Estimating aerosol emissions by assimilating aerosol optical depth in a global aerosol model

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ICAP 2012, 14-17 May, Frascati, Italy

Introduction

Hakami et al. (2005) : BC emissions are estimated over eastern Asia

Zhang et al. (2005) : Biomass burning emissions for 1997 by assimilating TOMS AI

Yumimoto et al (2007, 2008): Estimation of DD emissions of dust events by assimilating lidar measurements.

Dubovik et al (2008) : estimate intensity and location of fine and coarse mode aerosol emission

Objective

Estimate monthly emission of SO_2 and the main aerosol species (DD, SS, BC & OM) through the assimilation of total and fine mode aerosol optical depth (AOD).

Method:

$$J=(x-x_b)^T\boldsymbol{B}^{-1}(x-x_b)+(y-H[x])^T\boldsymbol{R}^{-1}(y-H[x])$$

$$x_a=x_b-(\mathbf{H}^T\boldsymbol{R}^{-1}\mathbf{H}+\boldsymbol{B}^{-1})^{-1}\mathbf{H}^T\boldsymbol{R}^{-1}(H[x_b]-y)$$

$$x_a=x_b+\mathbf{K}(y-H[x_b])$$

$\mathbf{K}=(\mathbf{H}^T\boldsymbol{R}^{-1}\mathbf{H}+\boldsymbol{B}^{-1})^{-1}\mathbf{H}^T\boldsymbol{R}^{-1}$

H= Linear operator

R = observation error covariance matrix

B = background error covariance matrix

Observations (y)

$$x_a = x_b - (\mathbf{H}^T \boldsymbol{R}^{-1} \mathbf{H} + \boldsymbol{B}^{-1})^{-1} \mathbf{H}^T \boldsymbol{R}^{-1} (H[x_b] - y)$$

- Daily Total and Fine mode AOD from MODIS-Terra Collection 5 (Level 3).
- Total AOD over land and ocean and Fine mode AOD only over ocean
- MODIS data (1° x1°) are thinned to model resolution (2.5° x3.75°)
- Additional data screening over ocean to remove outliers and correct biases (Zhang and Ried, 2006; Zhang et al., 2008):
  - Remove pixels with AOD>3
  - Remove pixels with cloud fraction larger than 80% (also applied over land)
  - No pixel south to 40° S is considered

Error characterization (R)

$$x_a = x_b - (\mathbf{H}^T \boldsymbol{R}^{-1} \mathbf{H} + \boldsymbol{B}^{-1})^{-1} \mathbf{H}^T \boldsymbol{R}^{-1} (H[x_b] - y)$$

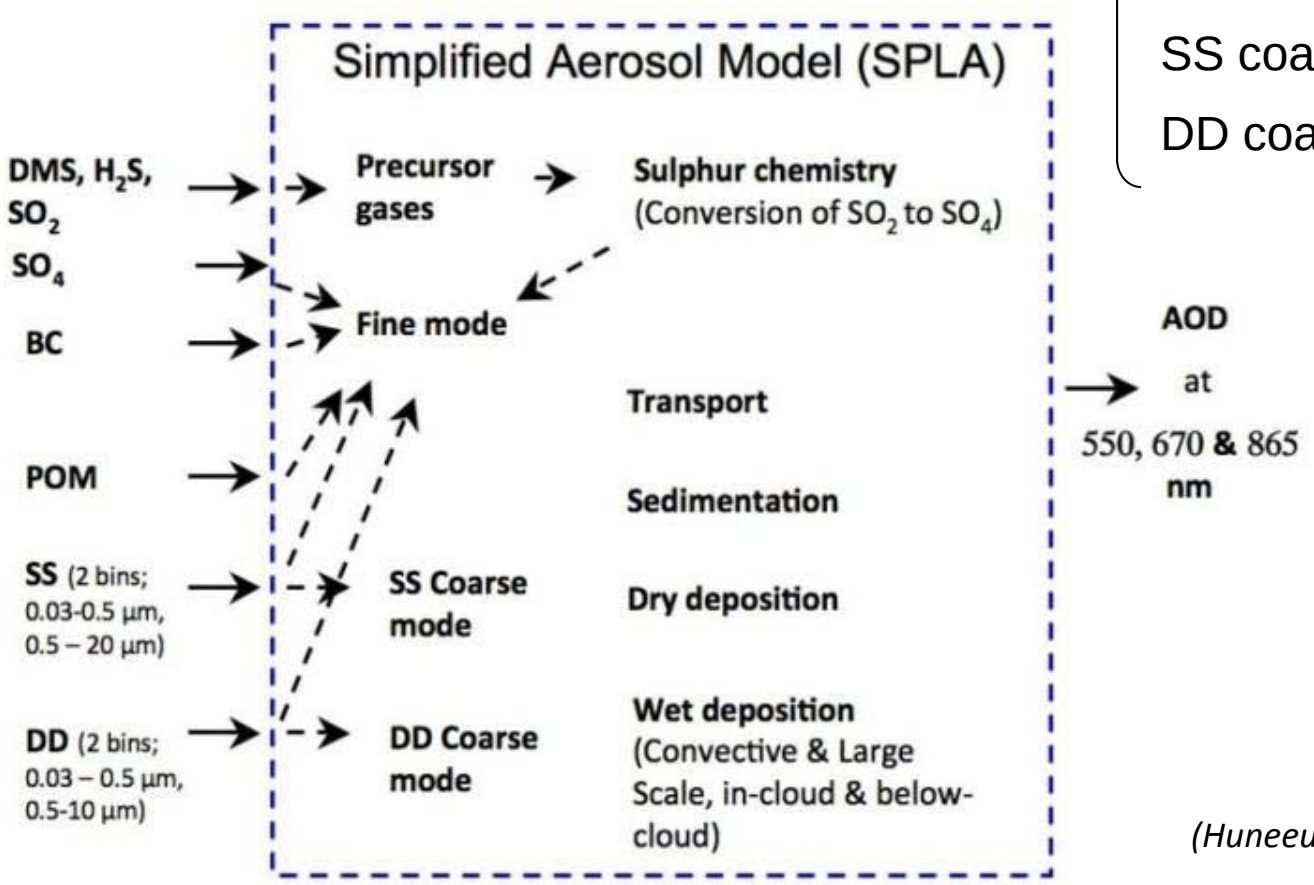
Observation Error $\begin{cases} \pm 0.05 \pm 0.15 * AO \\ \pm 0.03 \pm 0.05 * AO \end{cases}$ (ocean)

Observation operator *(H)*

$$x_a = x_b - (\mathbf{H}^T \boldsymbol{R}^{-1} \mathbf{H} + \boldsymbol{B}^{-1})^{-1} \mathbf{H}^T \boldsymbol{R}^{-1} (H[x_b] - y)$$

24 species in original model are grouped into 4 tracers

- Precursor gases
- Fine Mode
- SS coarse mode
- DD coarse mode



(Huneeus et al., 2009)

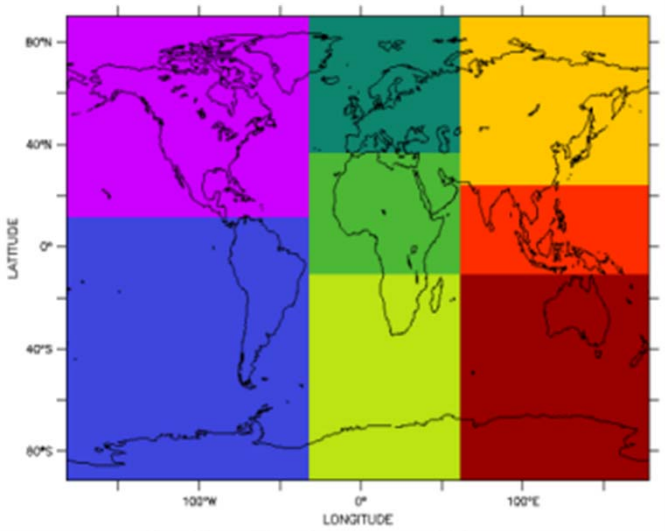
Model Error 0.02

State vector (x)

$$x_a = x_b - (\mathbf{H}^T \boldsymbol{R}^{-1} \mathbf{H} + \boldsymbol{B}^{-1})^{-1} \mathbf{H}^T \boldsymbol{R}^{-1} (H[x_b] - y)$$

Fine mode sea salt (global)

Coarse mode sea salt (global)

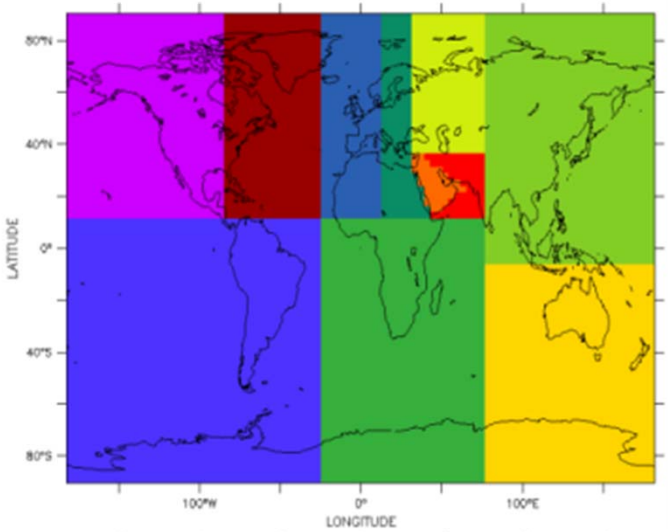


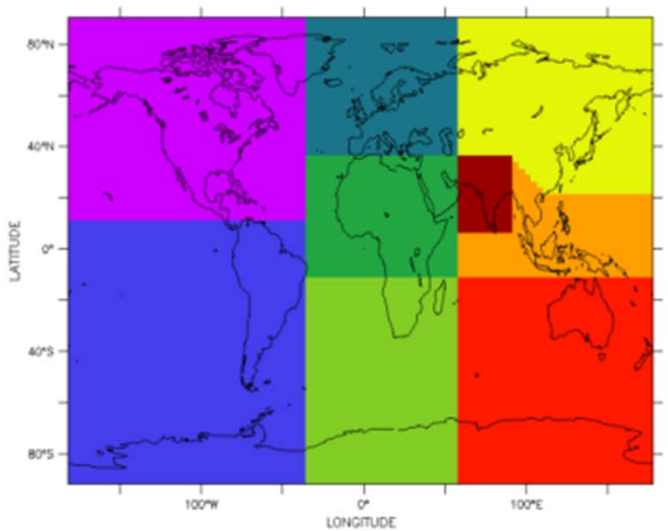
Sulfur Emissions (8)

Combustion of fossil fuels (8)

Fine mode desert dust (11)

Coarse mode desert dust (11)

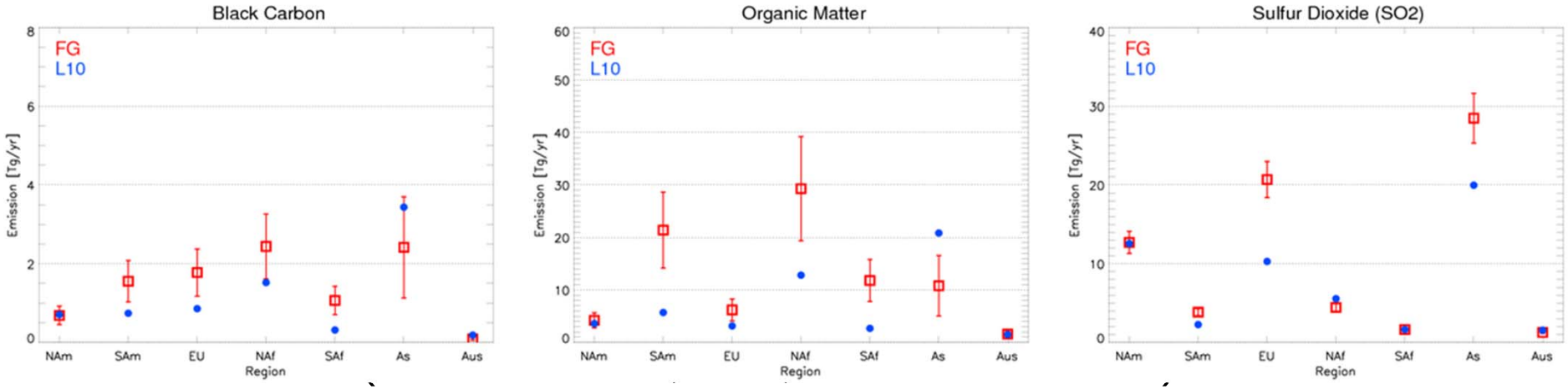




Biomass Burning (9)

A priori emissions (x_b)

$$x_a = x_b - (\mathbf{H}^T \boldsymbol{R}^{-1} \mathbf{H} + \boldsymbol{B}^{-1})^{-1} \mathbf{H}^T \boldsymbol{R}^{-1} (H[x_b] - y)$$



Error characterization (B)

$$x_a = x_b - (\mathbf{H}^T \boldsymbol{R}^{-1} \mathbf{H} + \boldsymbol{B}^{-1})^{-1} \mathbf{H}^T \boldsymbol{R}^{-1} (H[x_b] - y)$$

SO2: 11% (Smith et al., 2011)

Black Carbon: 25% (Bond et al., 2004)

Organic Matter: 25% (Bond et al., 2004)

Desert Dust: 62% (Huneeus et al., 2011)

Sea Salt:150% (Textor et al., 2006)

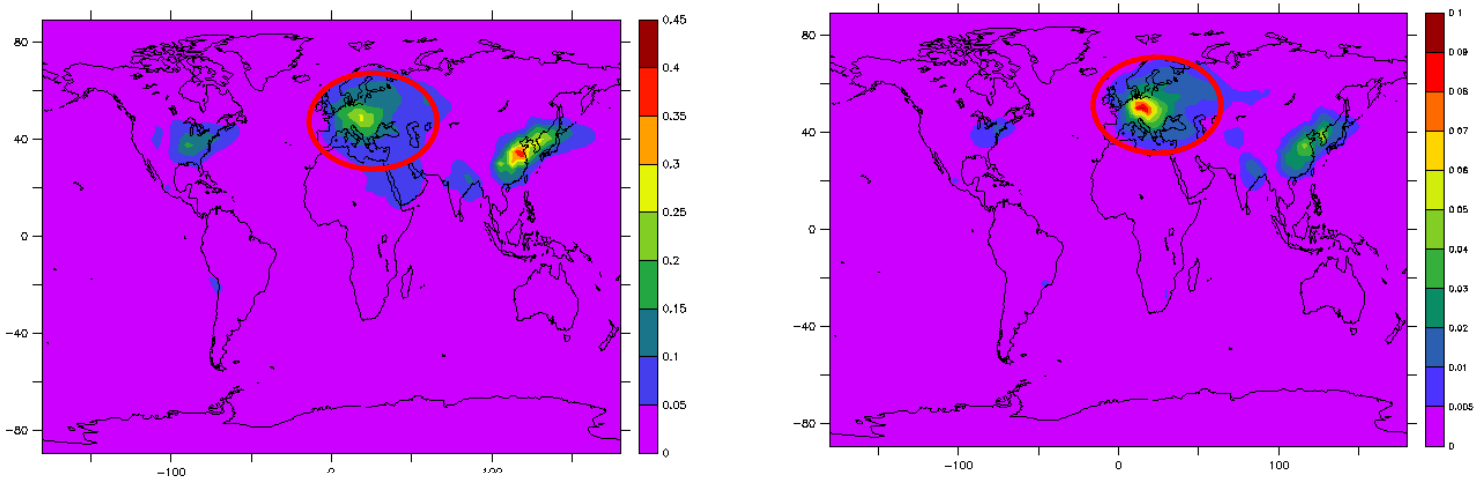
Sensitivities (H)

$$x_a = x_b - (\mathbf{H}^T \boldsymbol{R}^{-1} \mathbf{H} + \boldsymbol{B}^{-1})^{-1} \mathbf{H}^T \boldsymbol{R}^{-1} (H[x_b] - y)$$

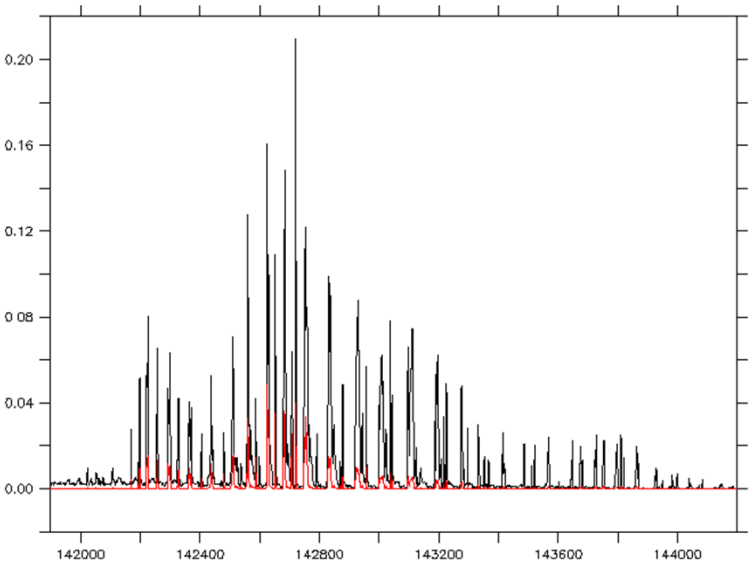
Anthropogenic SO_2

Fossil Fuel

July



$$\frac{\partial AOD}{\partial x}$$



Setup

•Inversion scheme is part of the assimilation system of LSCE used to estimate CO_2 (Chevallier et al, 2005).

•The system is applied to the entire year 2002.

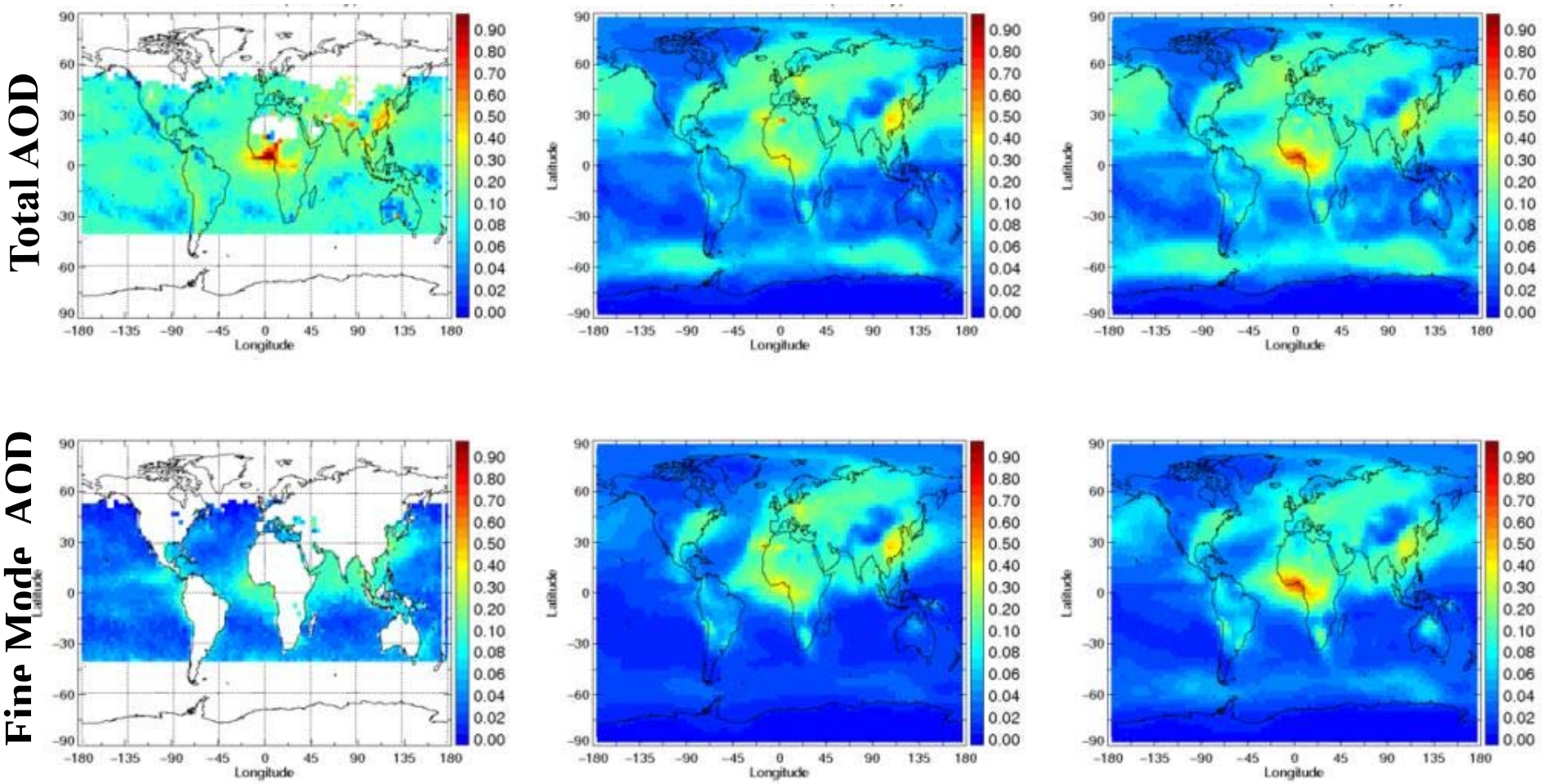
•**B** and **R** are defined as diagonal matrices.

•Monthly mean emissions are estimated for each aerosol species and SO_2

•The system allows to estimate the intensity of the emissions but not the location. It does not create new sources.

•The results are first compared against the assimilated observations and then against independent data.

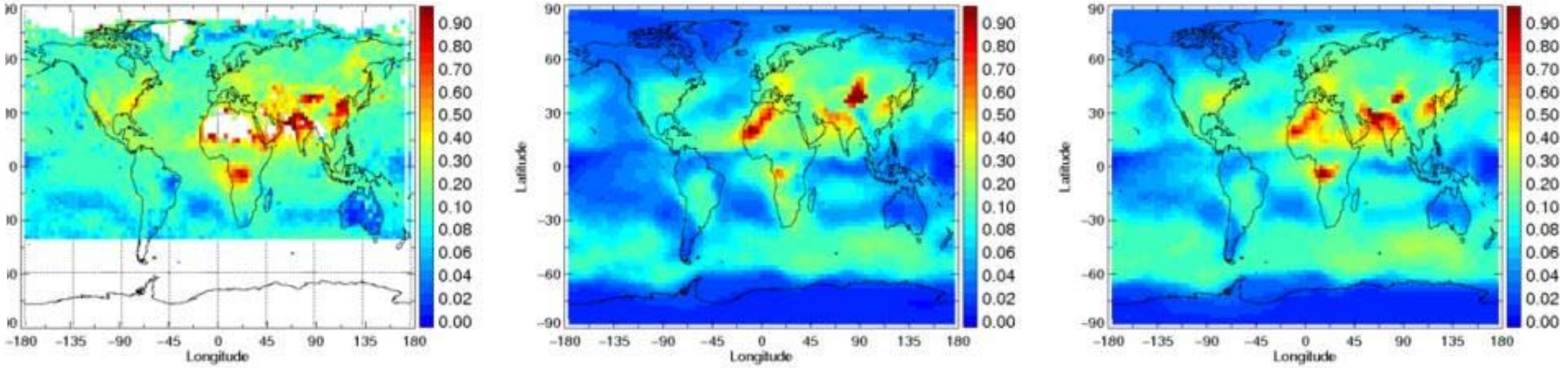
RESULTS: January 2002



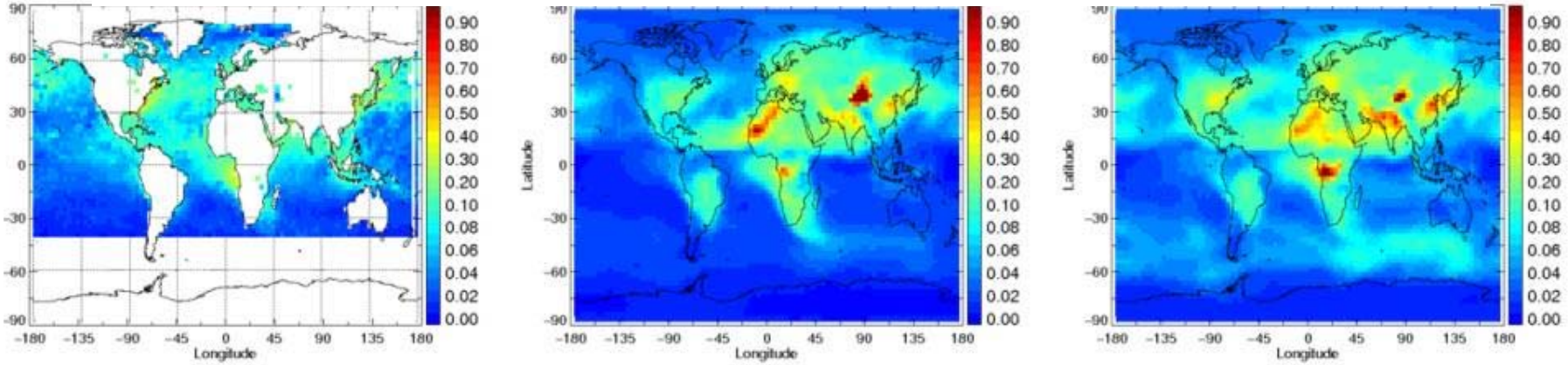
RESULTS: July 2002

MODIS **First Guess** **Analysis**

Total AOD



Fine Mode AOD



RESULTS: Full year 2002

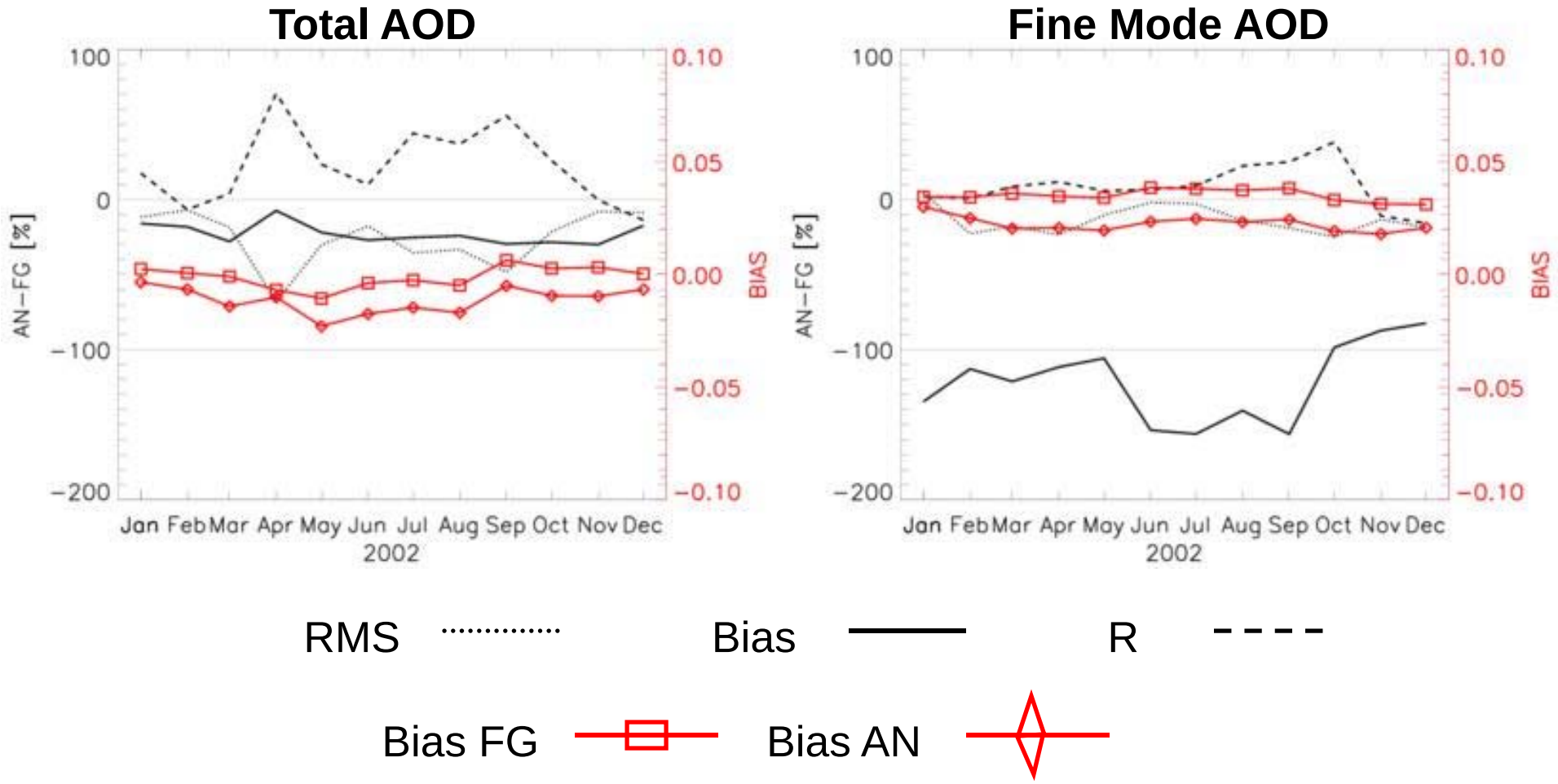
Total AOD

	RMS	Bias	Correlation
First Guess	0.18	-0.07	0.44
Analysis	0.11	-0.05	0.65

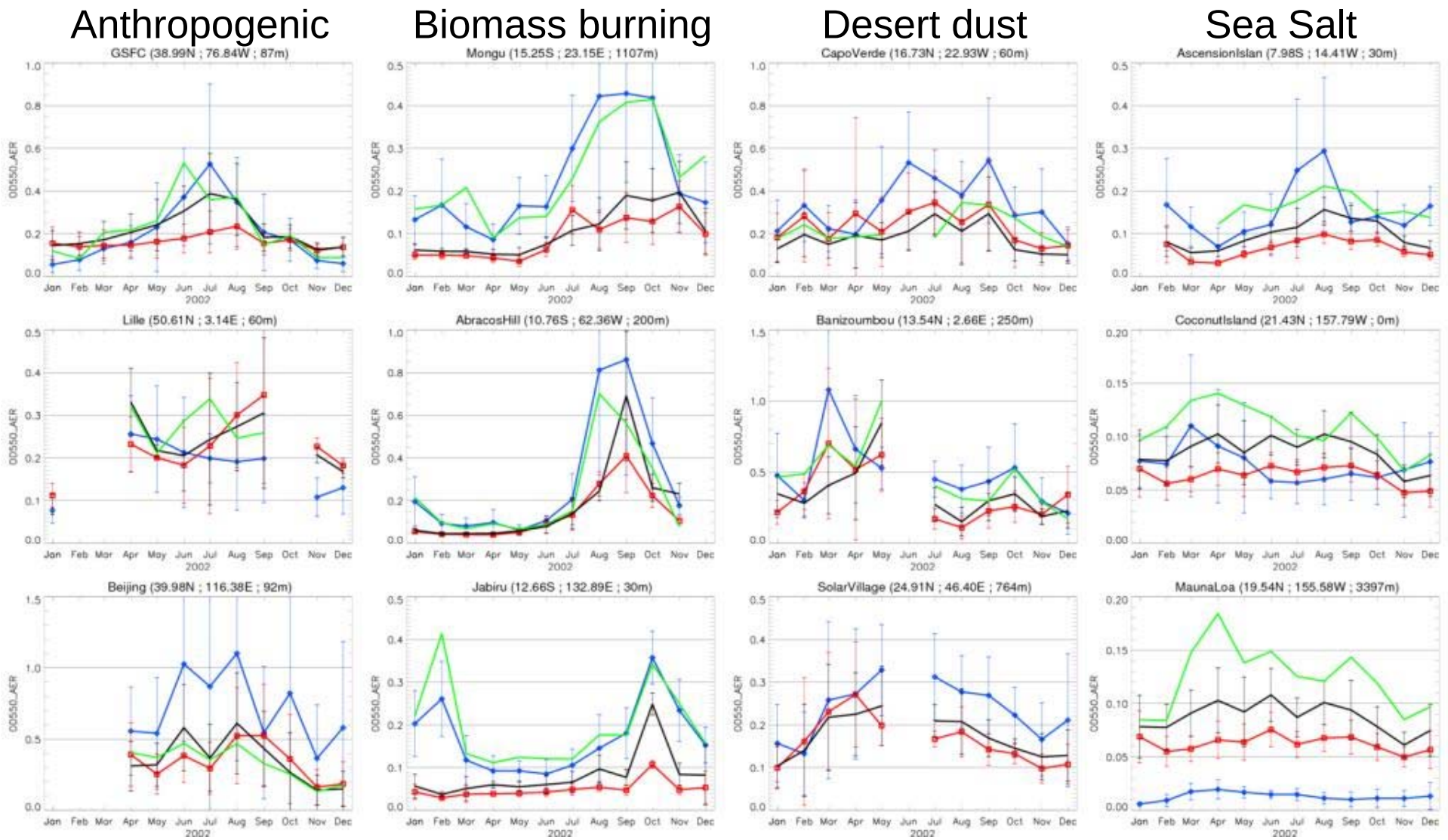
Fine Mode AOD

	RMS	Bias	Correlation
First Guess	0.05	-0.016	0.55
Analysis	0.04	-0.003	0.62

RESULTS: Full year 2002



With respect to AERONET



FG **AN** **MODIS** **AERONET**

RESULTS: Full year 2002

AERONET

Total AOD

	RMS	Bias	Correlation
First Guess	0.14	-0.07	0.70
Analysis	0.12	-0.05	0.76

Fine Mode AOD

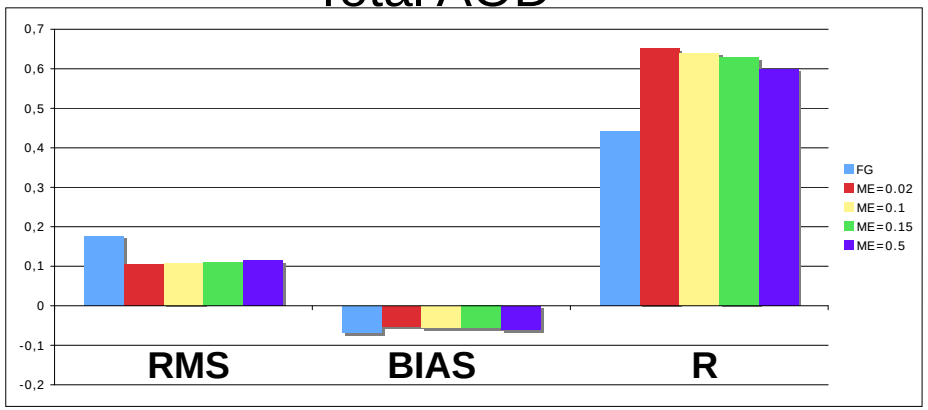
	RMS	Bias	Correlation
First Guess	0.12	-0.0082	0.60
Analysis	0.11	-0.0079	0.68

Uncertainty analysis

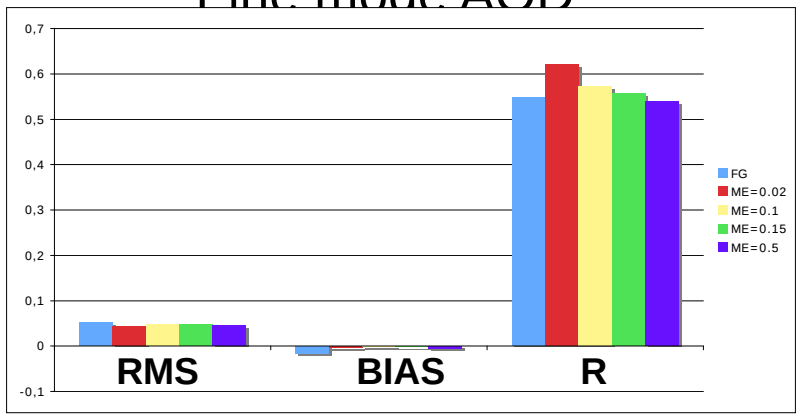
Model Error (ME)

FG ME=0.02 ME=0.1 ME=0.15 ME=0.5

Total AOD

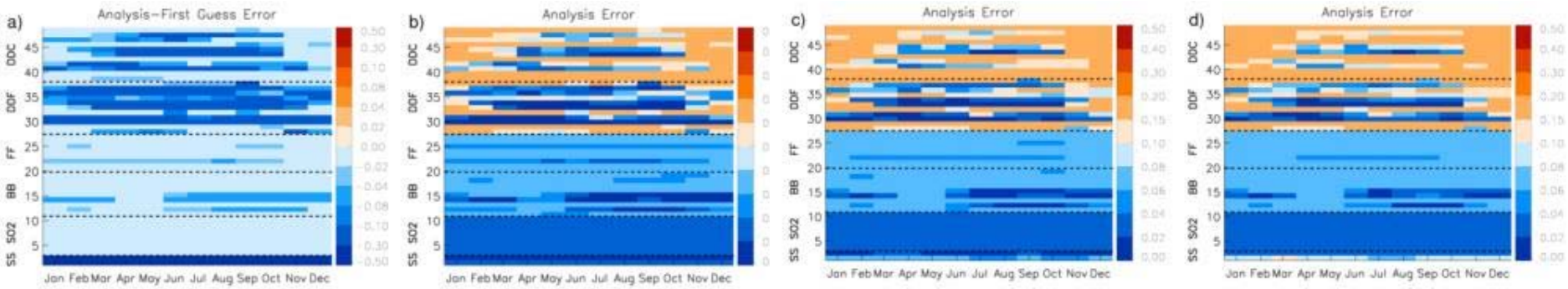


Fine mode AOD



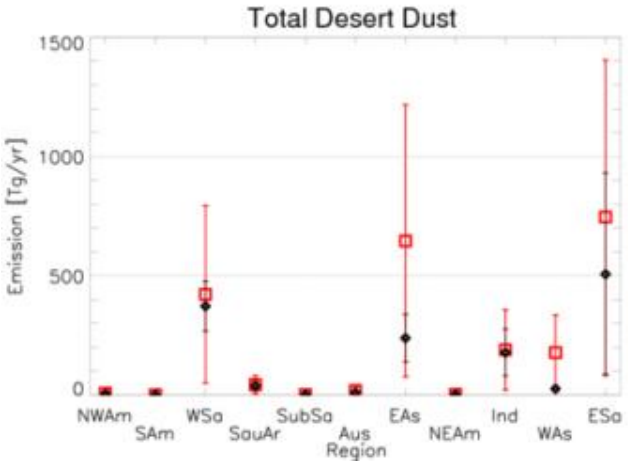
Analysis Error

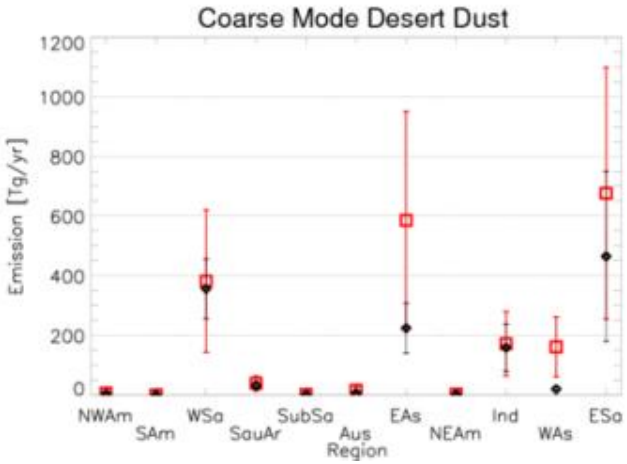
$$\mathbf{A}=(\mathbf{H}^{\mathrm{T}}\boldsymbol{R}^{-1}\mathbf{H}+\boldsymbol{B}^{-1})^{-1}$$

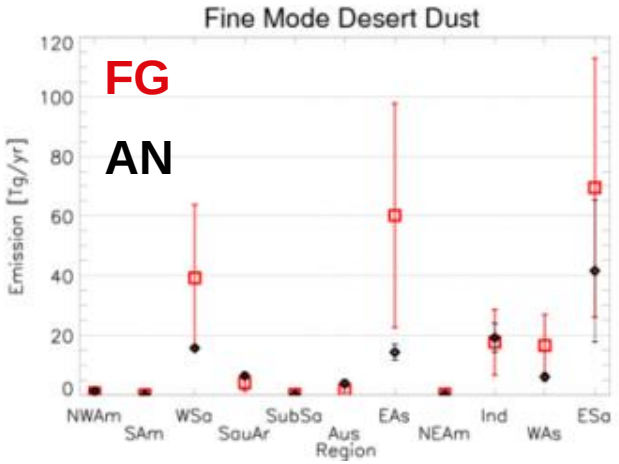


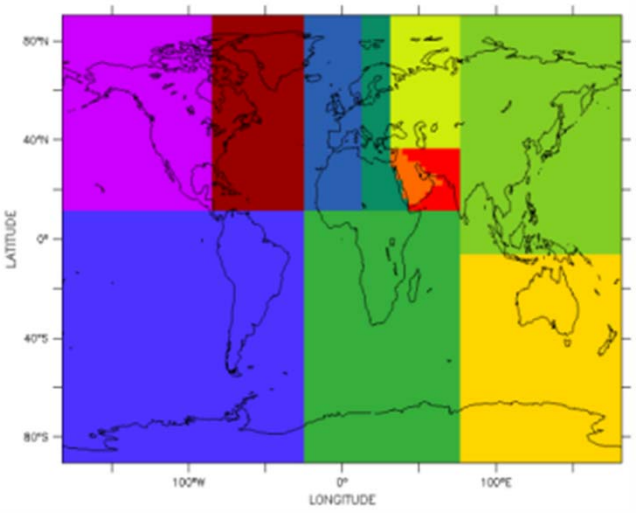
ME=0.02 **ME=0.1** **ME=0.15**

Emissions







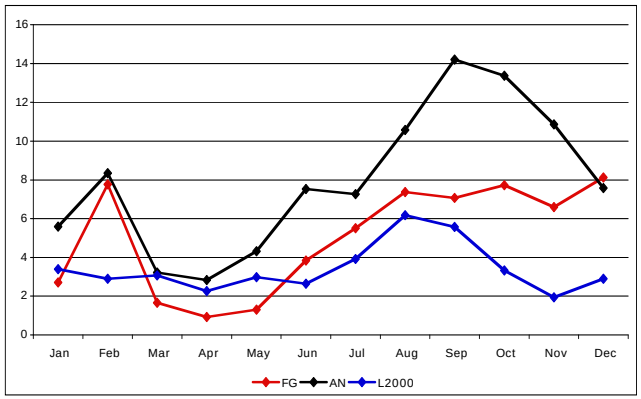


	Huneeus et al. (2011)	This work
Global emission (Tg/yr)	514-4313	1383 +/- 2916

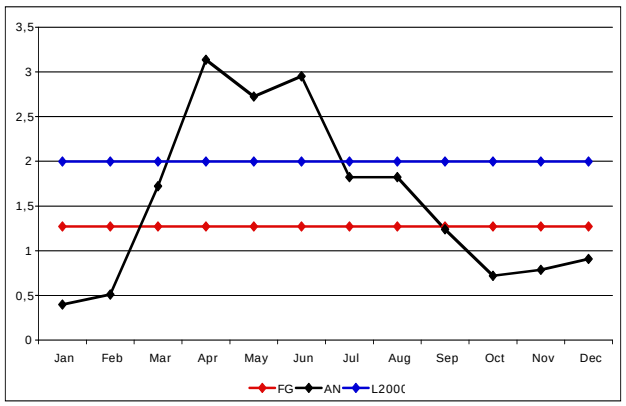
	Cakmur et al. (2006)	Huneeus et al. (2011)	This work
North Africa	964-1803	400-2271	879
Middle East	23-132	26-526	39

Emissions

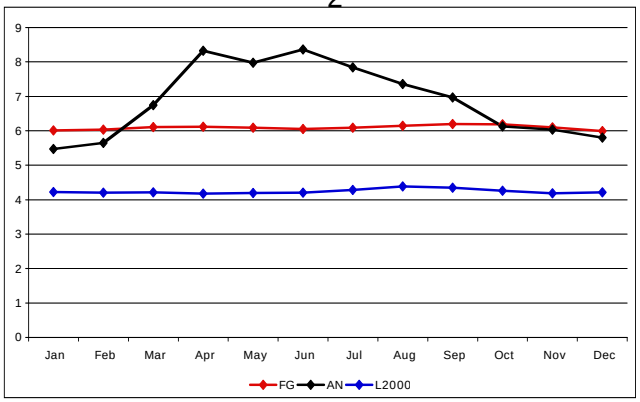
Biomass Burning



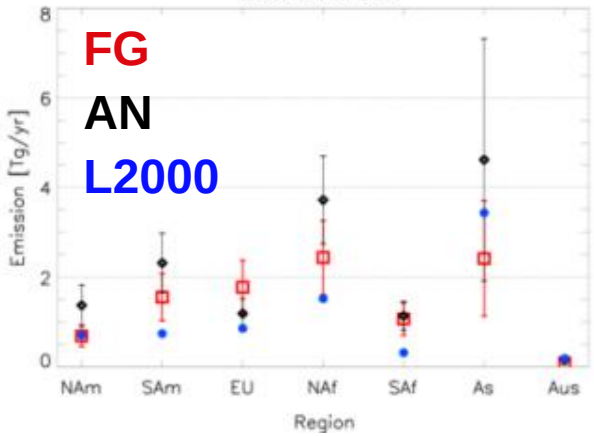
Fossil Fuel



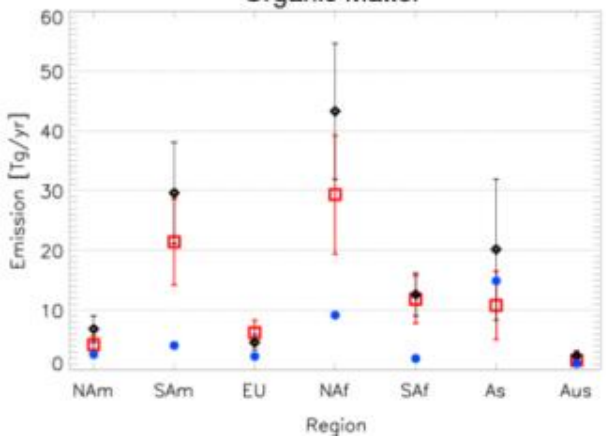
SO_2



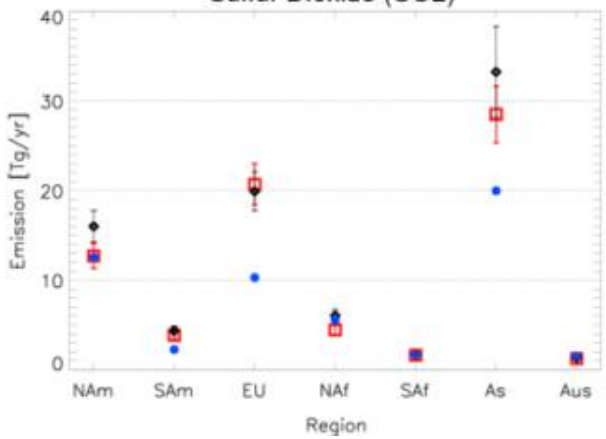
Black Carbon



Organic Matter

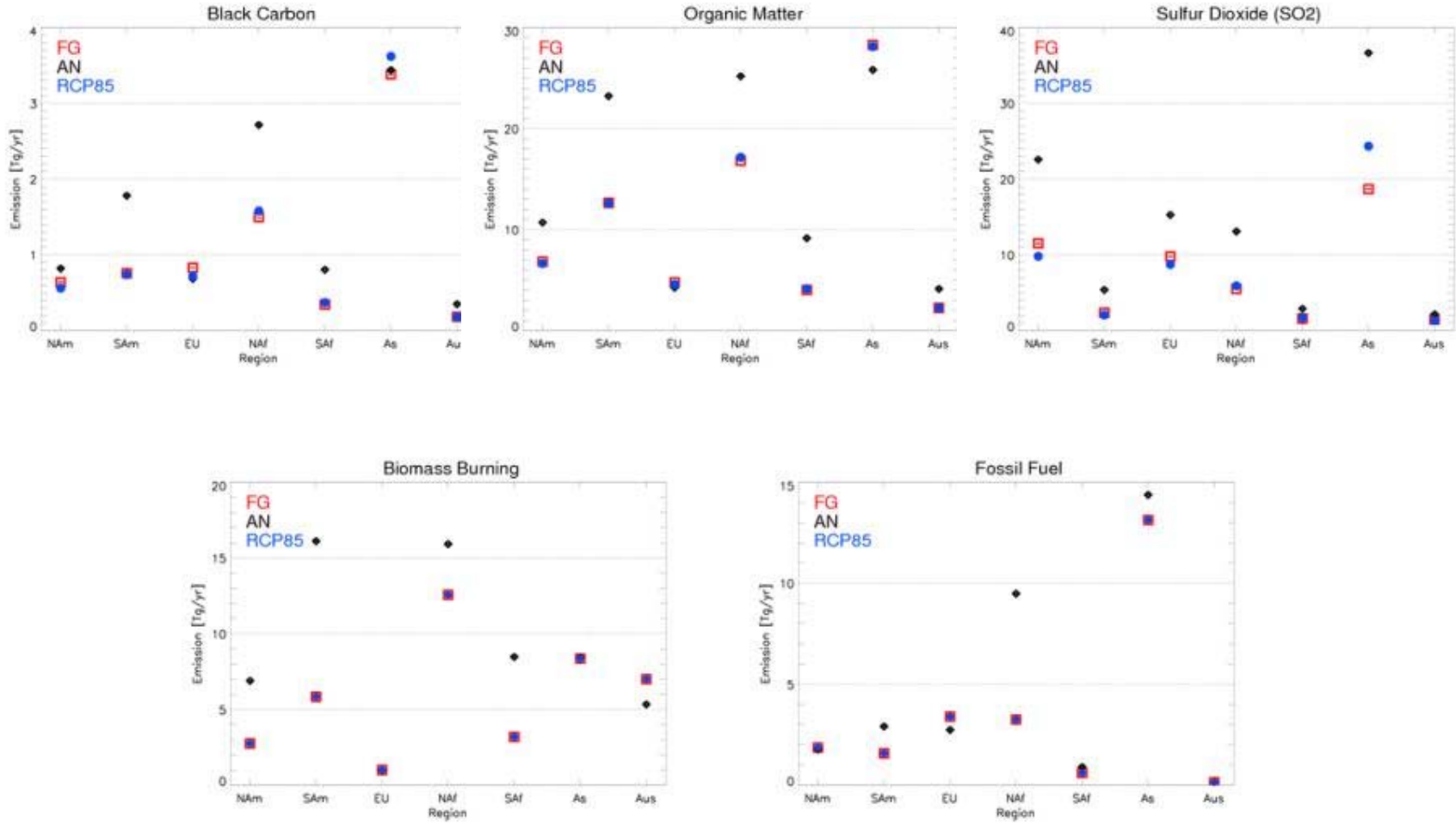


Sulfur Dioxide (SO2)

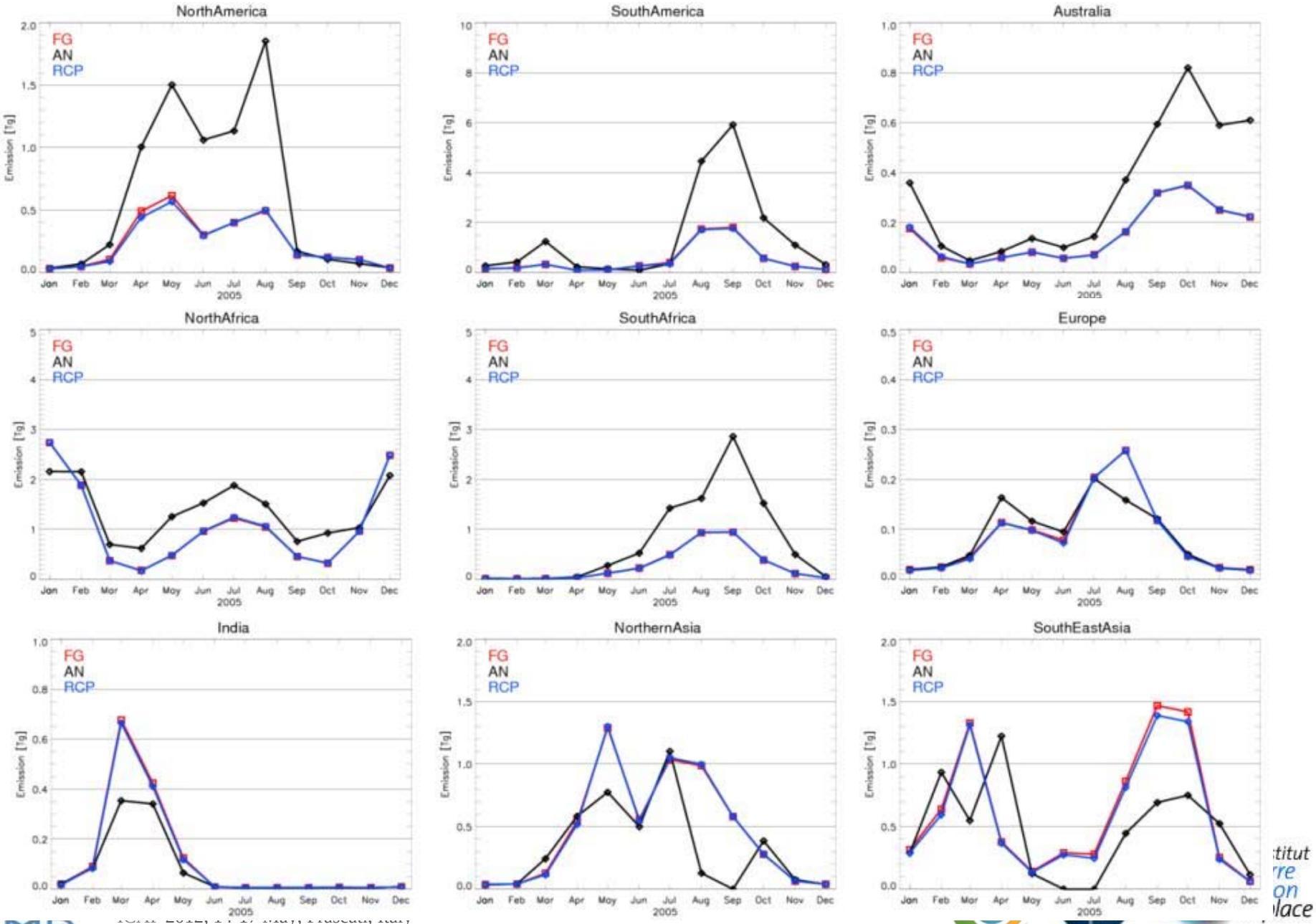


Estimated emissions (2005)

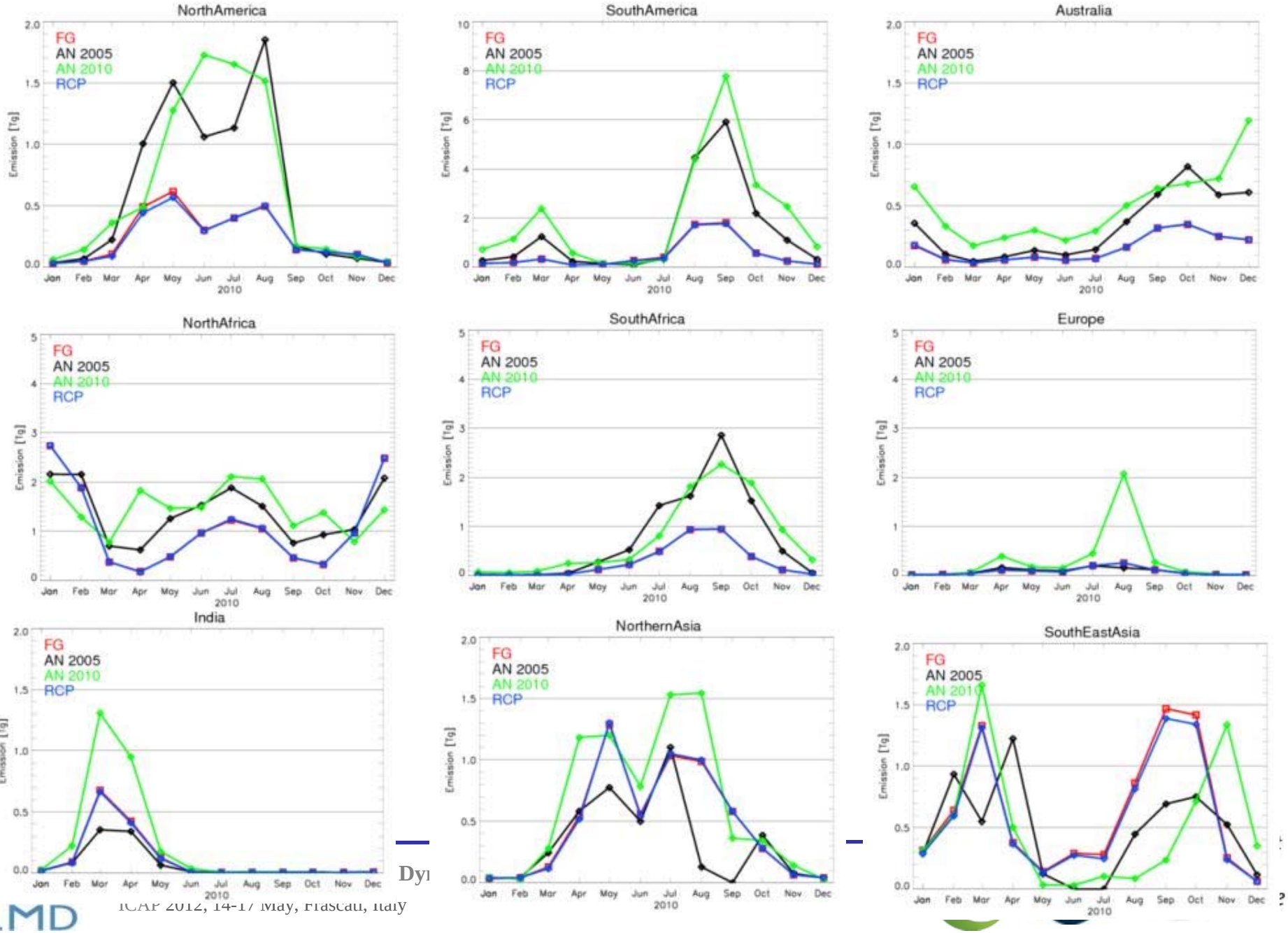
⟹ ACCMIP emissions for 2000 (Lamarque et al., 2010) as first guess.



Biomass burning fluxes per emission region (2005)



Biomass burning fluxes per emission region (2005 & 2010)



Conclusions

•A system has been developed that estimates the monthly emissions of SO2 and the main aerosol species by assimilating fine mode and total AOD.

•The assimilation improves total and fine mode AOD with respect to MODIS.

•Performance is also improved when comparing the output to independent data (AERONET).

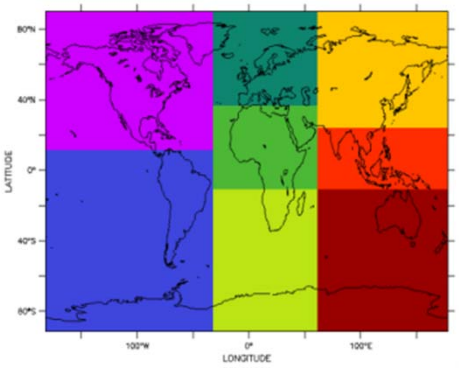
•Assimilation system allows to estimate the emission errors.

•Dust emissions are within range of AeroCom models.

•BC, OM and SO_2 are larger than ACCMIP emissions.

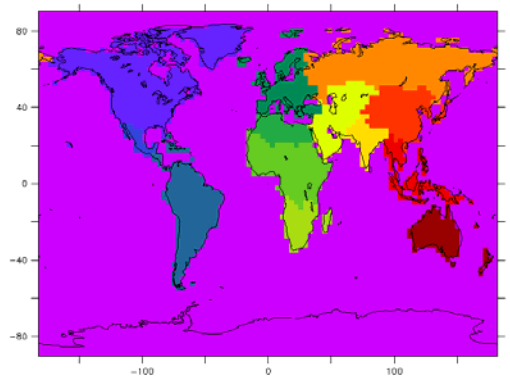
Perspective

- Define new emission regions

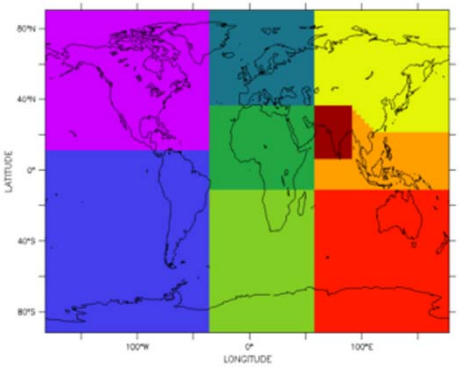


Sulfur Emissions (8)

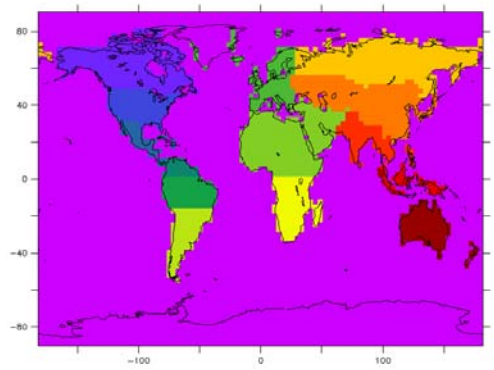
Combustion of fossil fuels (8)



13 regions



Biomass Burning (9)



14 regions

Perspective

•Use different combinations of emission inventories as first guess (GFAS, GFED, AeroCom, ACCMIP…)

•Assimilate PARASOL fine mode AOD over land.

•Use the estimated fluxes as input in aerosol models with increased complexity.

•Apply the system to the entire period of MODIS-Terra data (2000-2011)