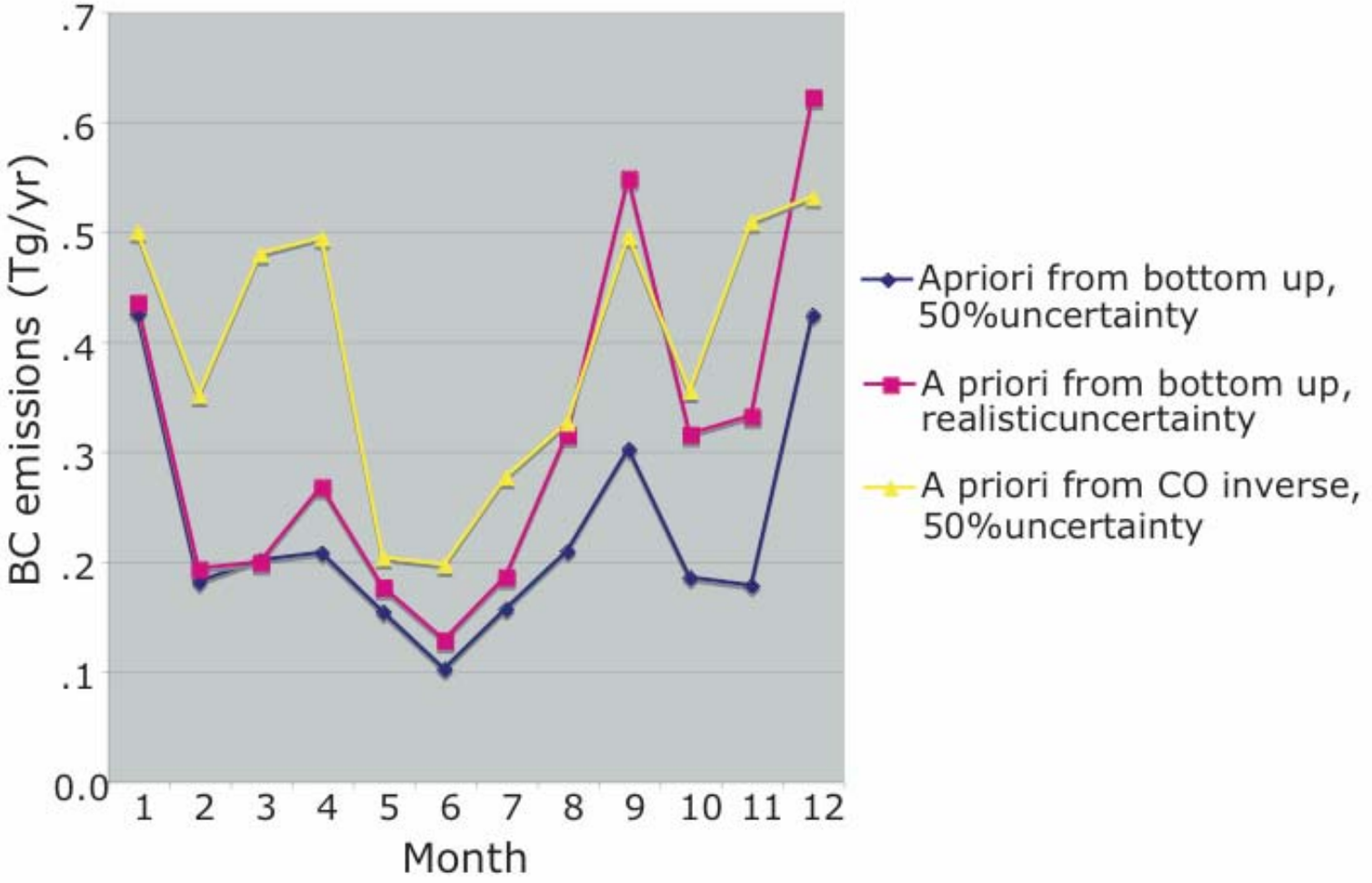
All cases lead to a better agreement with the data: Starting with a priori from the CO inverse study leads to the closest agreement with data



Total emissions 70% larger with the CO inverse study than the bottom up case and they are a factor of 3 larger than the bottom up estimates



The largest increases occur in the early part of the year



Total BC emissions are similar to those in IPCC

BC Source category	Source (Tg/yr)	Reference
Fossil fuel	3.43	Ito and Penner, (2005)
Biofuel	2.97	Ito and Penner, (2005)
Open biomass burning	4.72	This study
Total	11.12	This study

Conclusions (biomass aerosols)

- Using a combination of inverse models and different observations can lead to better estimates of sources. A priori estimates are more important than estimates of uncertainty in the a priori in determining inverse model results.

- For open biomass burning, better bottom up methods need to be developed: MODIS appears to be giving good estimates of burned area, but need better estimates of available fuel (Ito and Penner, 2005b).

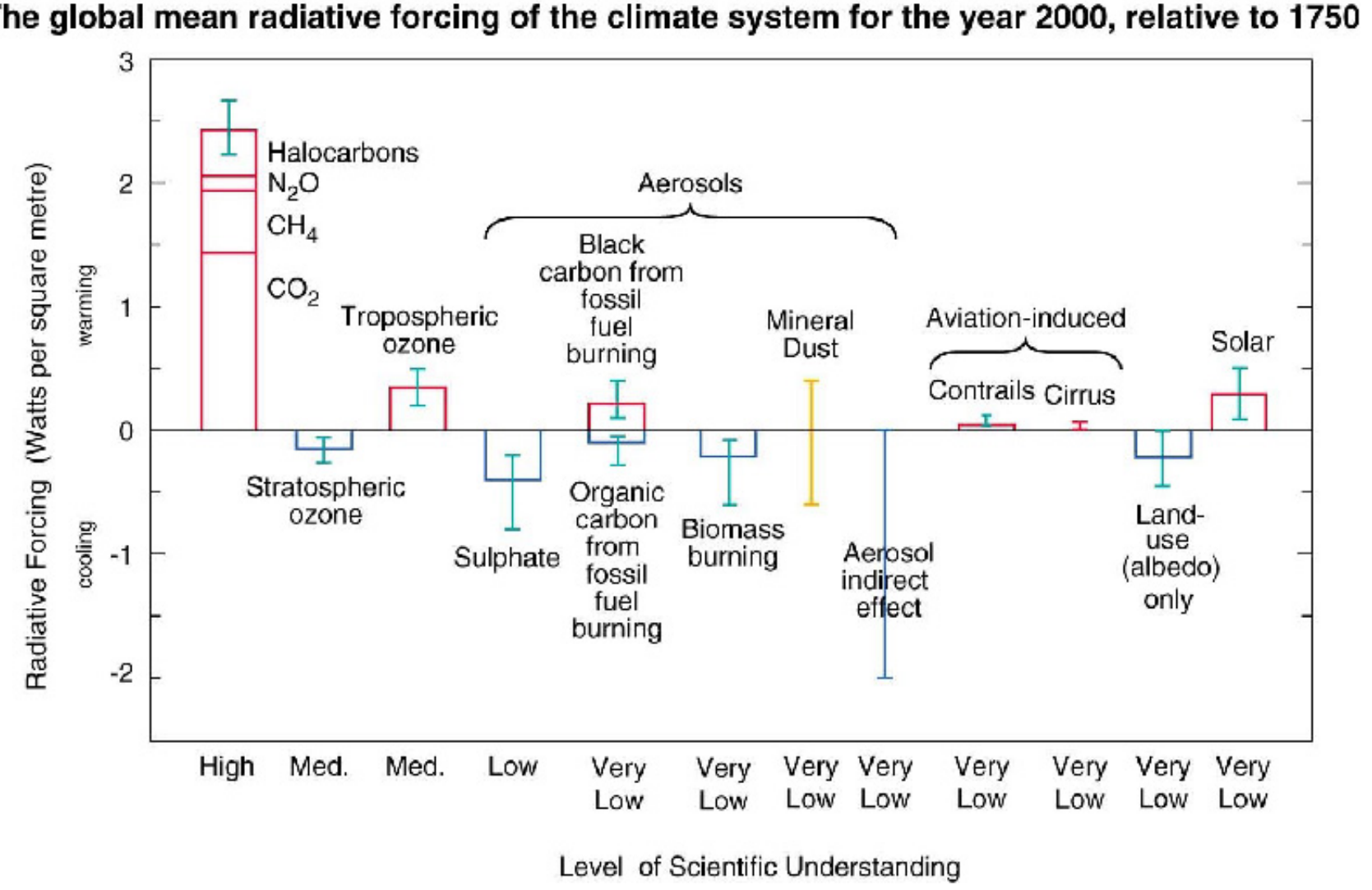
- Assuming model procedures for determining aerosol concentrations are correct, significant underestimates can be corrected using inverse methods

Research priorities:

-Combine bottom up and top down methods to narrow uncertainties in open biomass emissions

-Improve model procedures for predicting aerosol mass concentrations

Forcing estimated in IPCC, 2001:



How can we assign unbiased estimates of uncertainty?

- Estimates of uncertainty may be obtained from estimates of forcing together with uncertainty in factors involved in determining forcing. So for direct forcing:

$$\Delta F = F_d[T_a^2(1-f_c)][2(1-R_s)^2\bar{\beta}f_b M\alpha_s f(RH) - 4R_s M\alpha_s f(RH)((1-\omega_0)/\omega_0)]$$

- Where:
- F_d=net downward solar flux
- T_a=atmospheric transmissivity above the main aerosol layer
- f_c= global cloud fraction
- R_s= global average surface albedo
- β = up scatter fraction for isotropic incoming radiation
- f_b = hygroscopic growth factor for up scatter fraction
- M = global mean column burden for anthropogenic aerosol constituent, (gm^{-2})
- α_s = aerosol mass scattering efficiency, (m^2g^{-1})
- f(RH) = hygroscopic growth factor for total particle scattering
- ω_0 = single scattering albedo at ambient RH (assumed to be 80% for this analysis).

- Parameters depend on N_a, size distribution, chemical composition

Assuming the standard uncertainty analysis:

- The uncertainty is determined by the variation forcing associated with each parameter:

$$(F - F_0)^2 = \sum_i \left[\frac{\partial F}{\partial x_i}\right]^2 (\partial x_i)^2 + \sum_i \sum_j \mathrm{cov}(x_i, x_j) \left[\frac{\partial F}{\partial x_i}\right]\left[\frac{\partial F}{\partial x_j}\right]$$

Bottom-up estimates of uncertainty (Chapter 5, IPCC, 2001)

- Fossil fuel direct:
  - **-0.6 Wm^{-2}** **range: -0.1 Wm^{-2} to -1 Wm^{-2}**
- Biomass smoke direct:
  - **-0.3 Wm^{-2}** **range: -0.1 Wm^{-2} to -0.5 Wm^{-2}**
- Results do not account for biases in estimates

NOTE:

- Estimates of uncertainty are only as good as our theoretical and observational understanding (I.e. the models and data used to estimate ranges)