OMI measurements of SO_2 pollution over Eastern China in 2005-2008

N. Krotkov [1,3] , C. Lee [2], R. Martin [2], K. Pickering [3], J. Witte [4,3], S. Carn [5] , K. Yang [1,3], Greg Carmichael [6], C. Wei [6], D. Streets [7], Q. Zhang [7] , R. Dickerson [8], C. Li [9,3]

1. *Goddard Earth Sciences and Technology Center (GEST), UMBC, Baltimore, MD*
2. *Dalhousie University, Canada*
3. *Laboratory for Atmospheres, NASA Goddard Flight Center, MD*
4. *SSAI, Inc, Lanham, MD*
5. *Michigan Technological University , Houghton, MI*
6. *College of Engineering Center for Global and Regional Environmental Research, University of Iowa, Iowa City, IA United States;*
7. *Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL United States*
8. *Department of Atmospheric and Oceanic Physics, University of Maryland College Park, MD*
9. *ESSSIC, University of Maryland College Park*

ACC Workshop on Air Quality, ESRIN, Frascati, June 15-17, 2009

Bottom-up inventory of global sulfur emissions

Volcanic

Explosive (E)

Passive (P)

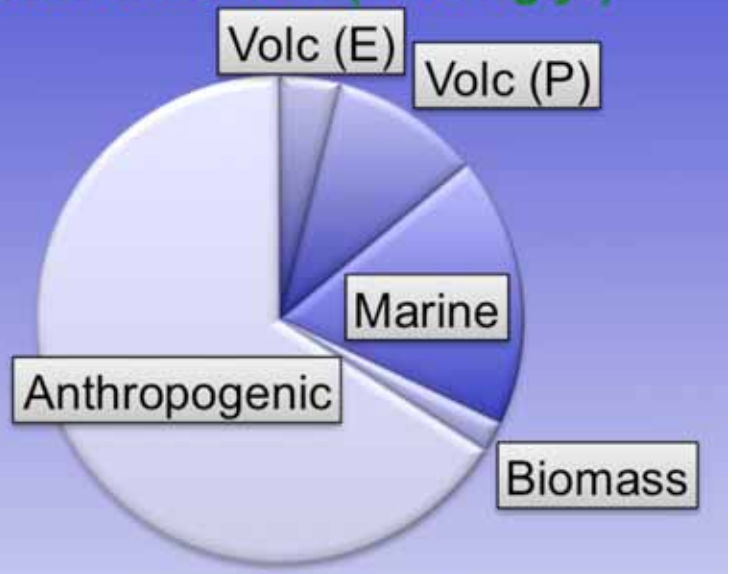
Marine and terrestrial DMS

Biomass burning

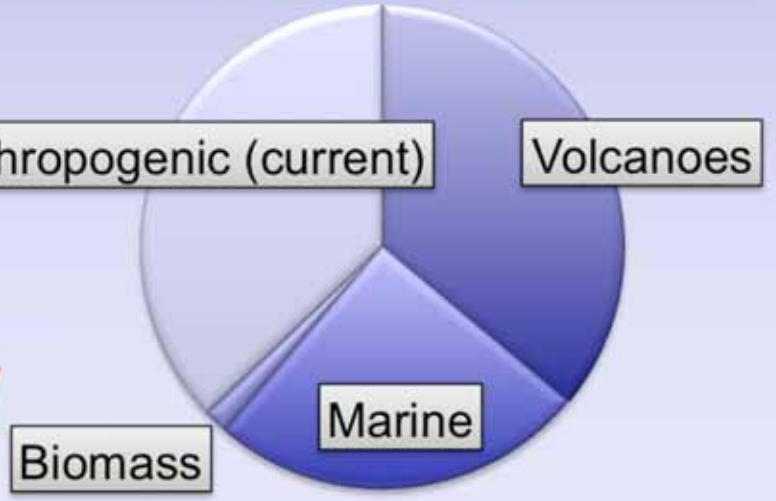
Fossil fuel use and industry

[Graf *et al.*, 1997; Andres & Kasgnoc, 1998]

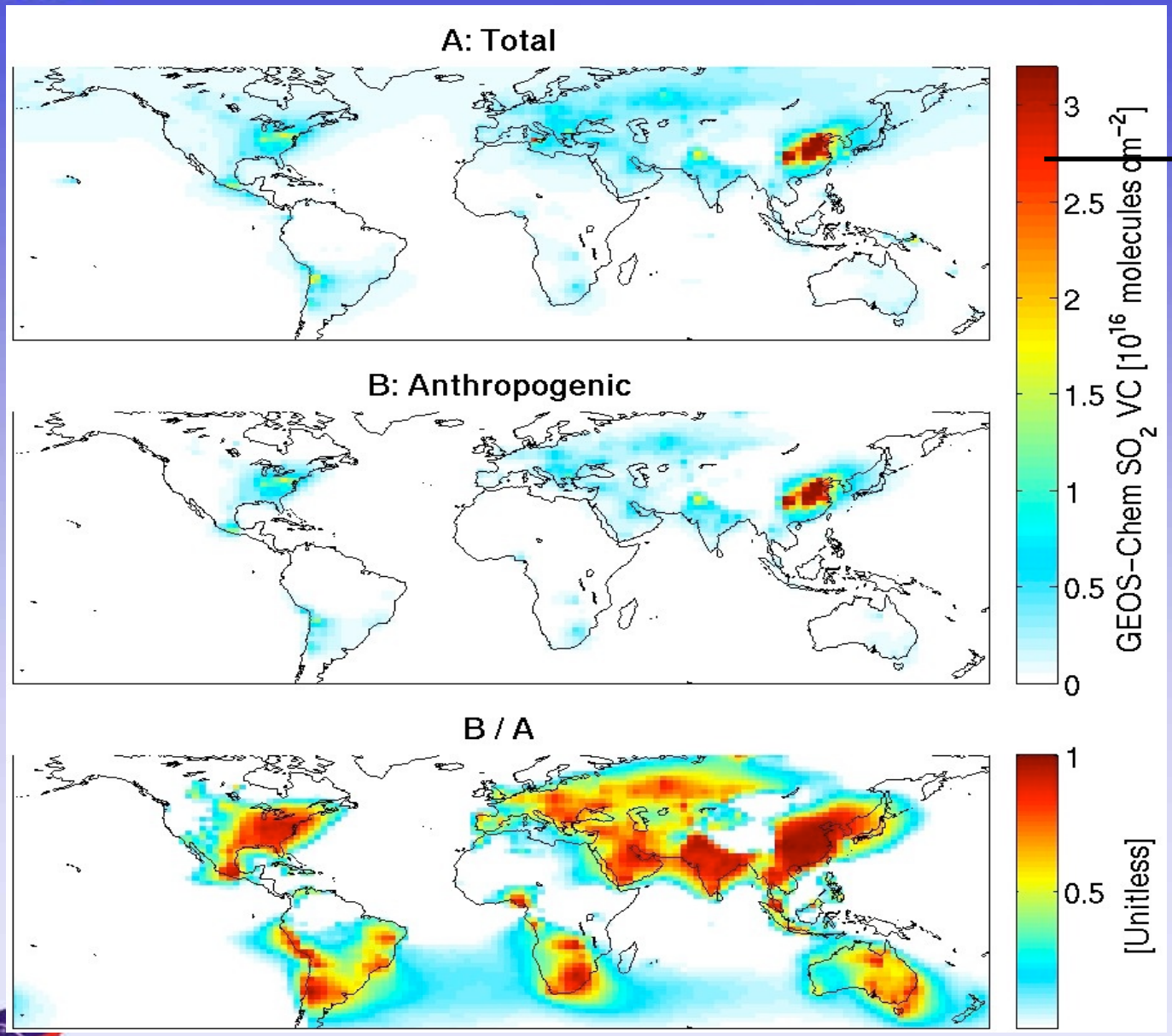
Sulfur emissions (~100 Tg/yr)



Sulfate burden



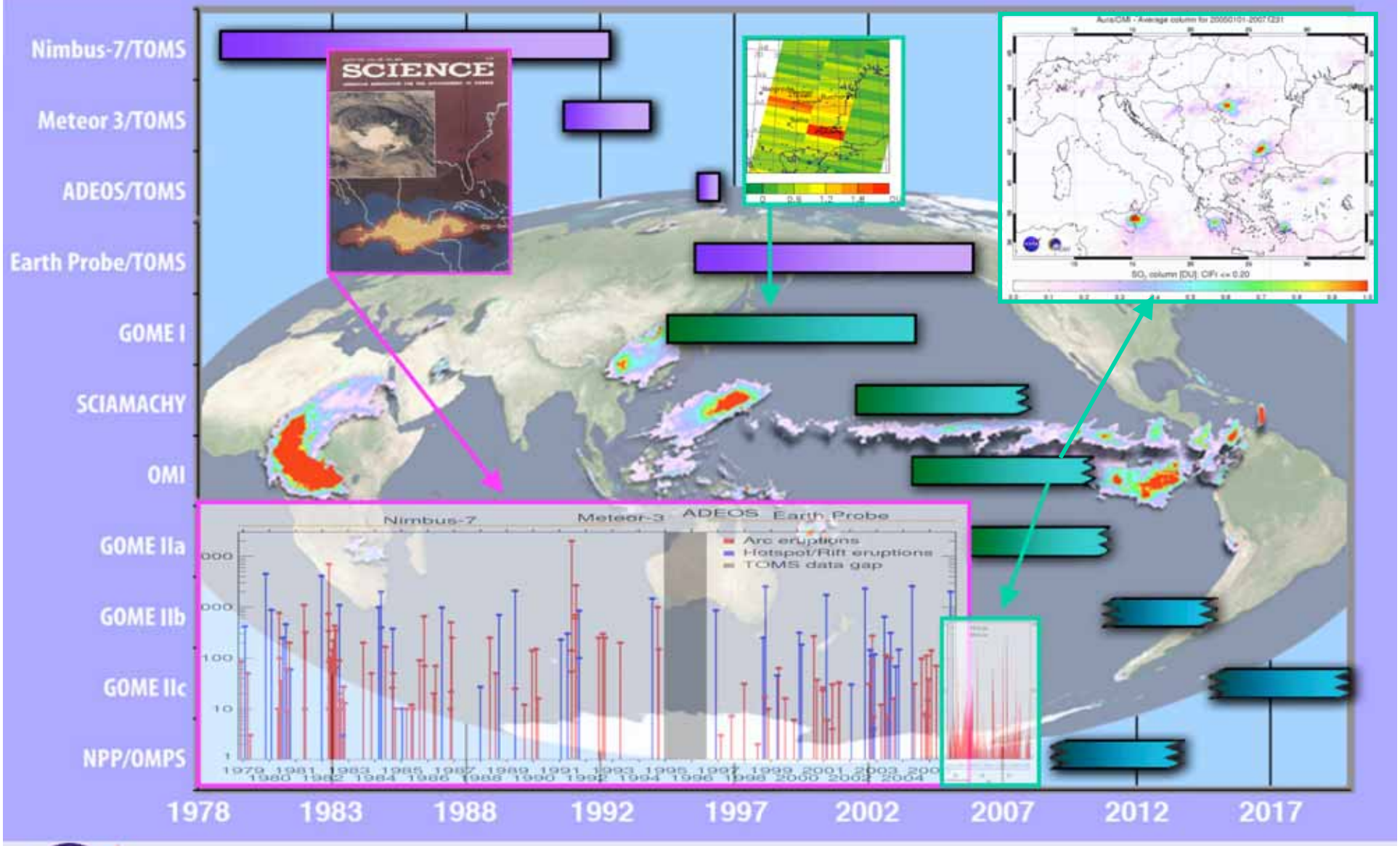
Fraction of anthropogenic SO_2



1 Dobson Unit ~ $2.69\ 10^{16}$ molecules cm-2

[Lee et al , JGR under review 2009]

Satellite BUV SO_2 data timeline



Satellite Backscattered UV (BUV) algorithms use Ozone and SO_2 absorption spectral features in reflected Sunlight to measure SO_2 slant column density (SCD)

A-priori Air-mass Factor (AMF) is required to convert to SO_2 Vertical column Density (VDC):
VCD=SCD/AMF [molecules/cm^2]

Mostly Stratospheric (Total Ozone)

Stratospheric Or tropospheric (SO2)

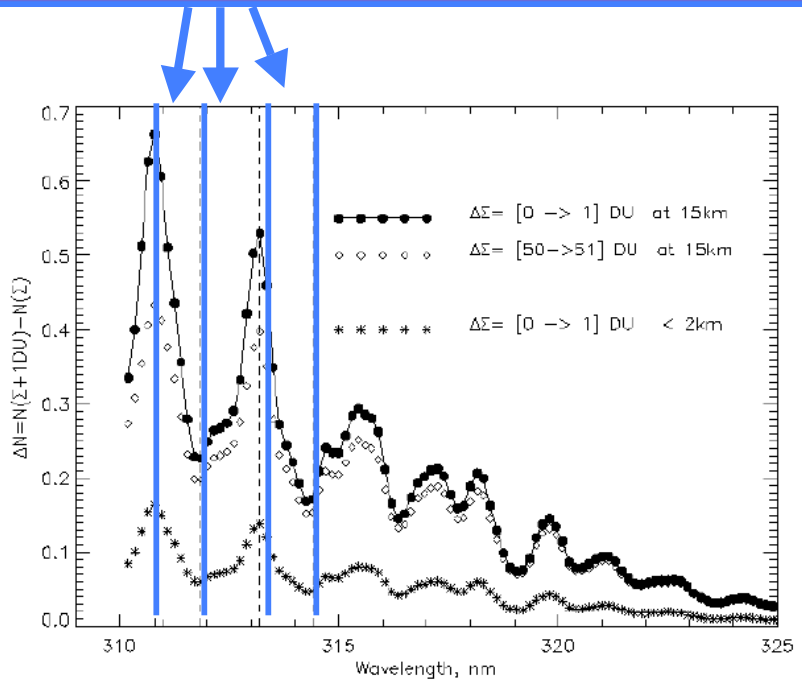
Cloud

Atmosphere

Surface

OMI operational PBL SO_2 data are produced with *provisional* BRD algorithm using 4 discrete UV2 wavelengths combined in 3 pairs

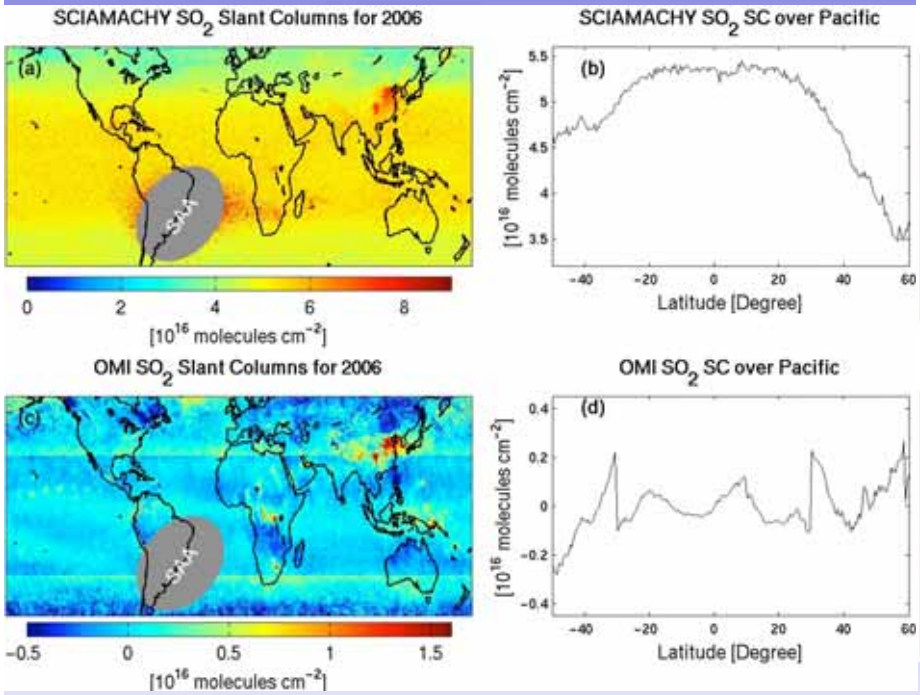
- **Operational PBL SO_2 retrieval uses constant Air Mass Factor AMF =0.36**
- **AMF is based on a-priori SO_2 vertical profile in Planetary Boundary Layer with Center of Mass Altitude (CMA) ~0.9 km**
- **No cloud correction for AMF**
- **SO_2 data should be used only for optimal viewing conditions:**
  - **SZA<50deg**
  - **OMI view angle < 40deg**
  - **Cloud fraction < 0.3**
  - **Terrain height < 1.5km**

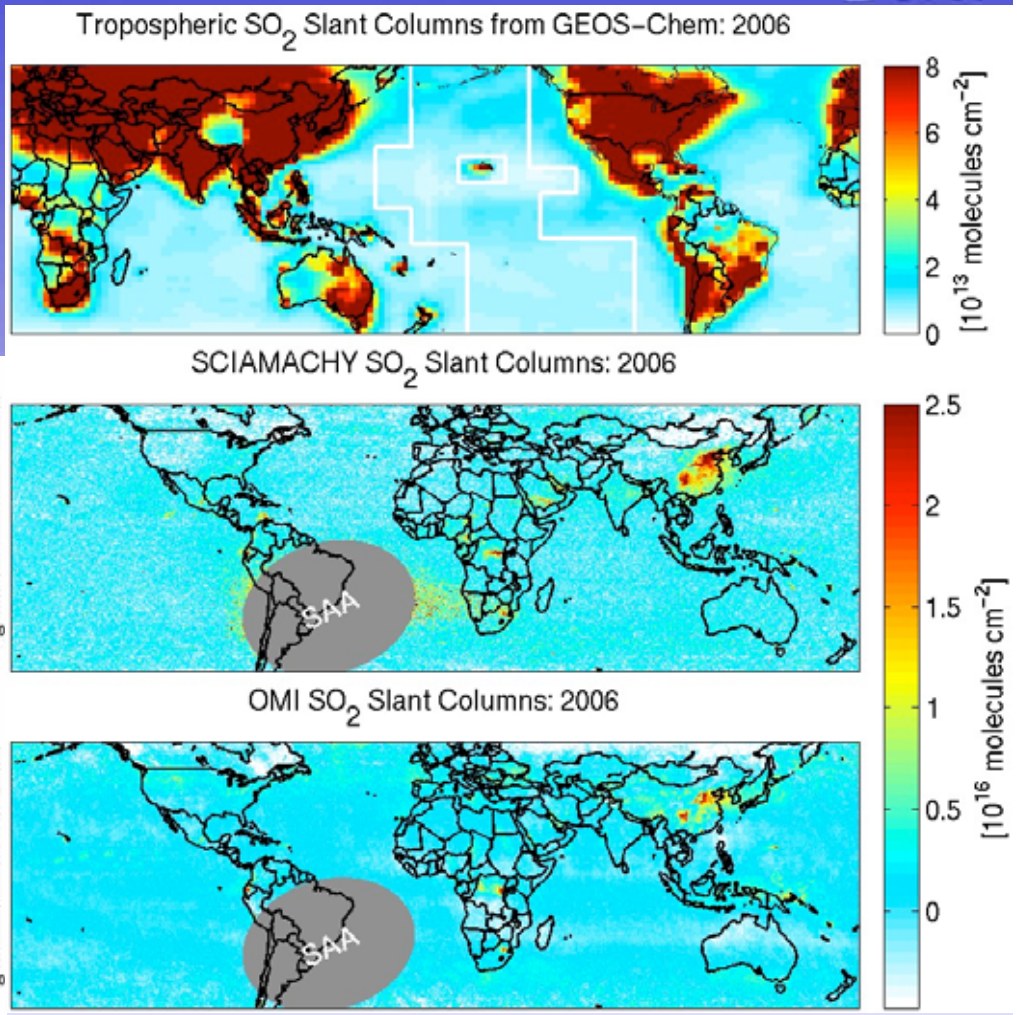


$OMSO_2$ algorithm [Krotkov et al 2006; Yang et al 2007] uses calibrated residuals at SO_2 absorption band centers produced by the NASA operational ozone algorithm (OMTO3 V8.5 [P.K. Bhartia]) and radiative cloud pressures from Rotational Raman algorithm [J. Joiner and A. Vasilkov]

Empirical corrections for SO_2 Slant Column Density

SCIAMACHY, GOME, GOME-2: reference sector correction





OMI: sliding median radiance residual correction [Yang et al JGR 2007]

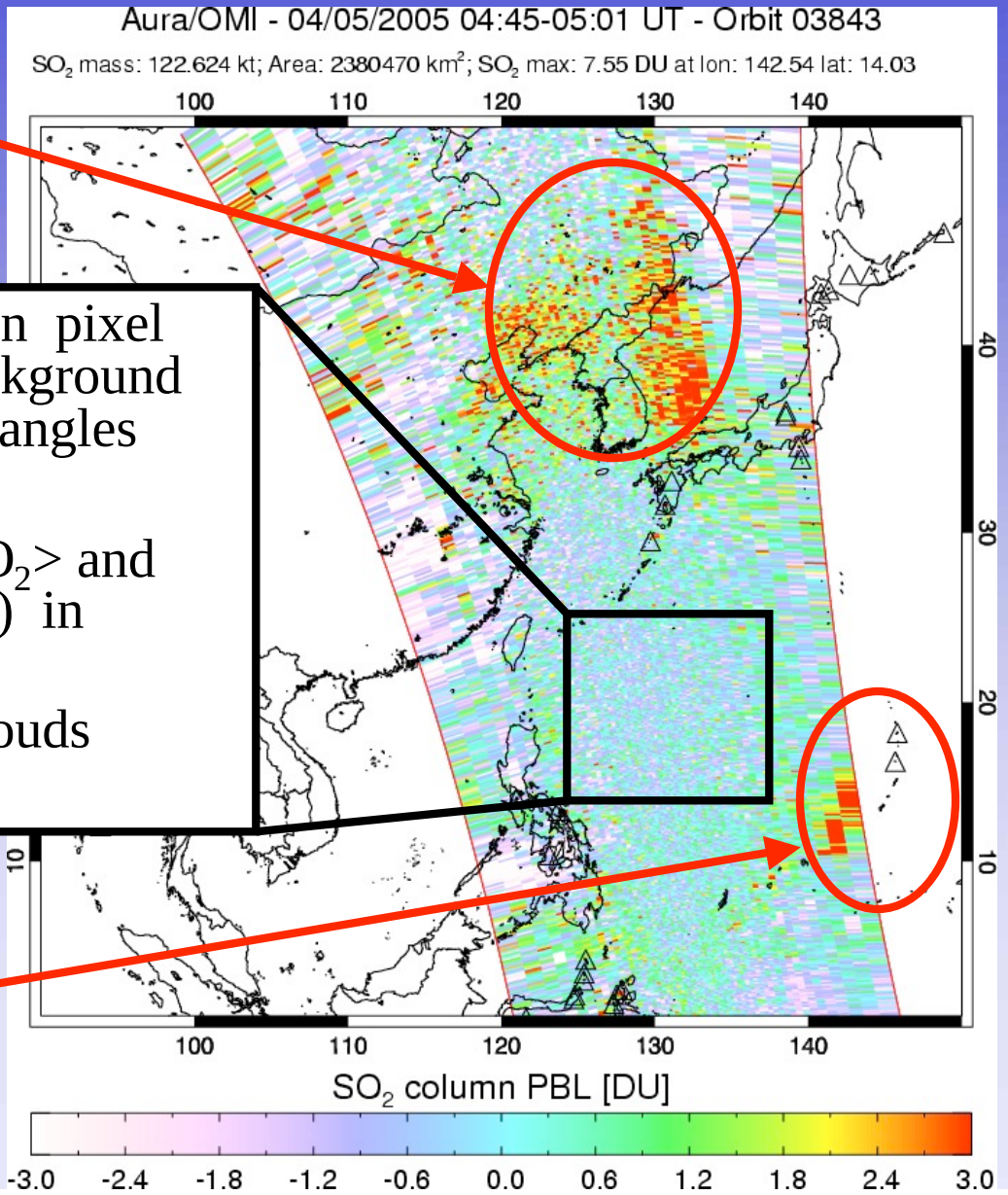
The gray oval labeled SAA on the OMI and SCIAMACHY maps is the area of South Atlantic Anomaly, where energetic particles of the Van Allen radiation belt bombard the orbiting instrument, drastically increasing the uncertainty of UV measurements

Pixel noise in operational PBL SO_2 data

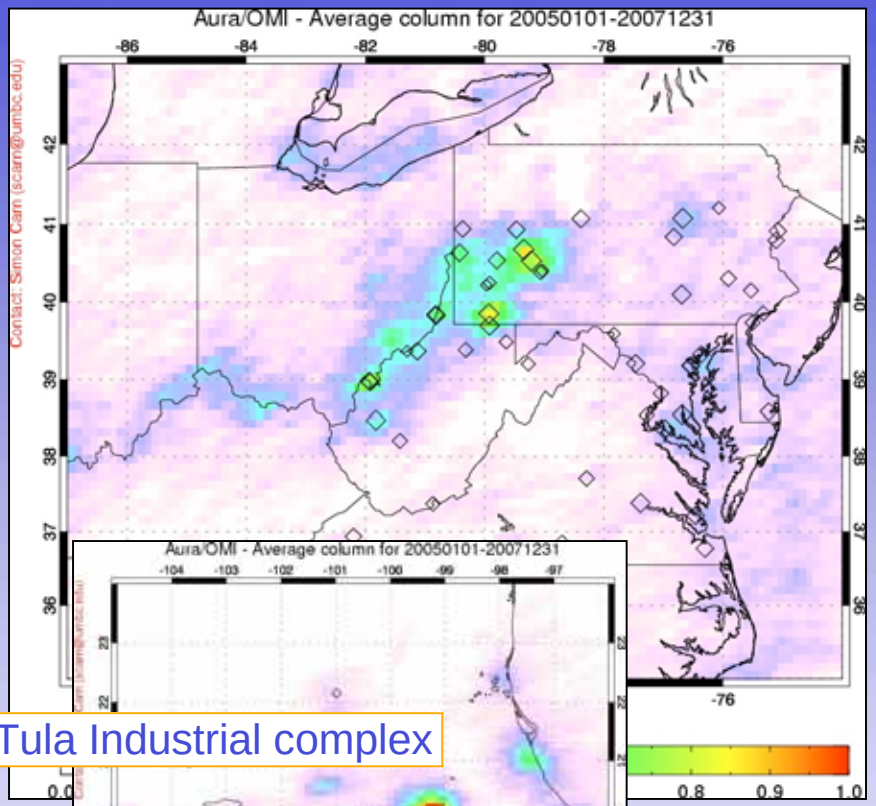
Pollution SO_2

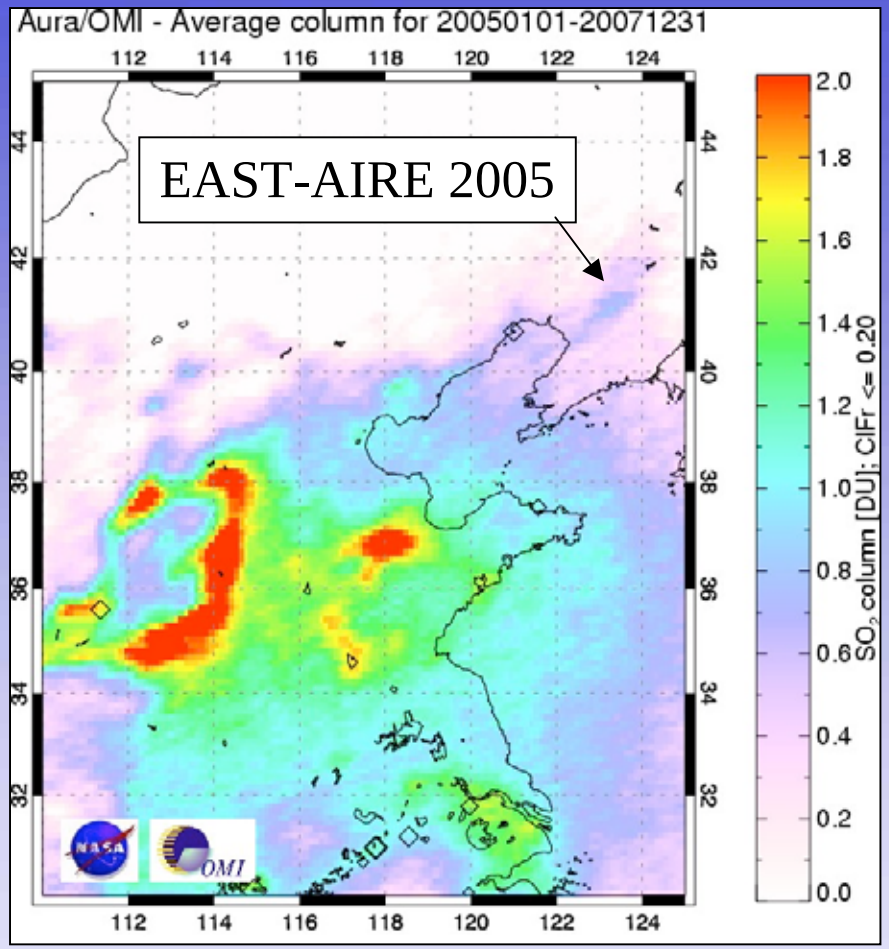
- Using AMF =0.36 results in pixel noise StDev~1DU over background areas and near –nadir view angles
- Near zero area average <SO_2> and reduced noise: 0.3 DU (1 σ) in 100km averages
- Negative artifacts due to clouds

Volcanic SO_2: use volcanic trop. or stratospheric data!



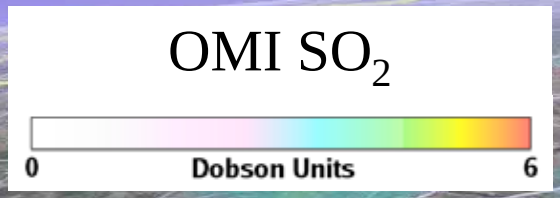
Quantitative comparisons of long-term SO_2 burdens in different regions of the world

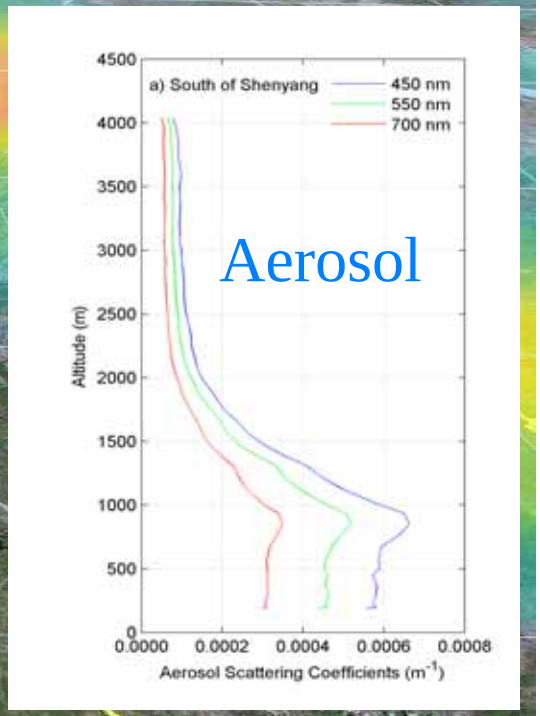


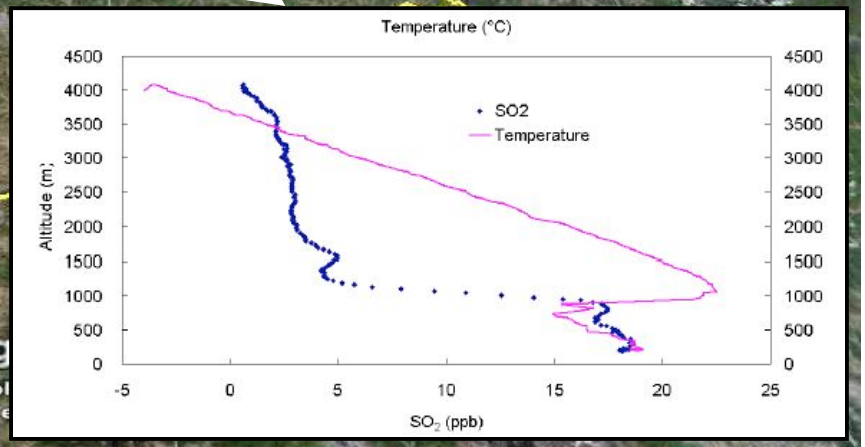


China is the world's largest producer of SO_2 mostly from coal burning power plants 25.5 million tons of SO_2 was emitted by Chinese factories in 2005 up 27% from 2000

OMI SO_2 data Validation







- In-situ aircraft measurements

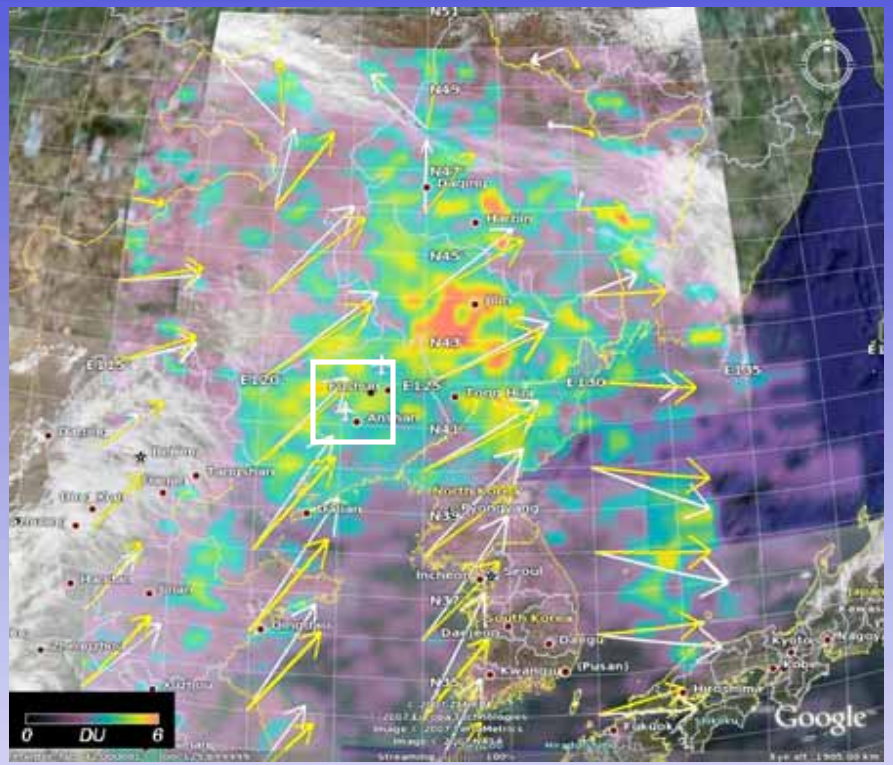
-EAST-AIRE- NE China2005 [Krotkov et al 2008]
-INTEX-A, B [Lee et al JGR 2009]
-TC4 South America 2007;
-China 2008

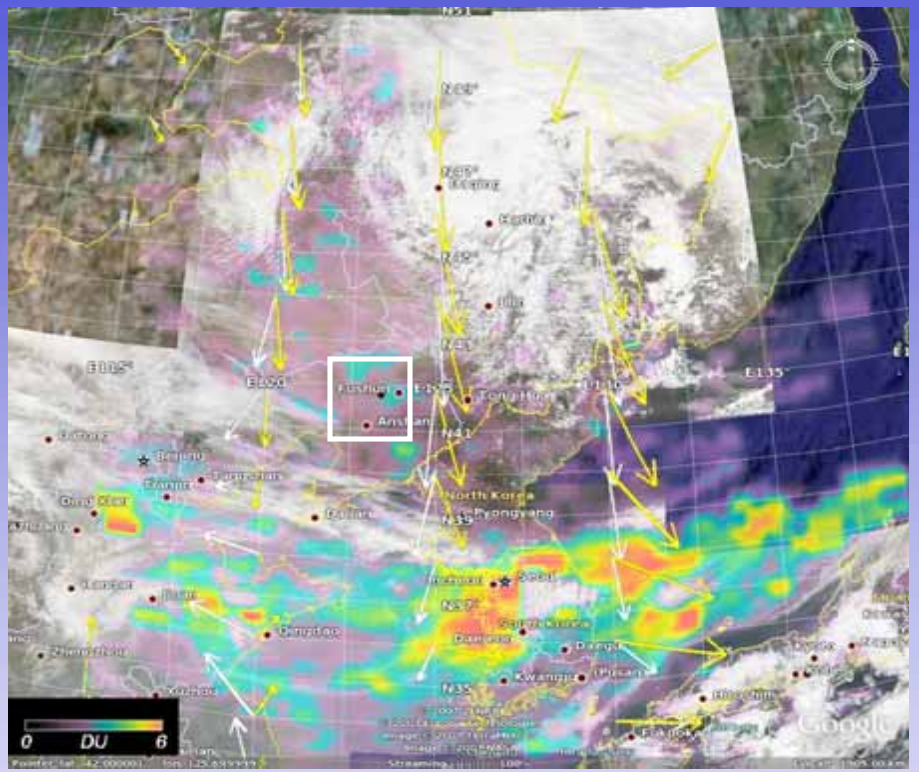
-http://avdc.gsfc.nasa.gov - overpass data sets for ~130 power plants and Brewer locations; Need improvements in operational Brewer algorithm

-New DOAS mini-spectrometers (PANDORA near pollution sources – Jay Herman & A. Cede, NOVAC near volcanoes– Bo Galle & S. Carn)

-SO_2 balloon (Gary Morris)

OMI monitors Chinese SO_2 pollution lofting above the PBL and long-range transport over Pacific ocean

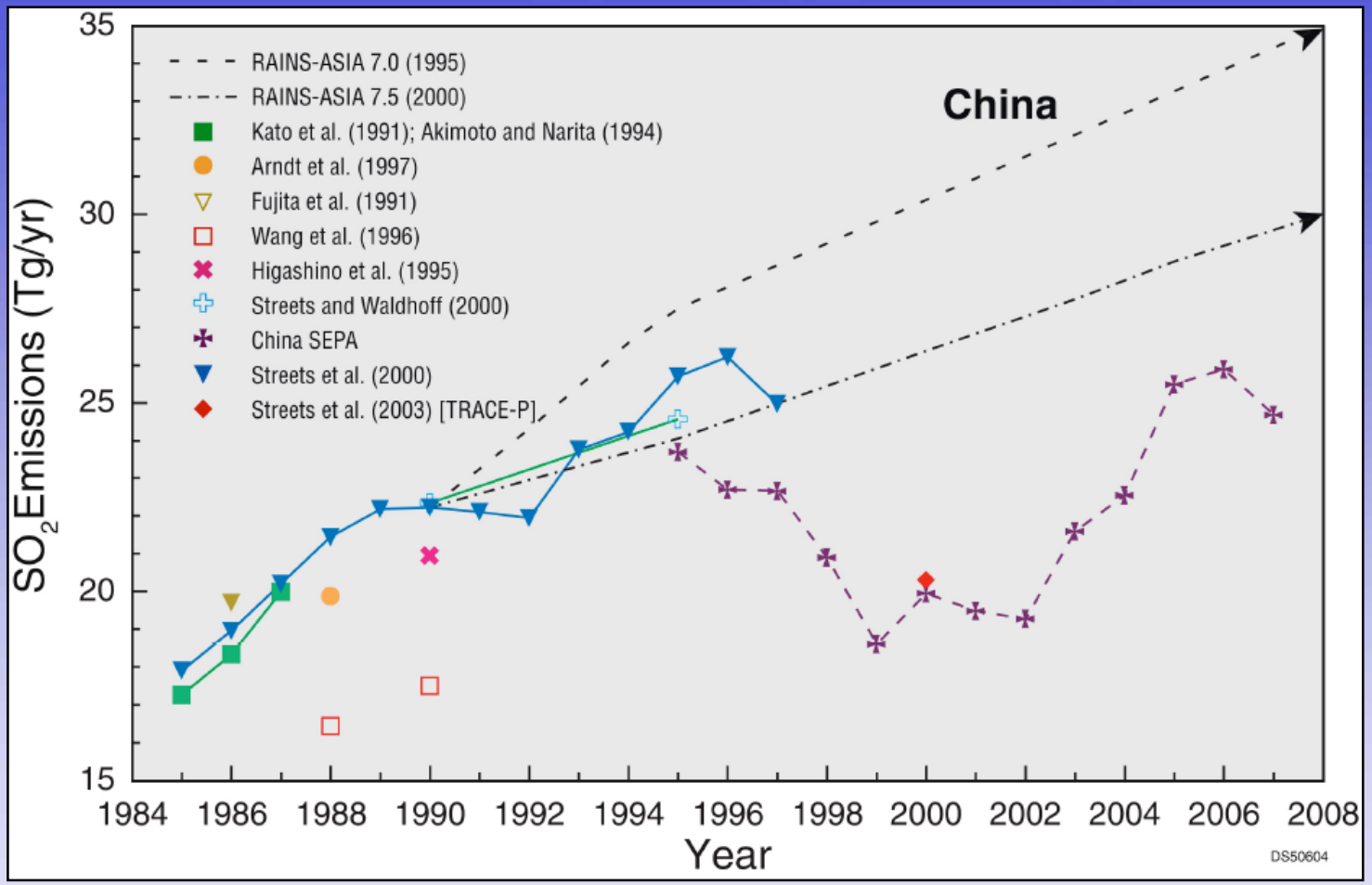




OMI data were confirmed with *in-situ* aircraft SO_2 profiles measured in the lower troposphere over China during the EAST AIRE campaign in April 2005. The satellite-derived measurements of SO_2 confirm the *in situ* observations of high concentrations of SO_2 ahead of the front and lower concentrations behind it and provide evidence for a large-scale impact of pollutant emissions

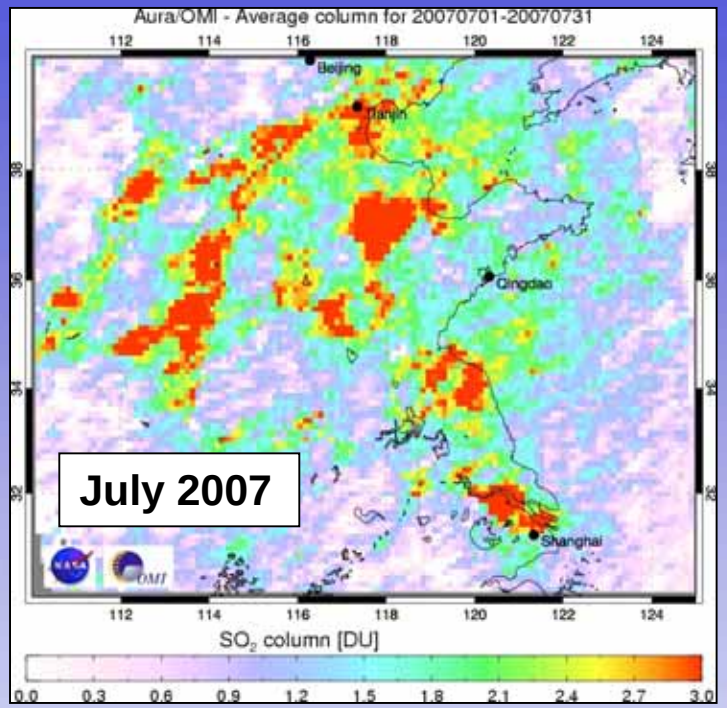
[*Krotkov et al JGR, 2008; Li et al submitted JGR 2009*]

Trends in Chinese SO_2 emissions



"SO_2 emission controls were given a major strengthening in the 11th Five-Year-Plan, with flue-gas desulfurization technology (FGD) required on all new plants and some old ones, and much better inspection and enforcement". – [David Streets , private communication]

OMI measured less SO_2 in summer 2008



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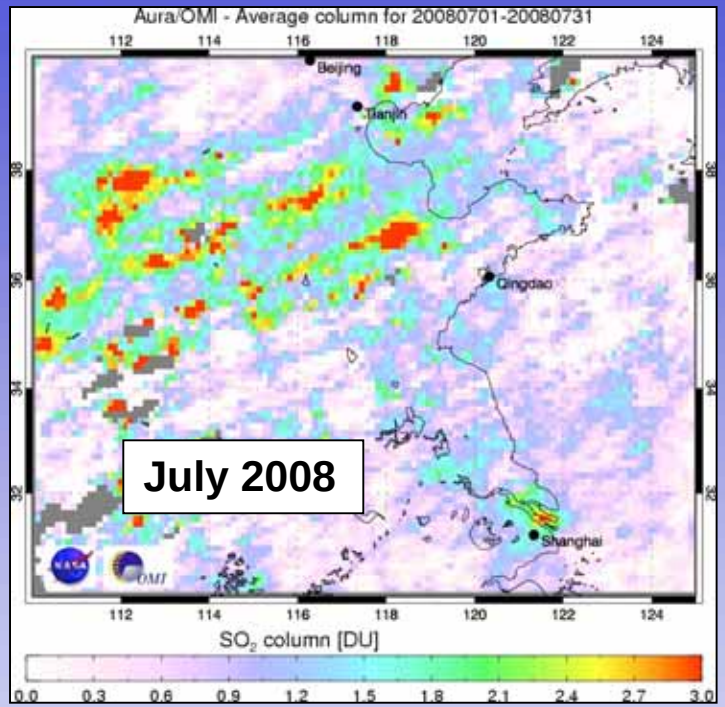
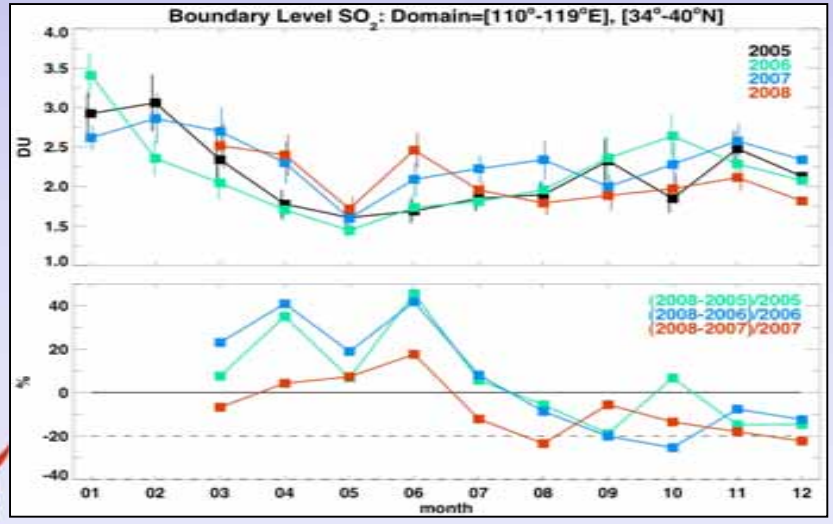
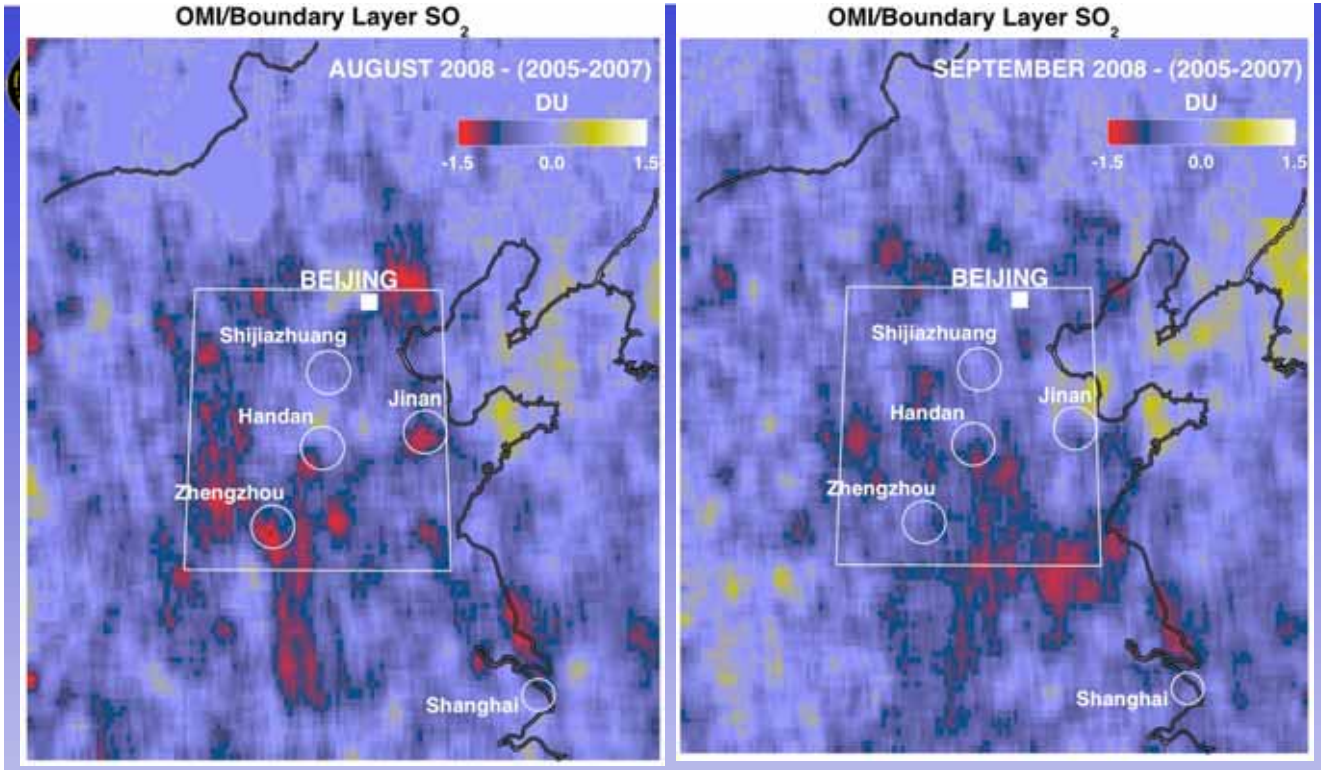
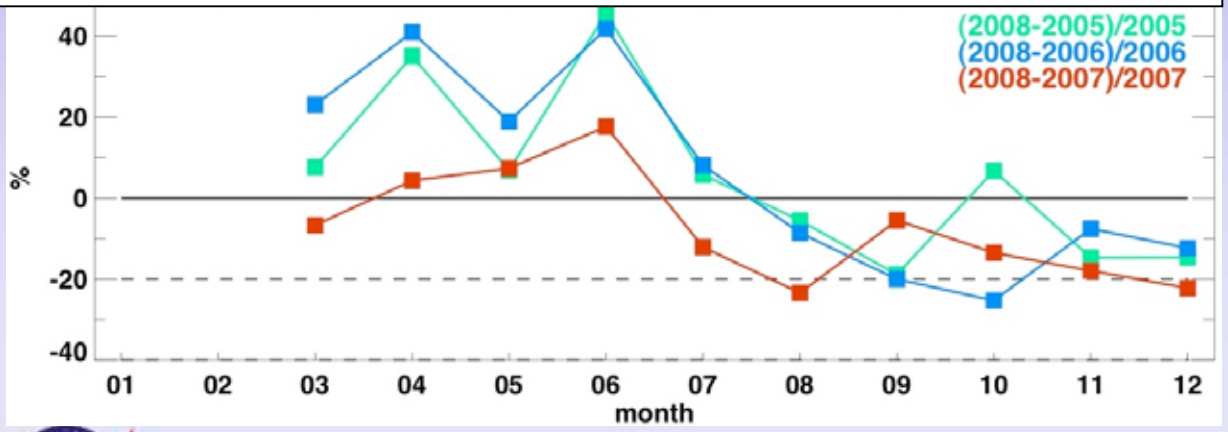




By mid July the 2008 SO_2 values were consistently lower than 2007 and prior years. The decline is widespread with highest SO_2 typically located to the south and southwest of Beijing in regions with large clusters of power plants and also around Shanghai. The decline also lasted beyond the Olympic season.



Boundary Layer SO_2 Domain: 110-119E, 34-40N

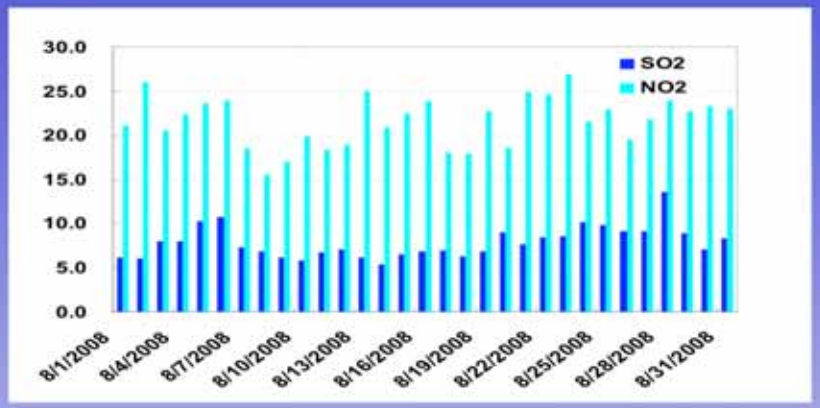


Emission Controls

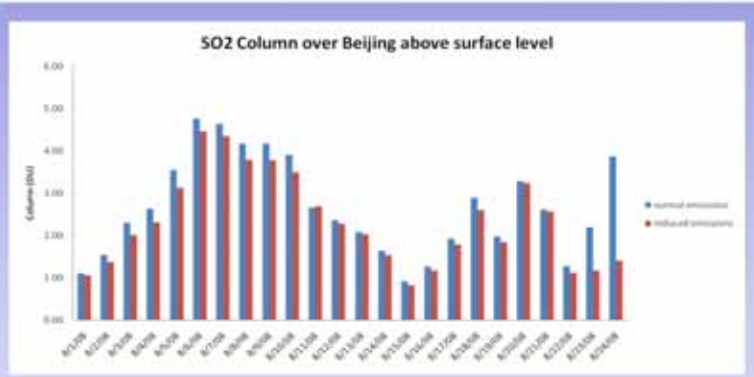
2008 - (2005-2007)	
July	-15%
August	-11%
September	-14%
July-September	-13%

[Witte et al AGU, 2009]

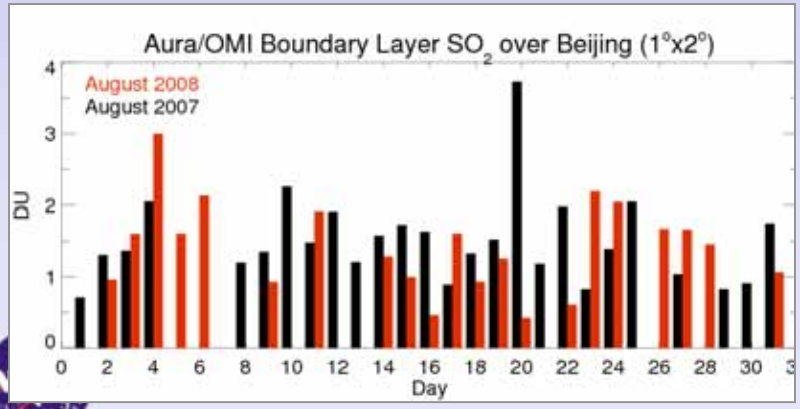
OMI daily data comparisons with University of Iowa STEM model in Beijing area during Olympic games



Surface concentration measurements http://www.bjepb.gov.cn), average daily concentrations from 27 monitoring stations around Beijing



Daily model SO_2 columns from STEM model: Spatial resolution: 60 km x 60 km, 21 sigma layers (0~23km); Meteorology model: WRF 60 km x 60 km.
Constant emissions for Olympic period.

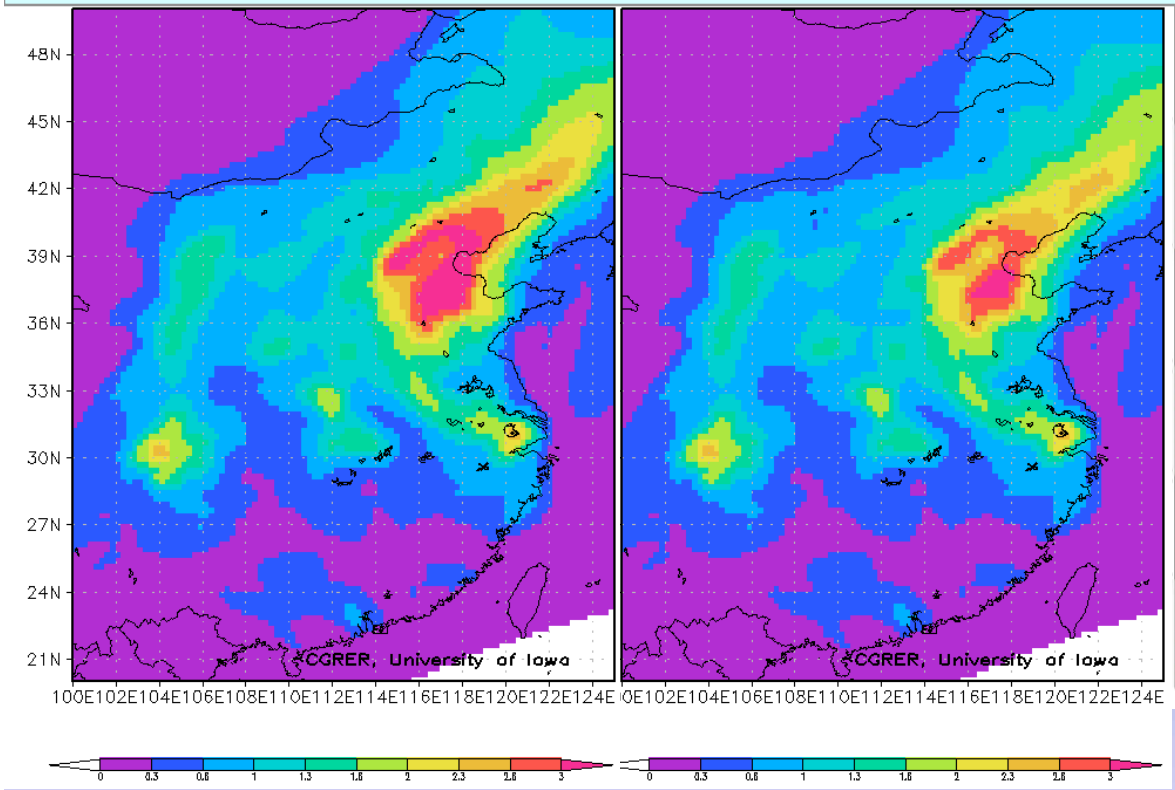


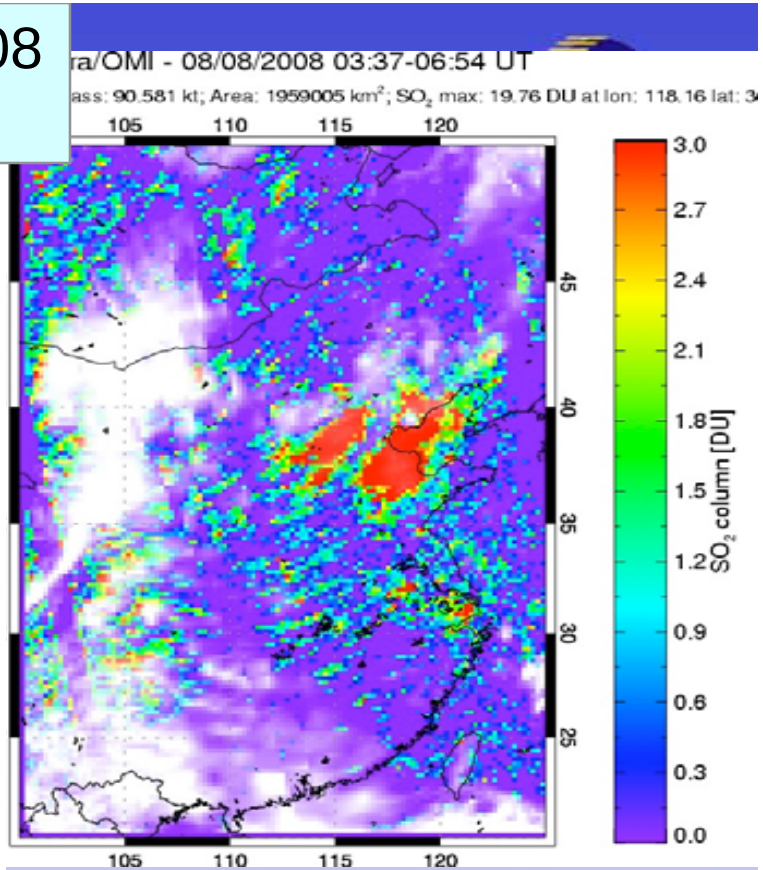
OMI daily PBL SO_2 daily burdens filtered by cloudiness (radiative cloud fraction < 0.3) and using constant AMF=0.36.

- Missing OMI values are due to cloud filtering.

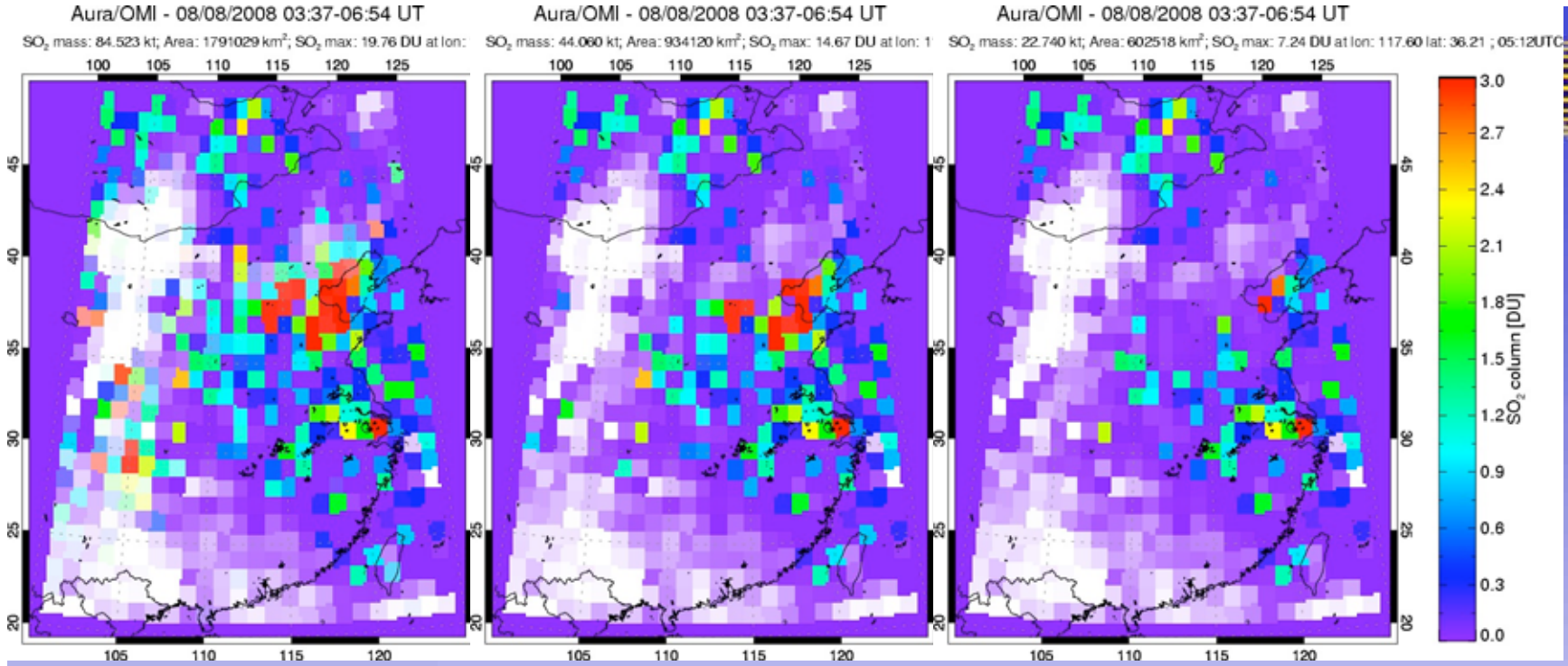
STEM model SO_2 columns on August 8 2008

normal emissions reduced emissions





OMI SO2 columns need to be corrected for clouds. The model provides SO_2 vertical distributions as well as aerosol vertical profiles that are needed to correct OMI operational SO_2 retrievals.

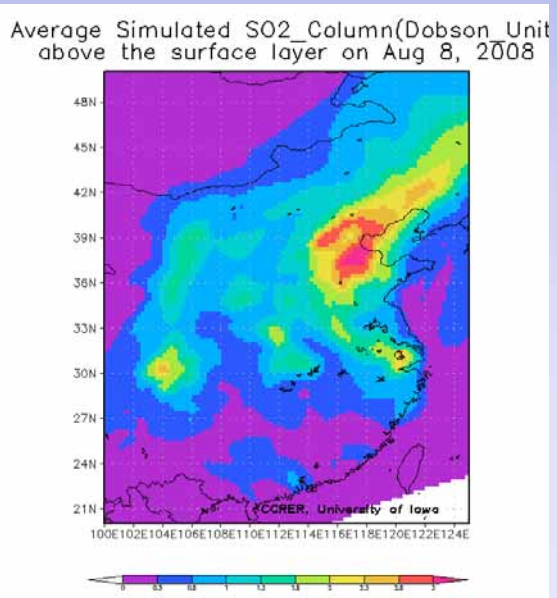


No OMI CldFrac filter

OMI CldFrac <0.5

OMI CldFrac <0.3

(used in monthly OMI maps)



-Satellite data should provide better corrections for partly cloudy scenes: filtering cloud pixels removes useful information;

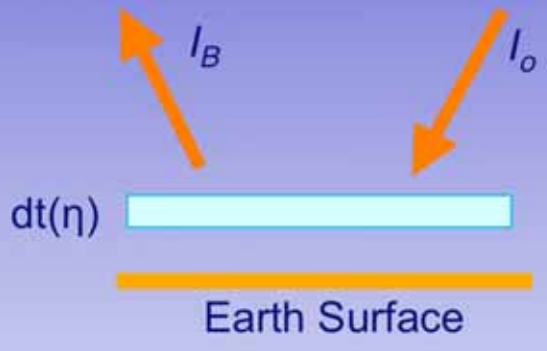
- A-priori information is needed on cloud effective height, aerosols and SO_2 profile shapes

- Model fields should be re-sampled consistently with satellite measurements (applying the same cloud filter)

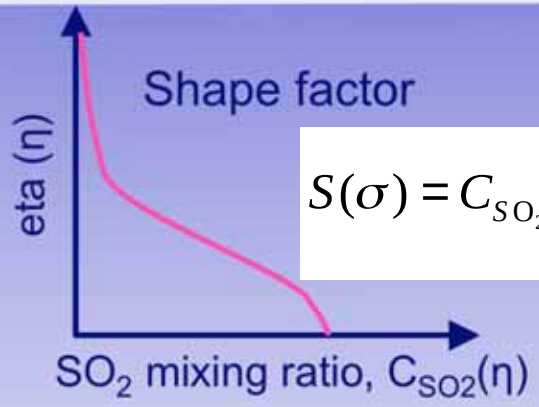
Air Mass Factor (AMF) Correction
Needs External Info on Shape of Vertical Profile

$$AMF = \frac{Slant\ Columns}{Vertical\ Columns} = AMF_G \int_{\eta_T}^{1} \omega(\eta) S(\eta) d\eta$$

Radiative Transfer Model



Atmospheric Chemistry Model



$$S(\sigma) = C_{SO_2}(\sigma) \frac{\Omega_{air}}{\Omega_{SO_2}}$$

Scattering weight $\omega(\sigma) = -\frac{1}{AMF_G} \frac{\alpha(\sigma)}{\alpha_e} \frac{\partial(\ln I_B)}{\partial \tau}$

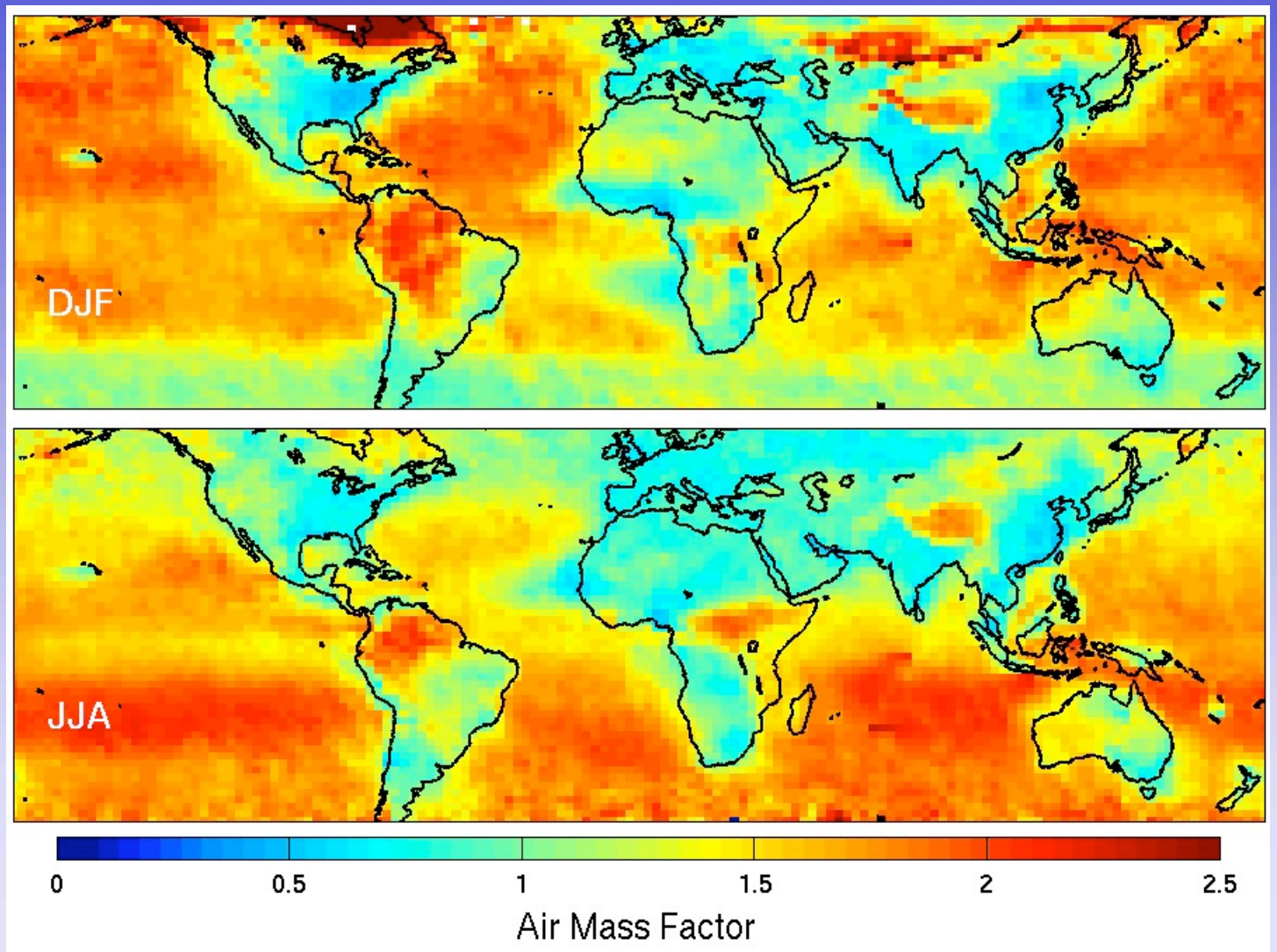
$\alpha(\eta)$ is temperature-dependent cross-section

Using GEOS-CHEM model for SO_2 profile shape correction
[Lee, et al JGR, under review]

Calculate $\omega(\eta)$ as function of:

- solar and viewing zenith angle (θ_s, θ_v)
- surface reflectivity, pressure
- aerosol
- O_3 column

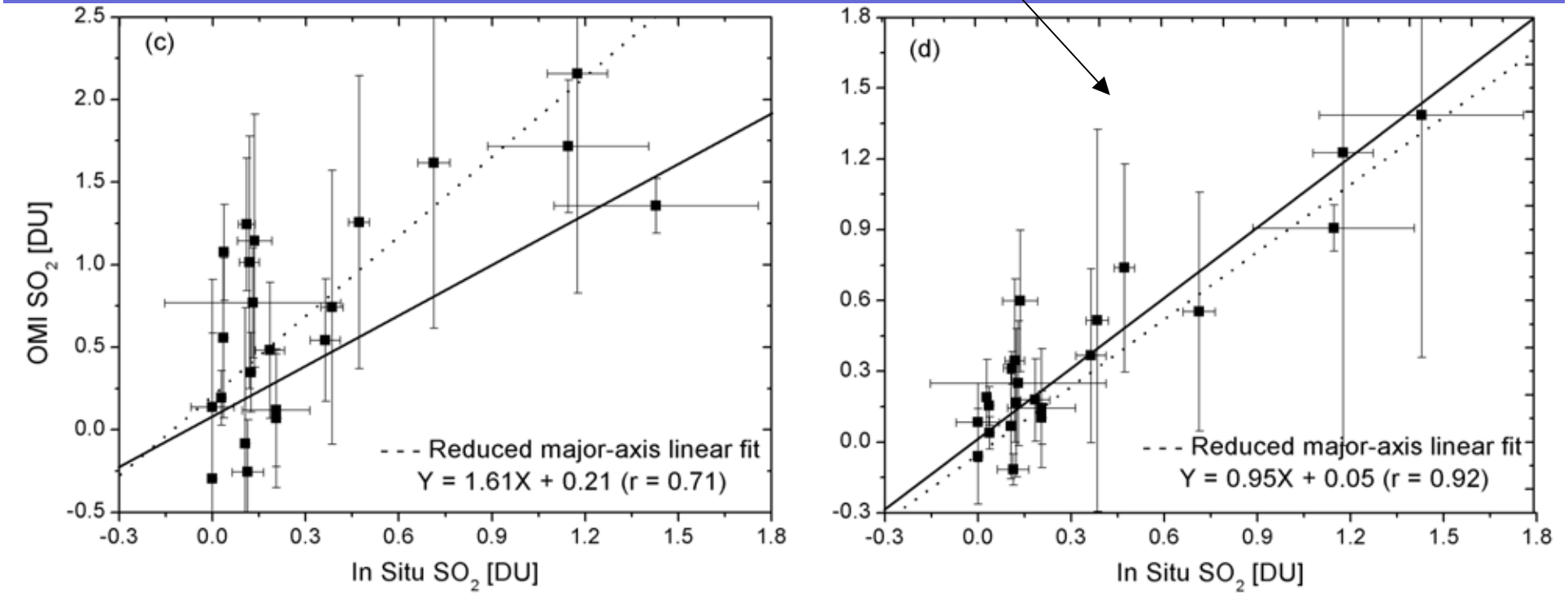
OMI pollution SO_2 post-correction using GEOS-CHEM local AMF



- Calculated at 313.2 nm; Cloud Radiance Fraction < 0.2; SZA < 70

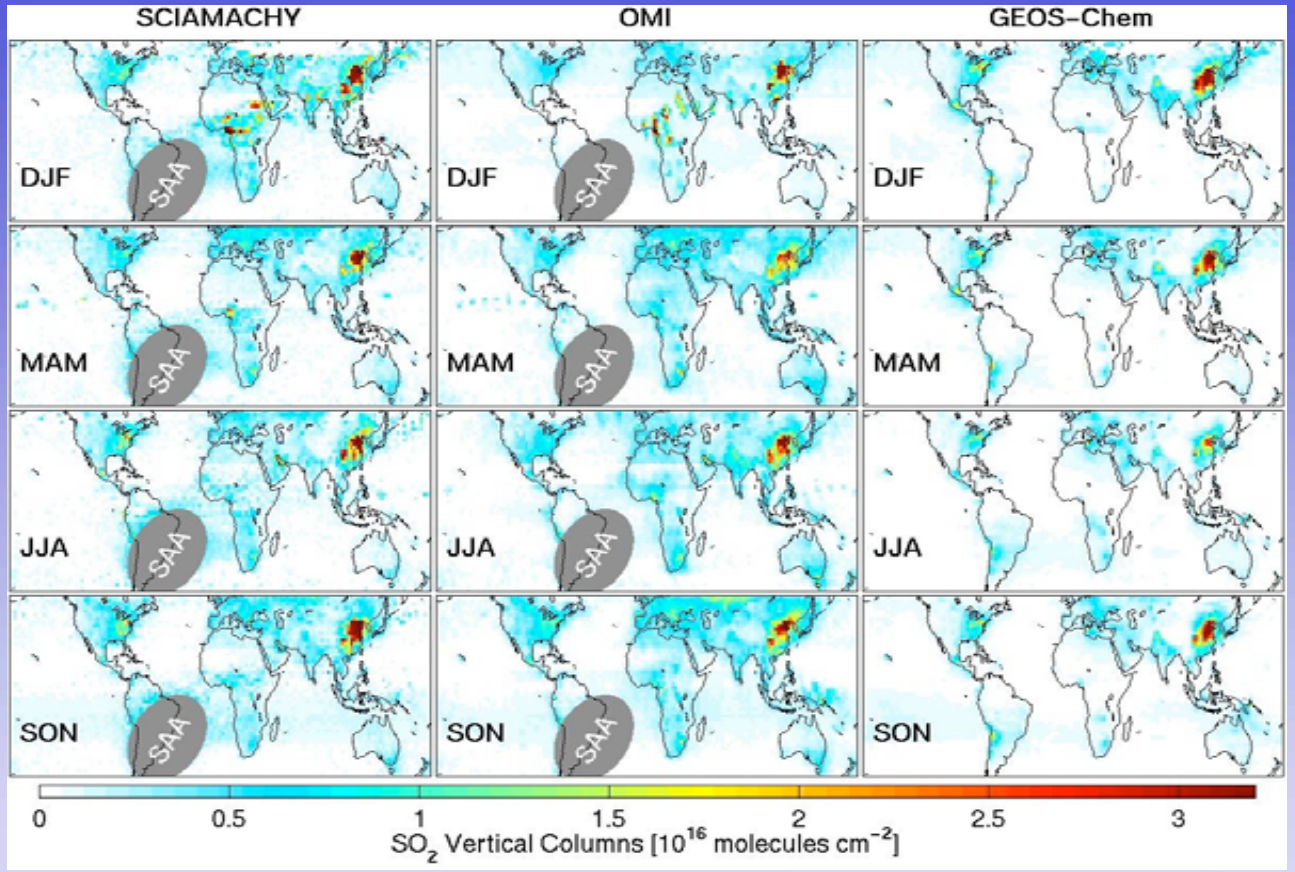
[Lee et al , JGR under review 2009]

Local AMF improves agreement with aircraft



Validation of tropospheric SO2 vertical columns from OMI versus those from in-situ measurements during INTEX-A (triangles) and INTEX-B (squares). The constant AMF refers to the OMI operational PBL product [Krotkov et al 2008]. The local AMF is developed in Lee et al., [2009]. Error bars indicate the standard deviations of in situ measurements and the OMI retrieval error. Solid line represents 1:1 line.

Corrected SO_2 Vertical Columns for 2006



Correlation with GEOS-Chem (GC)

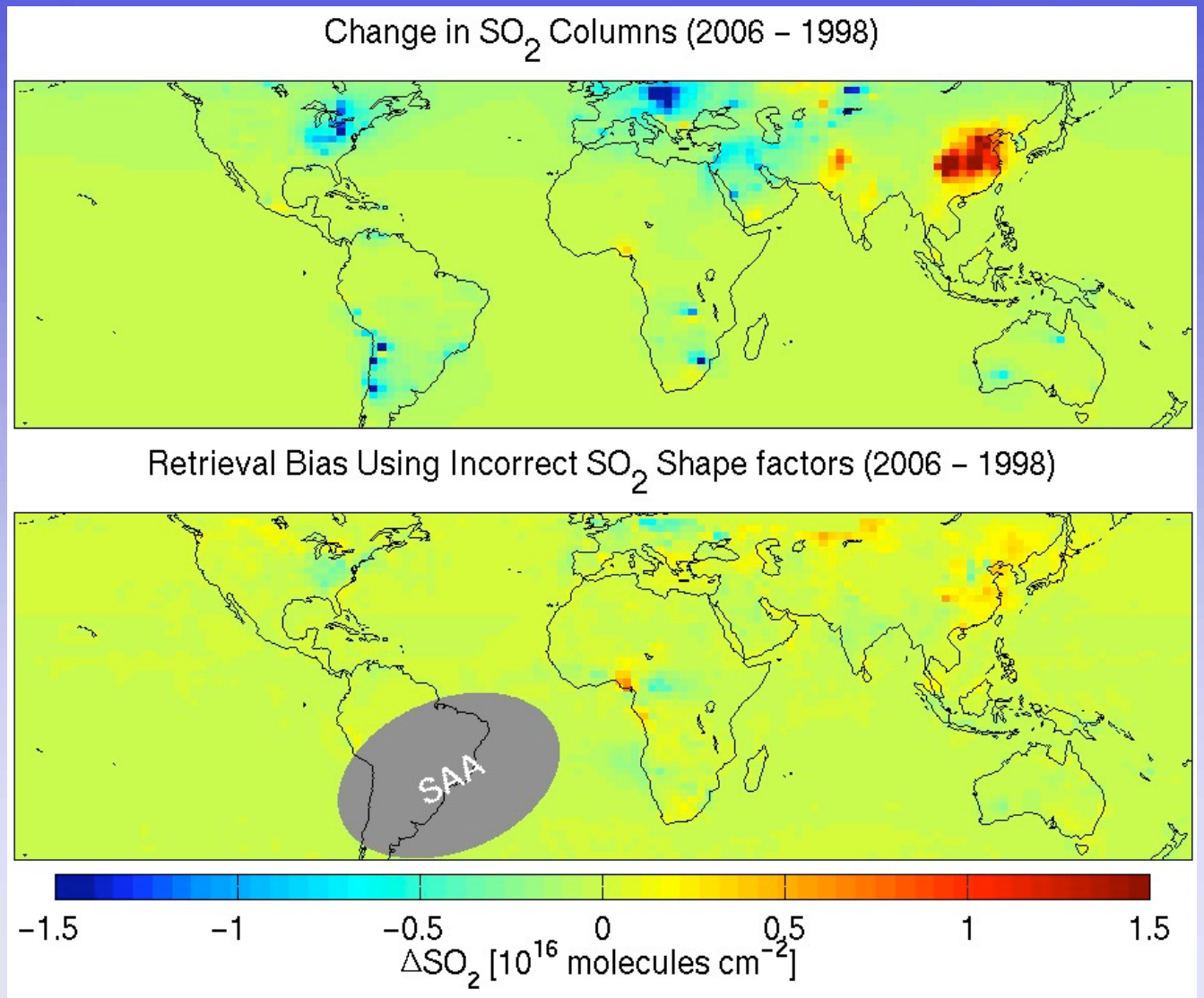
: Globally r ~0.78

: ~0.84 over US

: ~0.83 over China

Seasonal mean tropospheric vertical columns of SO_2 for cloud-free (cloud radiance fraction < 0.2) conditions determined from SCIAMACHY,OMI and the GEOS-Chem CTM. The model outputs were sampled coincidently with the observations. The gray oval labeled SAA on the OMI map is the area of South Atlantic Anomaly, where energetic particles of the Van Allen radiation belt bombard the orbiting instrument, drastically increasing the uncertainty of UV measurements [Lee et al 2009]

Sensitivity of Retrieved SO_2 to ΔEmissions



GEOS-Chem ΔSO_2

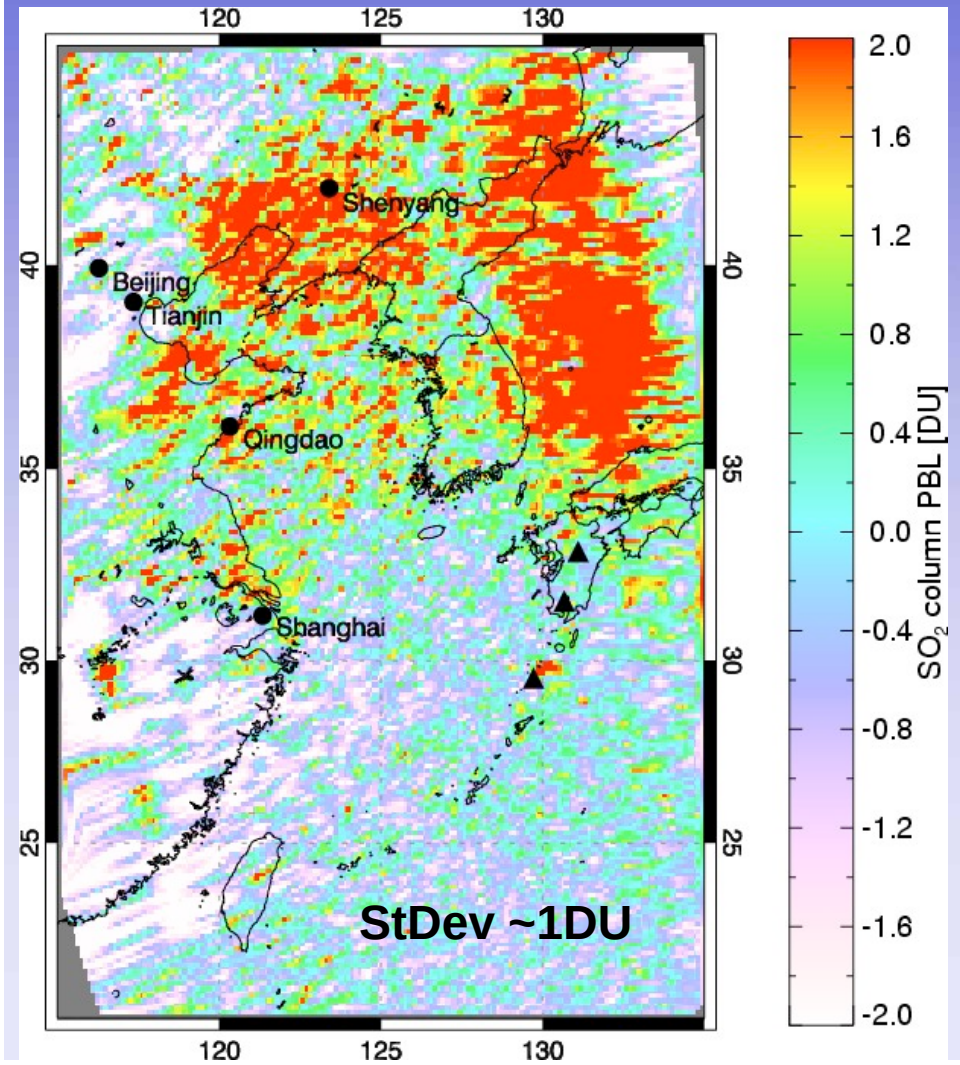
OMI SO_2 AMF changes < 30%

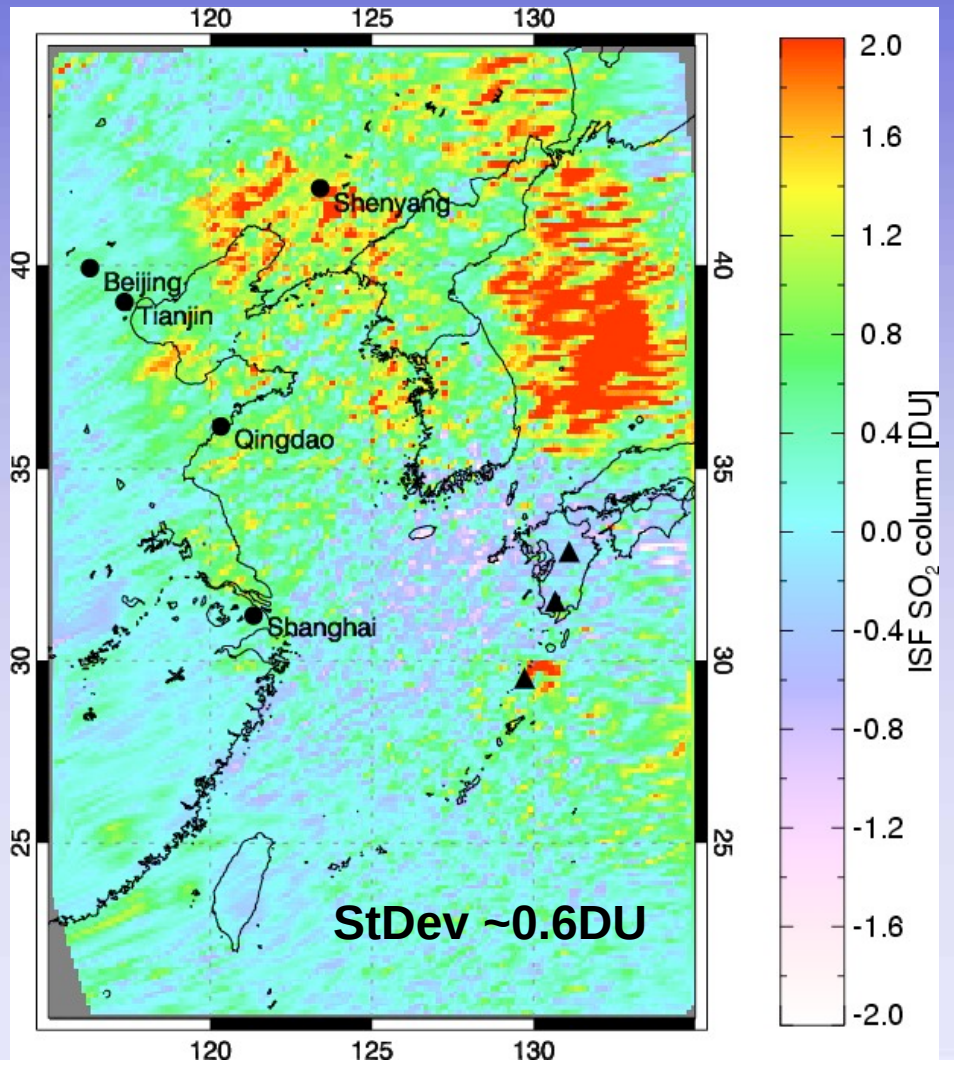
[Lee et al , JGR under review 2009]

Satellite SO_2 algorithm improvements: OMI direct spectral fitting [*Yang et al GRL 2009*]

Operational algorithm (discrete wavelengths)

OMI improved iterative spectra fit (ISF) algorithm results in significant noise and bias reduction.





Summary

- During the stringent emission control measures July-September 2008 OMI measured decreases of ~13% in Boundary Layer SO_2 over a wider region, compared to previous years for the same months.
- We observe a persistent minimum in Boundary Layer SO_2 monthly means after the controls were lifted, possibly reflecting the permanency of various emission control measures.
- Satellite operational SO_2 data require further improvements:
  - Local AMFs improve agreement of OMI and SCIAMACHY with airborne in-situ measurements for INTEX-A and B
  - Direct spectral fitting reduces retrieval noise and biases
  - Advanced Cloud/aerosol AMF corrections require information on radiative cloud fraction and aerosols.
- Large signal from anthropogenic emissions in retrieved SO_2 columns