Modeling atmospheric aerosols and synergies with observations: Opportunities, challenges, and way forward

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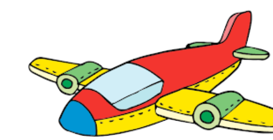
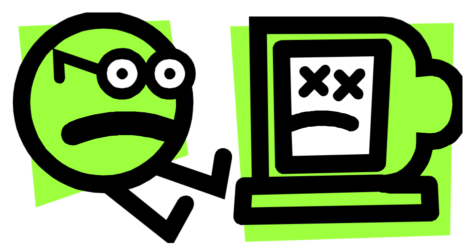




ACAM training school, June 2017

Introduction

- Aerosols have a number of important effects on the Earth's environment and lives: climate, weather, geochemical cycles, and air quality
- Aerosols are mixtures of different species with the most common ones are sulfate, nitrate, black carbon (BC), organic carbon (OC), dust, and sea salt
- They come from different sources, such as fossil fuel combustions, agriculture or forest fires, volcanic eruptions, oceans, vegetation, deserts
- They also have different particle sizes
- Some of them are emitted directly to the atmosphere ("primary aerosol") but others are formed in the atmosphere ("secondary aerosol")
- In contrast with long-lived greenhouse gases (many years), aerosols are short lived (a few days), thus they exhibit significant regional and seasonal variations

Modeling of atmospheric aerosols

- A model can integrate the current best knowledge into a global or regional computational framework to understand the atmospheric processes, chemical, physical, and optical properties of aerosols
- A model can explain the observed quantities with physical understanding
- Only a model will be able to project the future change with the future emission scenarios
- However, the model simulated results have to be objectively evaluated against observations in order to have credibility

All models are wrong, but some are useful.

– George Box

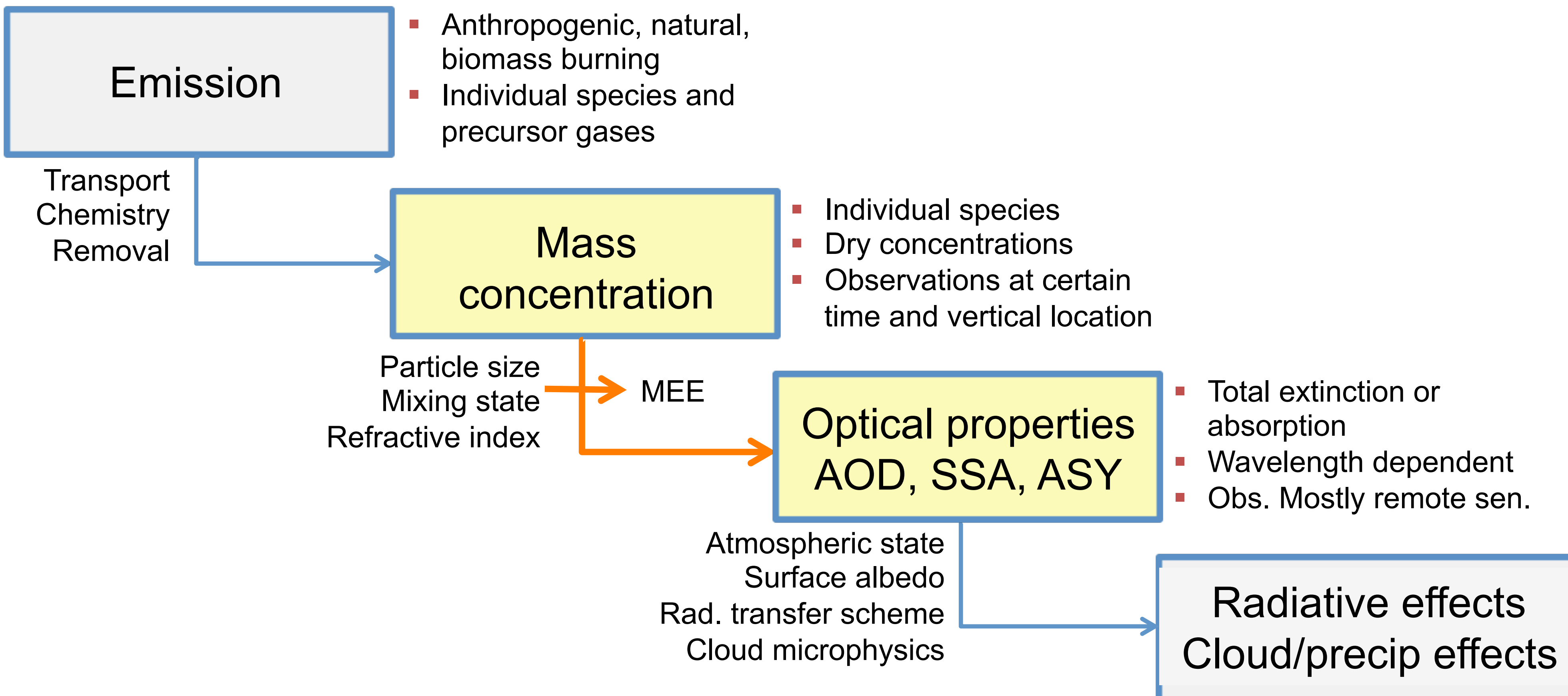
Today's talk

1. Basics of modeling atmospheric aerosols
2. Types of observations of atmospheric aerosols and Evaluation of model with different types of observations
3. Examples of recent research and analysis projects using model and observations
4. Discussion of opportunities, challenges, and way forward

1

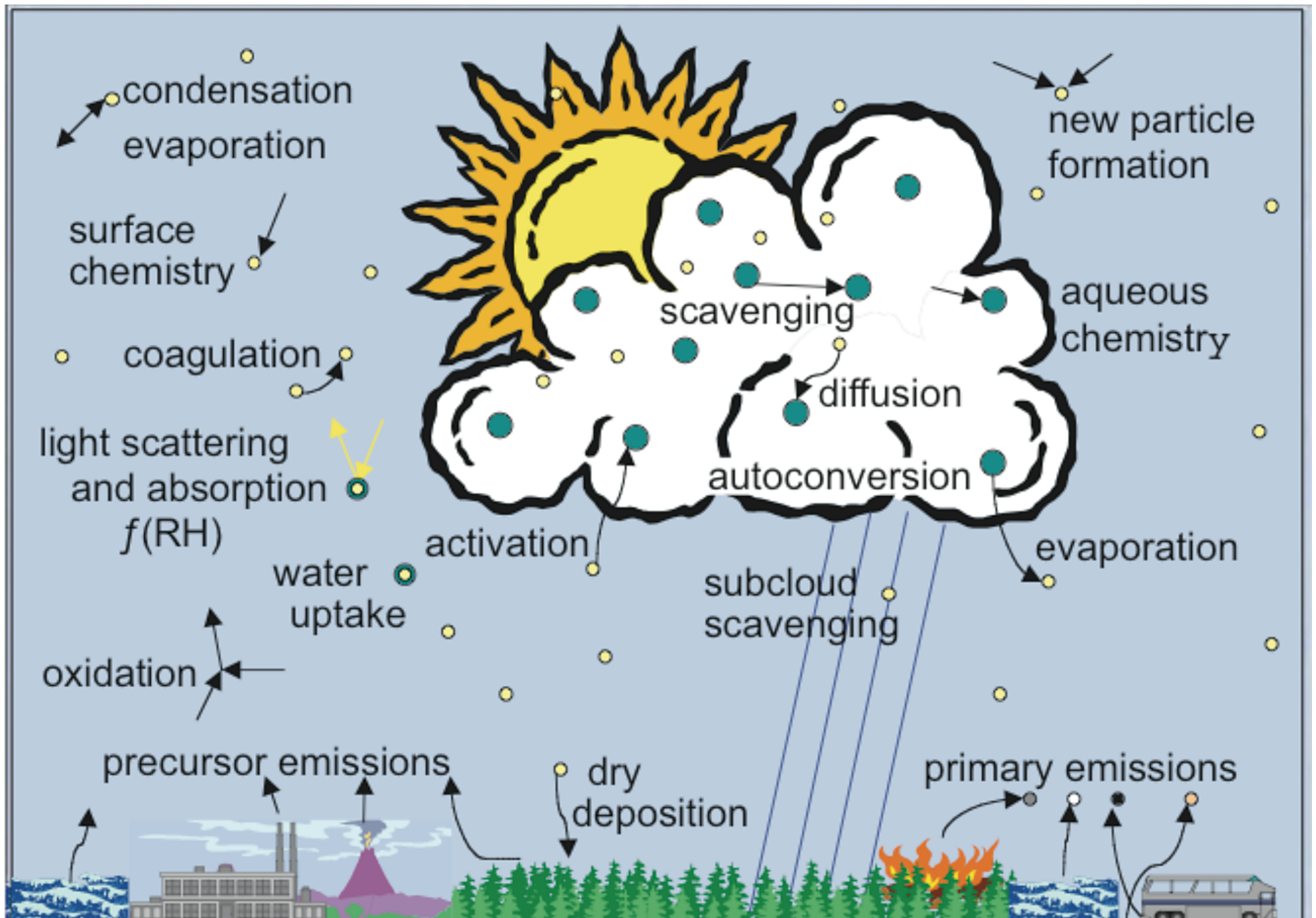
BASICS OF MODELING ATMOSPHERIC AEROSOLS

From emission to concentration to climate forcing: What does a model do



Each process has substantial uncertainties and the model approach has a wide range of sophistication/simplification/parameterization

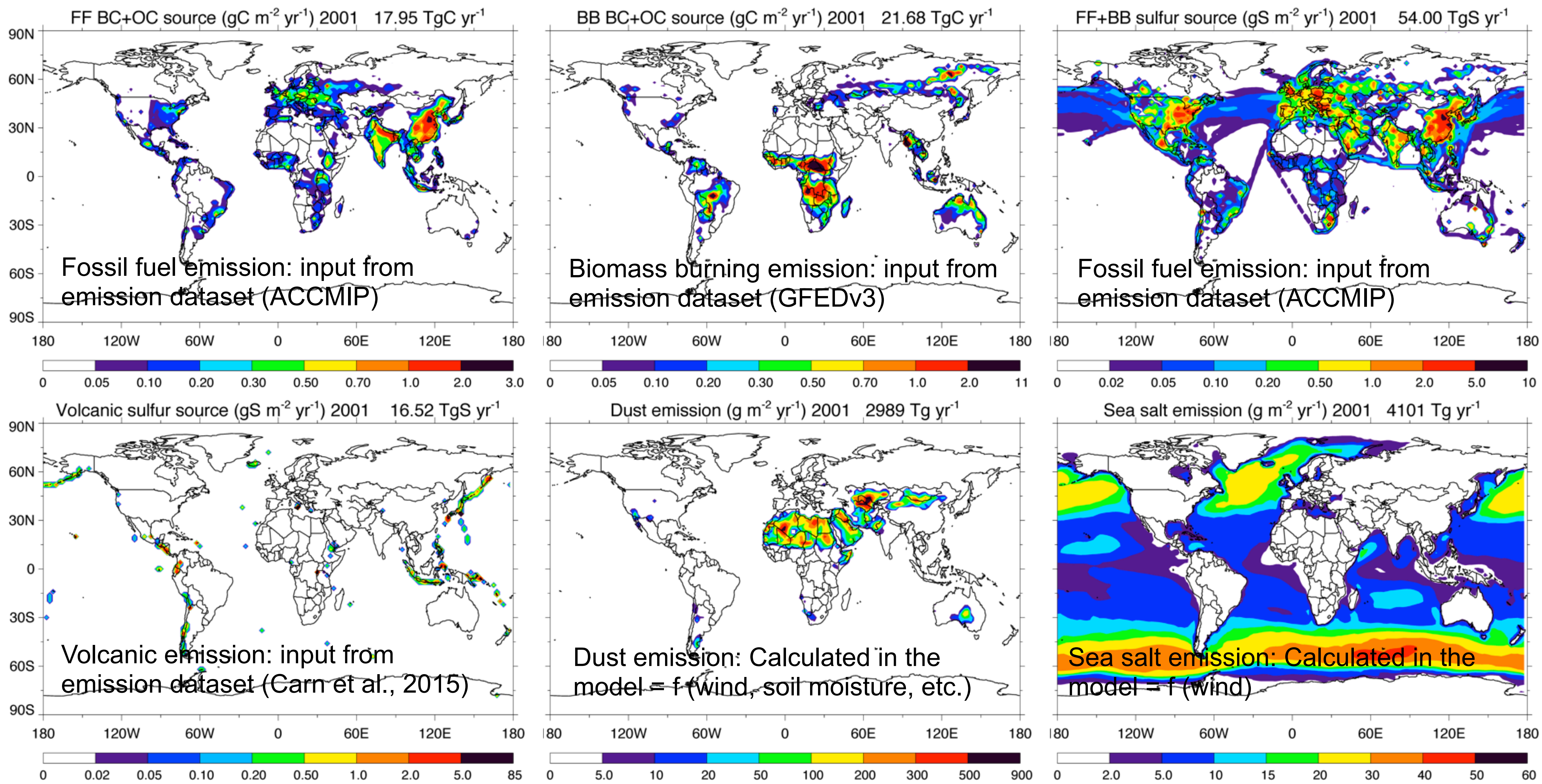
Aerosol life cycle



Emission

- Emission inventories based on energy use, fuel type, emission factors, environmental regulations, etc.
- Estimated from satellite/ground based observations, such as MODIS fire counts, OMI volcanic SO_2
- Calculated on-line in the model based on meteorological conditions (e.g., winds, temperature, RH)
- It is difficult to directly verify if the emission is accurate

Examples of emissions used by the models



Aerosol mass in the atmosphere

- Model calculated atmospheric mass concentration/ loading are the results of atmospheric processes in the model, including emission, chemistry, transport, dry deposition, and wet removal
- In many cases those processes are difficult to be directly verified from measurements, especially the removal rates (≠ removed amount)
- Model calculated species concentrations can be compared directly with in-situ observations

Aerosol optical properties

- From the aerosol mass loading (M_{dry}) to AOD:

$$AOD = MEE \times M_{dry}, \quad where \;\; MEE = \frac{3Q_{ext}}{4\pi\rho r_{eff}} \bullet \frac{M_{wet}}{M_{dry}}$$

- M_{dry} is the result from model-simulated atmospheric processes
- MEE embodies the aerosol physical (including microphysical) and optical properties
- Since Q_{ext} varies with the wavelength of radiation, so do MEE and AOD
- AOD is the most commonly used quantity retrieved from remote sensing measurements and is frequently used for model evaluation

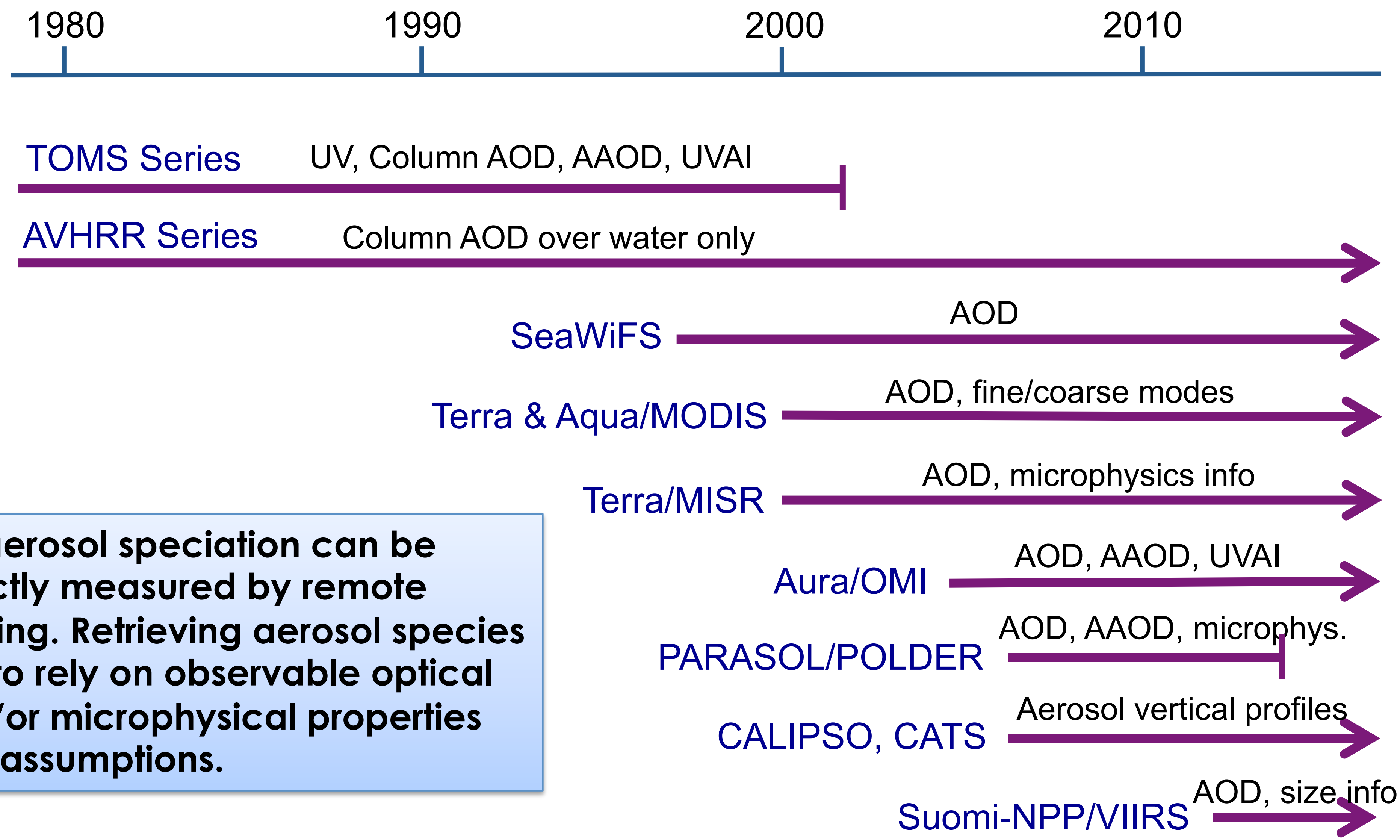
2

TYPES OF OBSERVATIONS AND EVALUATION OF MODELS WITH THEM

Satellite remote sensing of aerosol

- A measurement-based characterization of aerosols on a global scale can be realized only through satellite remote sensing, which is the only means of characterizing the large spatial and temporal heterogeneities of aerosol distributions
- Satellite retrieves aerosol amount based on the amount of light that is attenuated by aerosols
- "Passive sensor": depending on light source from the sun (or moon, or stars)
- "Active sensor": shooting its own light (lidar) to earth
- Passive sensors have much wider horizontal coverage than active sensors, but they offer little information on vertical profile; active sensors measures vertical distributions, but they have very small horizontal footprint

Past & Present polar-orbiting UV/VIS/IR instruments for aerosols



No aerosol speciation can be directly measured by remote sensing. Retrieving aerosol species has to rely on observable optical and/or microphysical properties with assumptions.

Global distributions of AOD from passive sensors

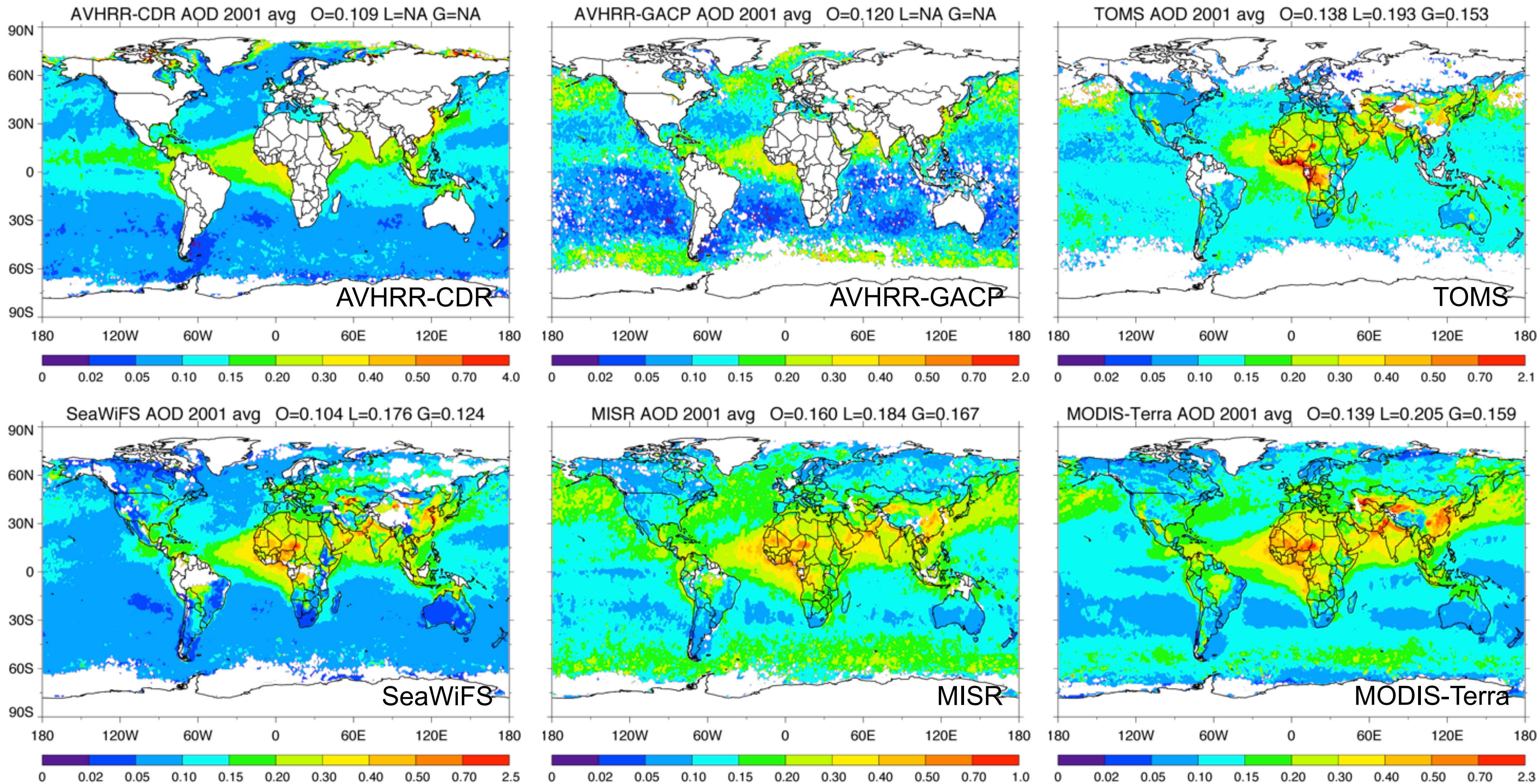
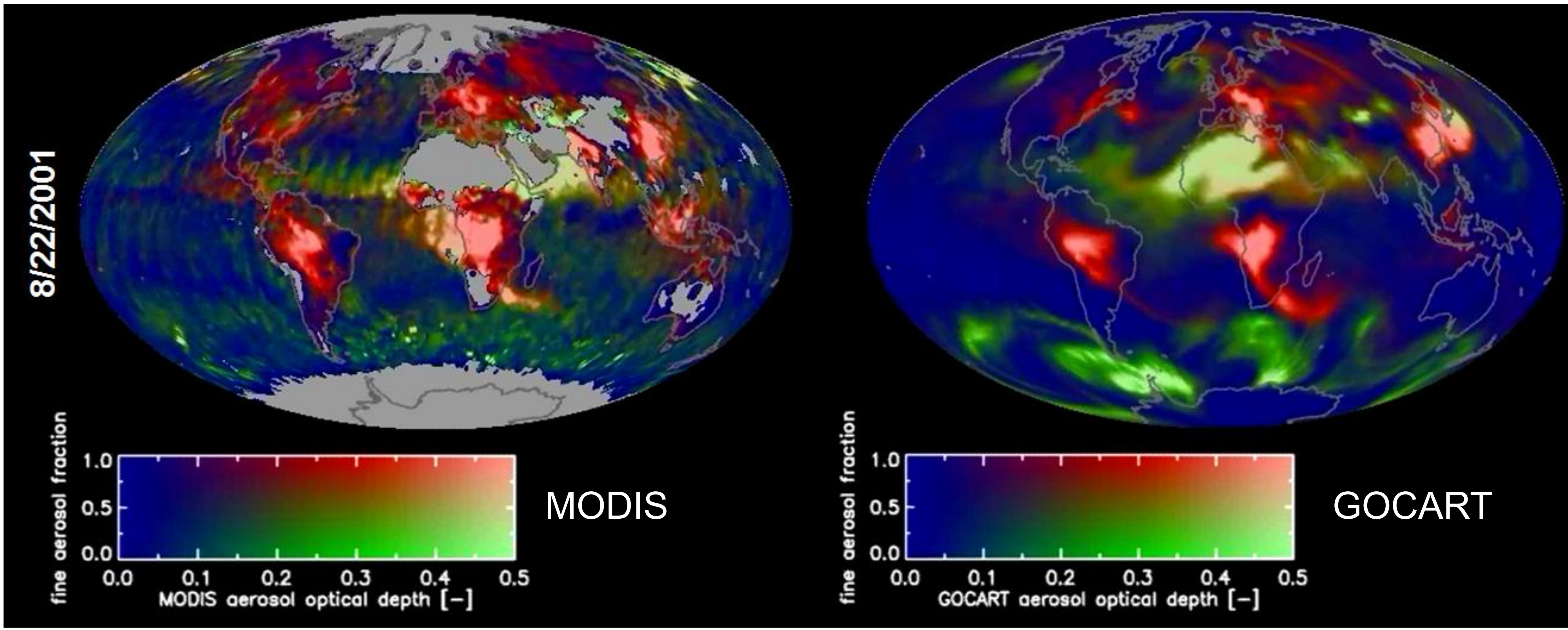


Figure from Chin et al., 2014

AOD and particle size information



AOD from MODIS retrieval and GOCART model simulation. Figure in Chin et al., 2007. Original was from Yoram Kaufman, 2002. Red: find mode AOD; green: coarse mode AOD. The brightness of color indicates the depth of the aerosol.

Aerosol vertical profile from active sensor CALIOP

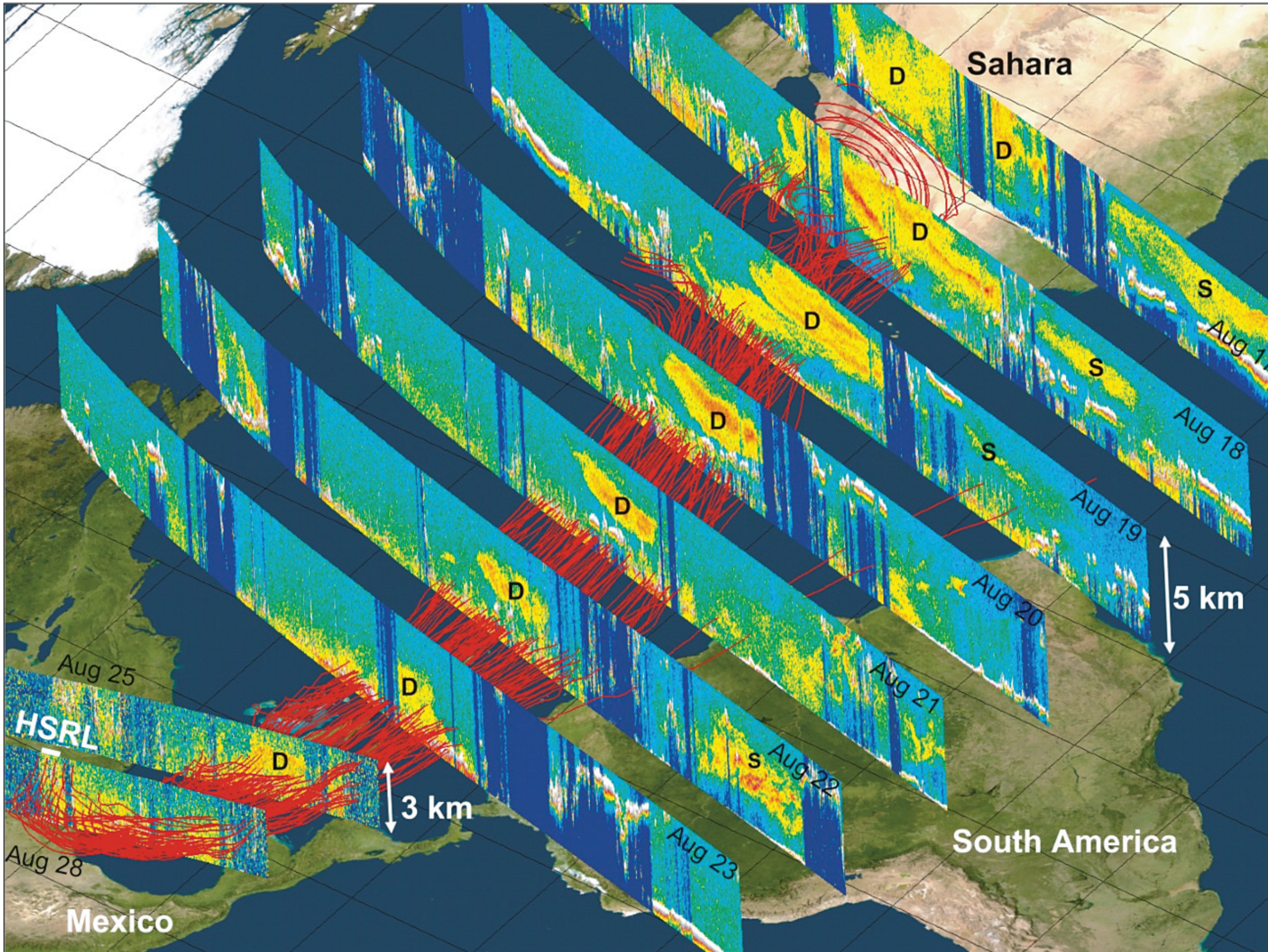
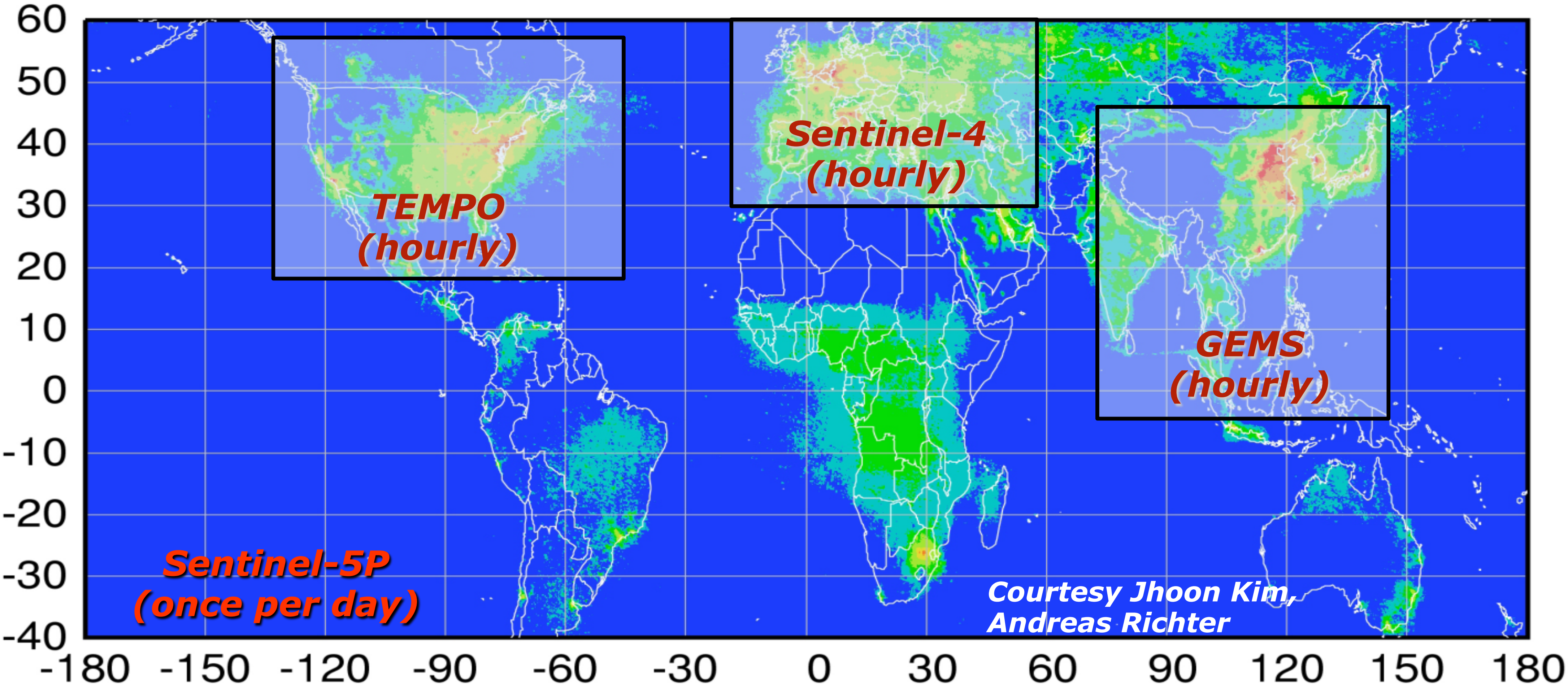


Figure from Liu et al., 2008

Global pollution monitoring constellation:

Tropospheric chemistry missions funded for launch 2017–2022



Policy-relevant science and environmental services enabled by common observations

- Improved emissions, at common confidence levels, over industrialized Northern Hemisphere
- Improved air quality forecasts and assimilation systems
- Improved assessment, e.g., observations to support United Nations Convention on Long Range Transboundary Air Pollution

Ground-based remote sensing

- Passive technique:
  - Sunphotometer measurements of column AOD, such as those measured by AERONET
  - Data are usually considered to be "ground truth" that are used for satellite retrieval validation and model evaluation
  - Data access and information: https://aeronet.gsfc.nasa.gov/
- Active technique:
  - Lidar measurement of aerosol vertical profiles

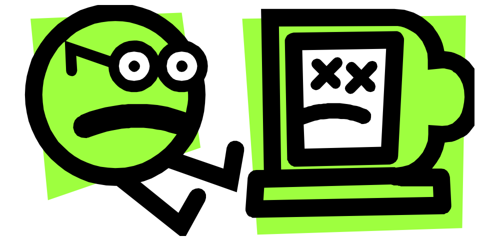
In-situ measurements

- Focused field campaigns
  - With clearly defined objectives
  - Usually involves aircrafts or ships or trucks to measure compositions, chemistry, and microphysical and optical properties of aerosols
  - Supplemented by ground-based and satellite observations
- Ground measurements networks
  - Provide stable, long-term monitoring of aerosol species

Laboratory measurements

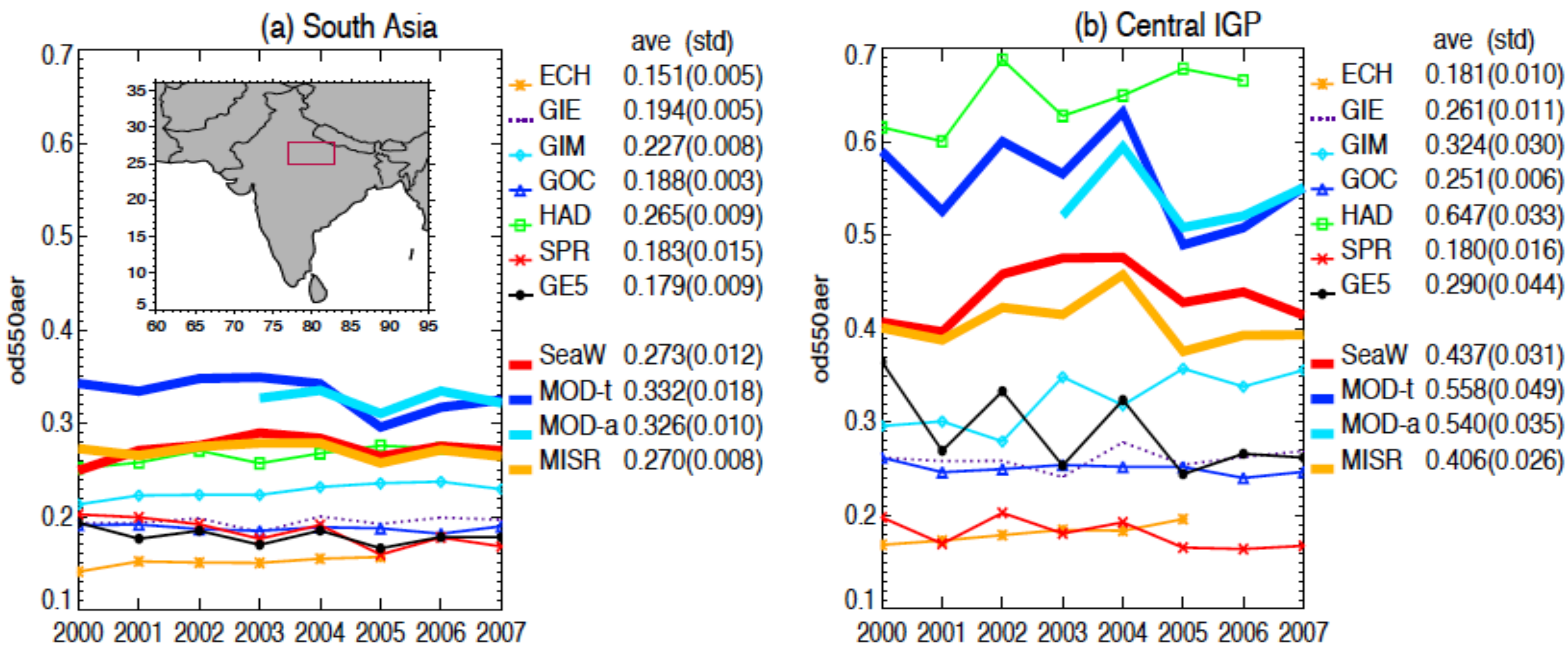
- Measuring chemical reaction rates and products in well controlled conditions
- Measuring physical and chemical properties
- Analyzing samples collected in the fields
- Testing and calibrating instruments

Model simulations evaluated with observations: Examples from AeroCom studies



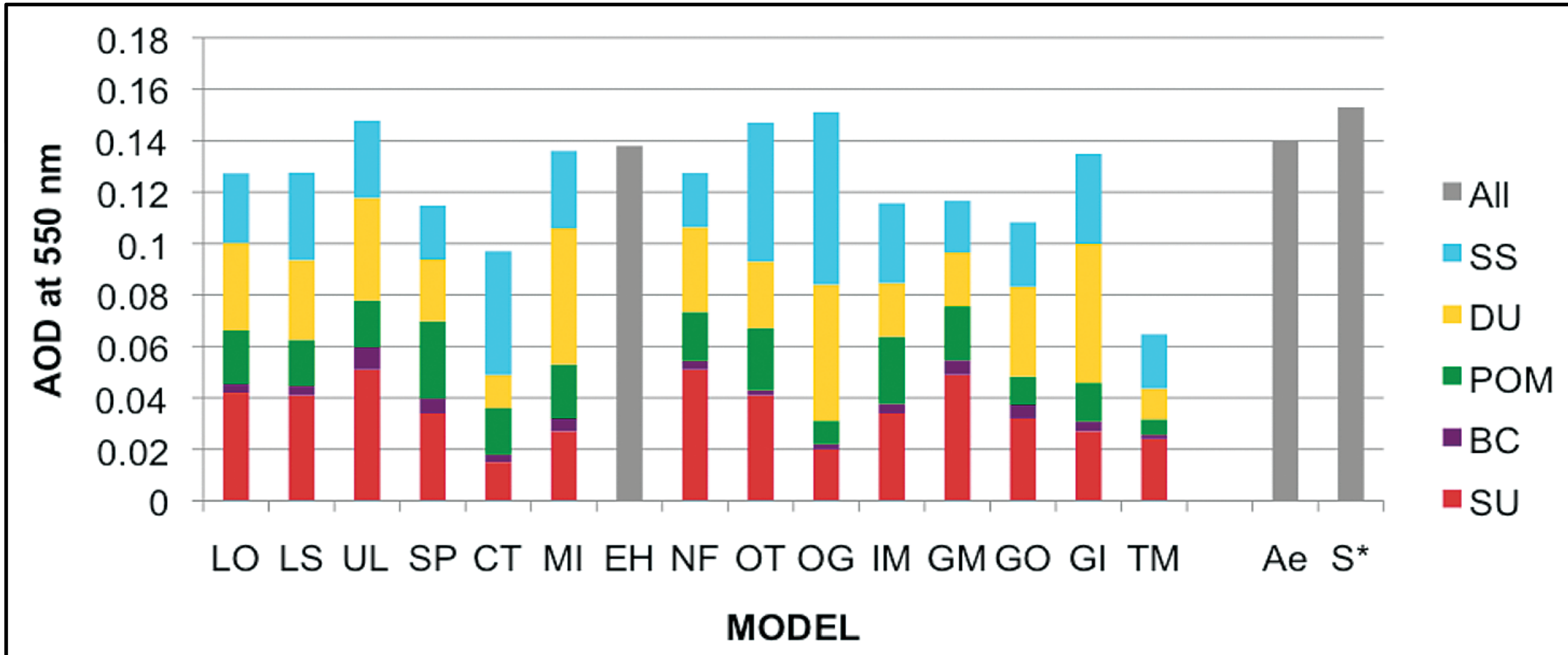
- AeroCom: aerosol comparisons between observations and models
- AeroCom is an open international initiative of scientists who are interested in understanding aerosol effects on environment with global models that are evaluated by satellite and other platform data
- AeroCom activities are all volunteering without dedicated funding
- AeroCom was initiated in 2003 and has had 15 workshops so far. The next one will be in Helsinki in the week of October 9, 2017
- More information and specifics can be found at http://aerocom.met.no/

Comparisons between models and satellite data over South Asia: Annual mean AOD, 2000-2007



Most models underestimate AOD over South Asia compared to the satellite retrievals

Comparisons of AOD with satellite and AERONET



Models are much more diverse in aerosol composition than total AOD

AOD at 550 nm	Mean	Median	Range	Stddev/Mean x 100%
Sulfate	0.035	0.034	0.015-0.051	33%
Black carbon	0.004	0.004	0.002-0.009	46%
Organic matter	0.018	0.019	0.006-0.030	36%
Dust	0.032	0.033	0.012-0.054	44%
Sea salt	0.033	0.030	0.02-0.067	42%
Total AOT at 550 nm	0.124	0.127	0.065-0.151	18%

Figure adapted from Kinne et al., 2006

Comparisons with satellite dust AOD

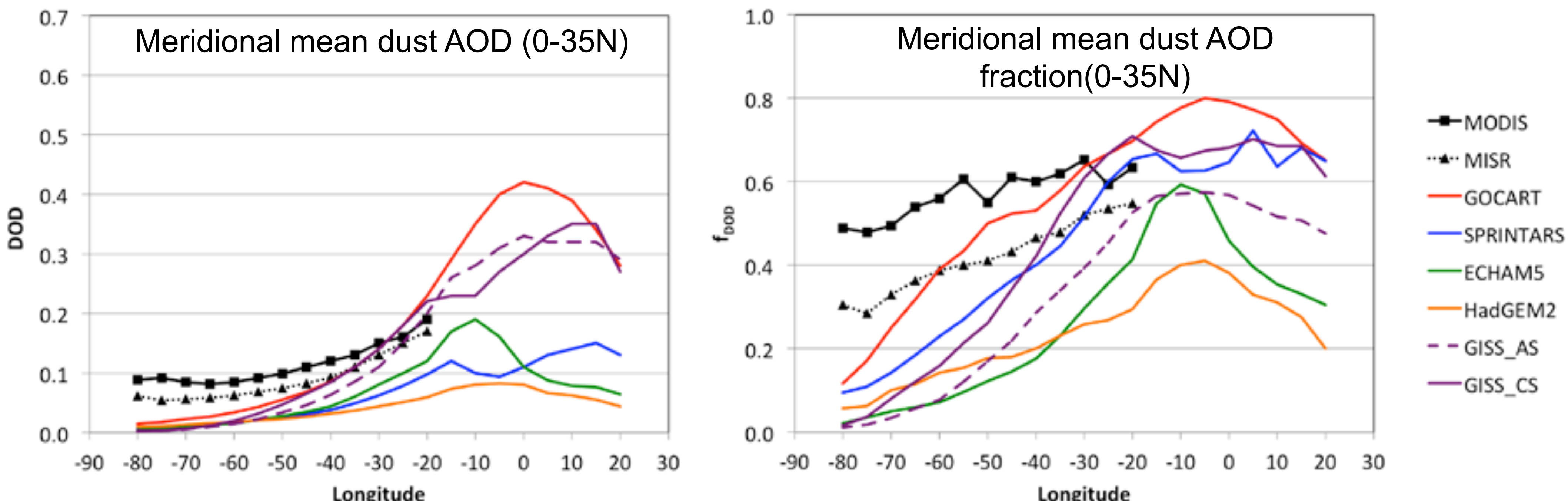
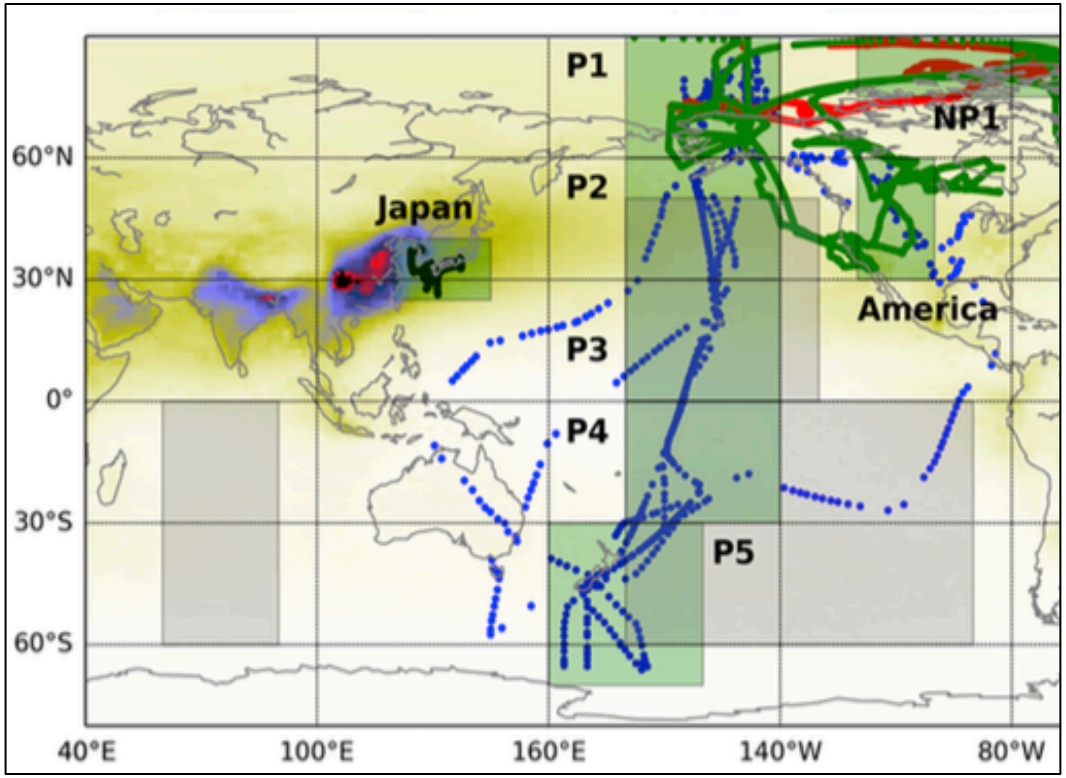


Figure from Kim et al., 2014

The comparisons show that models are generally have steeper longitudinal gradient of dust decreasing from east to west over the North Atlantic, implying too fast removal of dust during transport

Comparisons of BC vertical profile with HIPPO aircraft data



Most models over estimate BC concentrations in the free troposphere, indicating a common problem of BC removal in the free troposphere

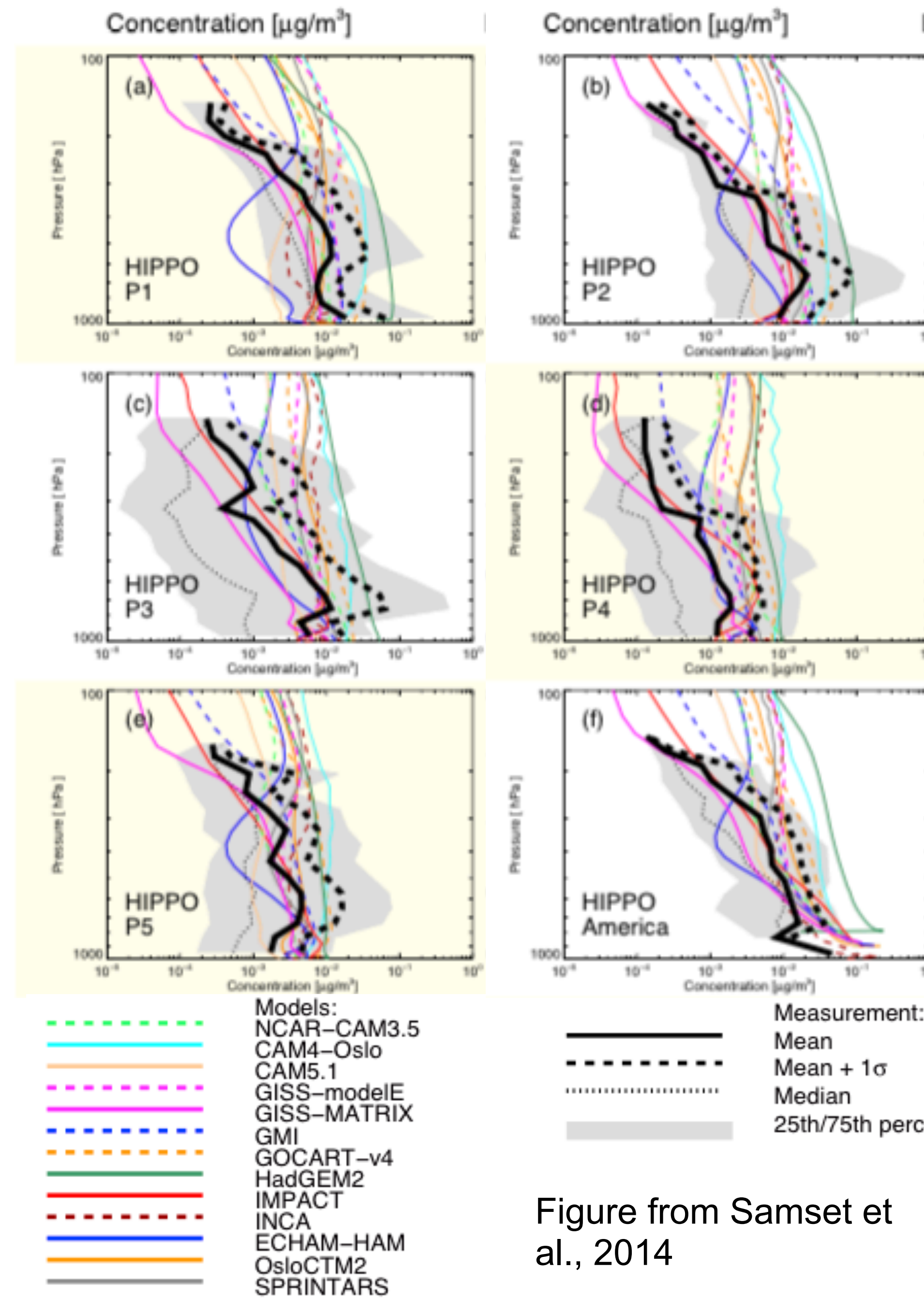


Figure from Samset et al., 2014

Evaluation with data reveals model strengths and weaknesses and leads to model improvements

- It is very important to evaluate the models with data from many different angles
- Thorough evaluation should lead to model improvements to establish the model credibility for its applications
- Evaluation should be objective and quantitative – using the phrase like "they agree well" sounds subjective and does not provide information on "how well" is well
- AeroCom is a very attractive platform for such evaluation with extensive archived data and tools and science expertise

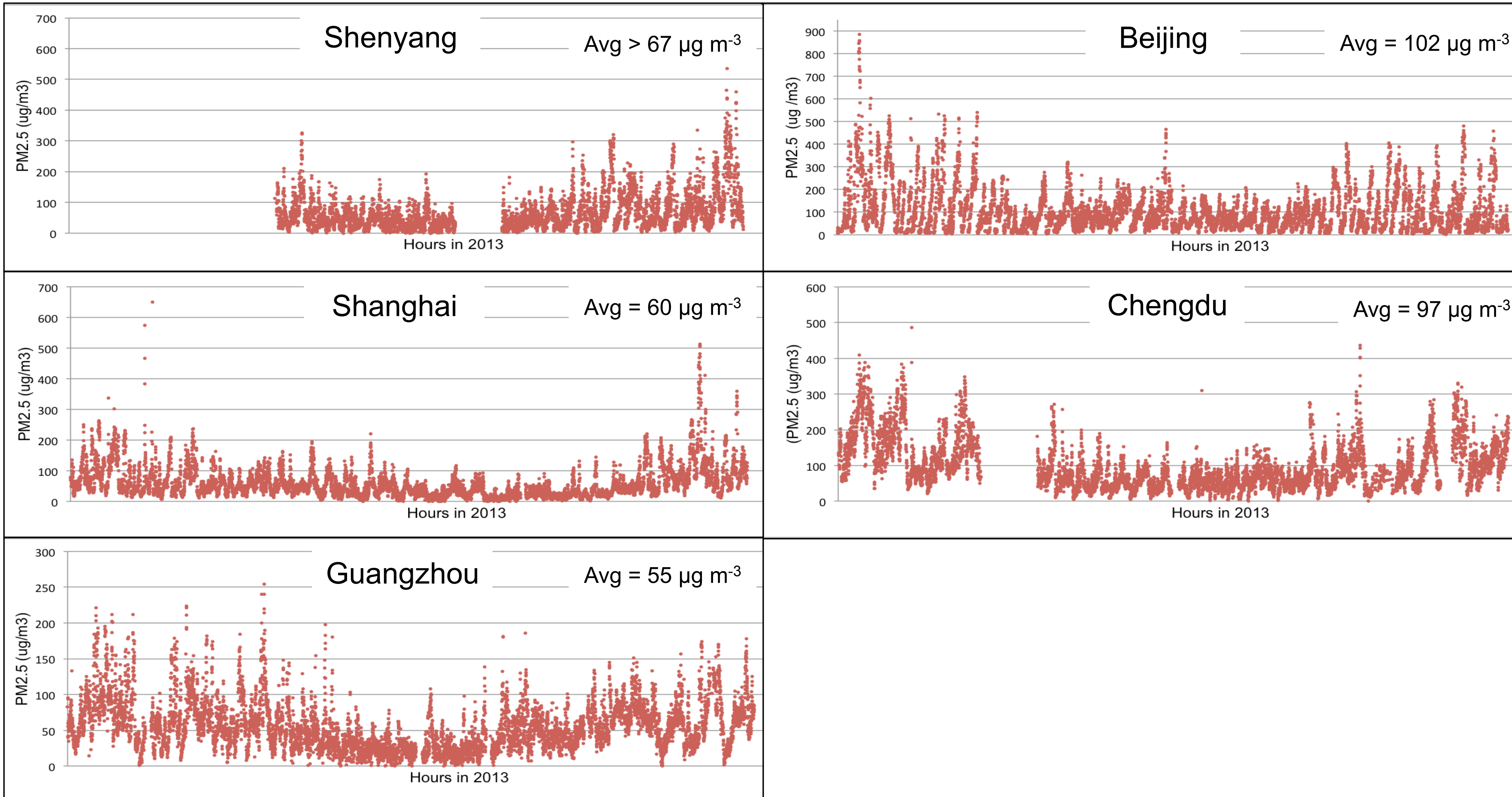
3

EXAMPLES USING A MODEL FOR TARGETED ANALYSIS

A) EAST ASIAN WINTER MONSOON AND AIR POLLUTION IN CHINA

B) HEMISPHERIC TRANSPORT OF AIR POLLUTION

A) East Asian winter moon and air quality in China: Particle pollution is a serious problem in East Asia, especially in winter

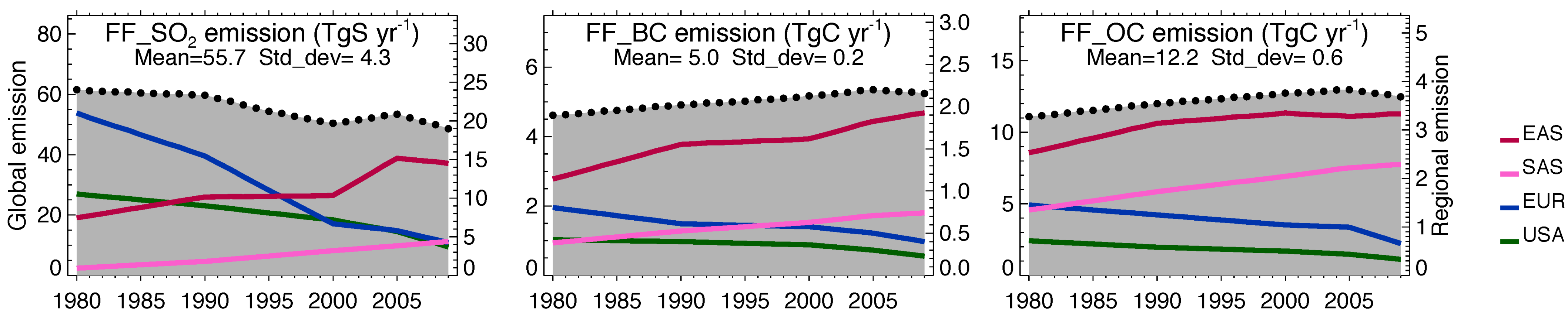


Modeling approach

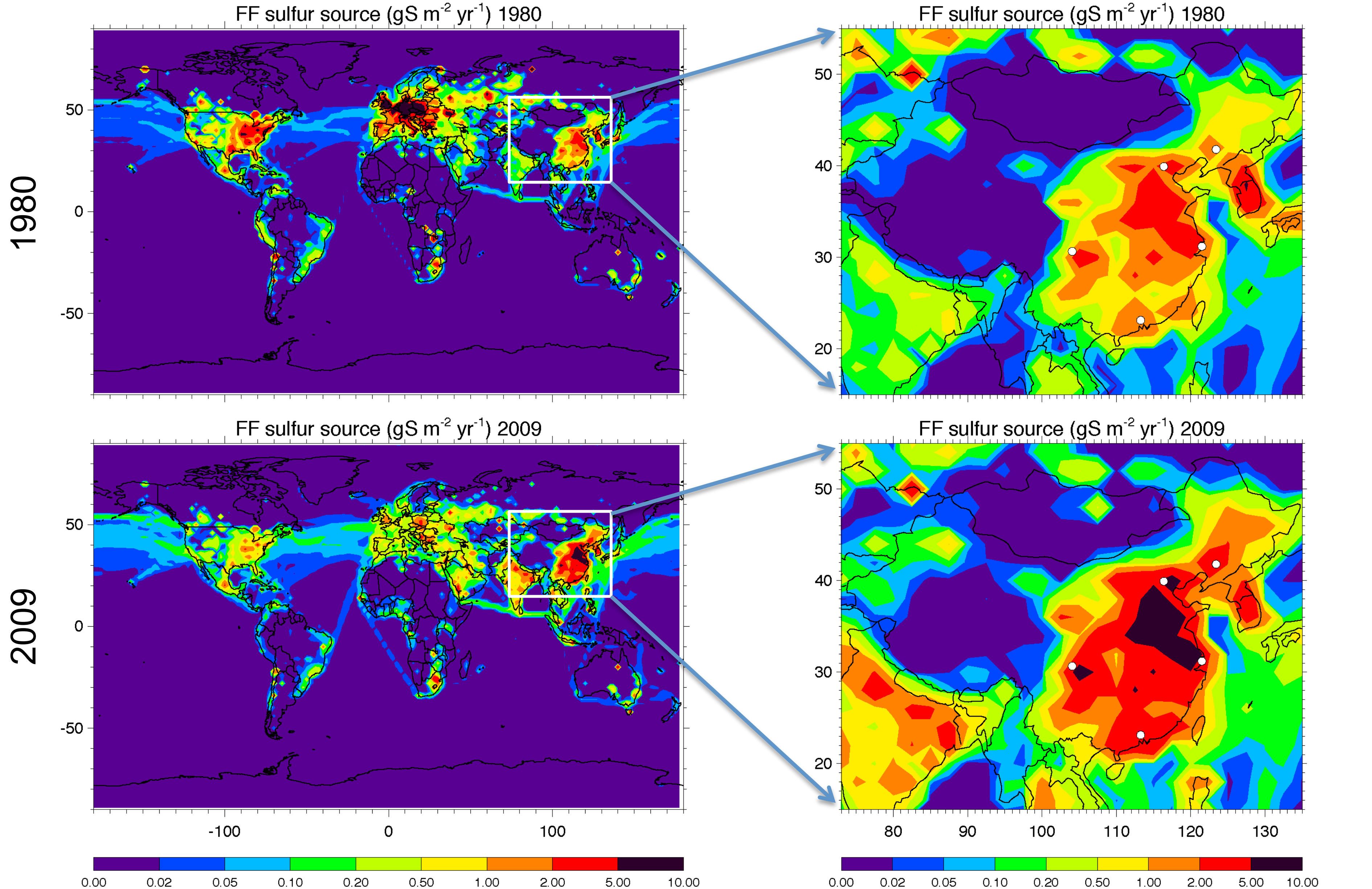
- Using a global model simulation and meteorological data reanalysis from 1980 to 2009 to examine the role of anthropogenic emission and meteorological conditions in controlling the particle pollution levels in winter
- Examining the relationship between a few key meteorological variables with East Asian winter monsoon index (EAWMI) and discuss the feasibility of using them to predict the pollution levels in different parts of China
- Sensitivity study on aerosol effects on meteorology and feedbacks

Model and meteorological reanalysis used in this study, 1980-2009

- Meteorological data:
  - NASA Modern-Era Reanalysis for Research and Applications (MERRA)
- Aerosol simulation:
  - GOCART model driven by the meteorological fields from MERRA reanalysis for 1980-2009, 2°×2.5° resolution
  - Anthropogenic and biomass burning emission: A2-ACCMIP
  - Natural sources: biogenic, volcanic, dust, sea salt



Anthropogenic sulfur missions, 1980 vs. 2009

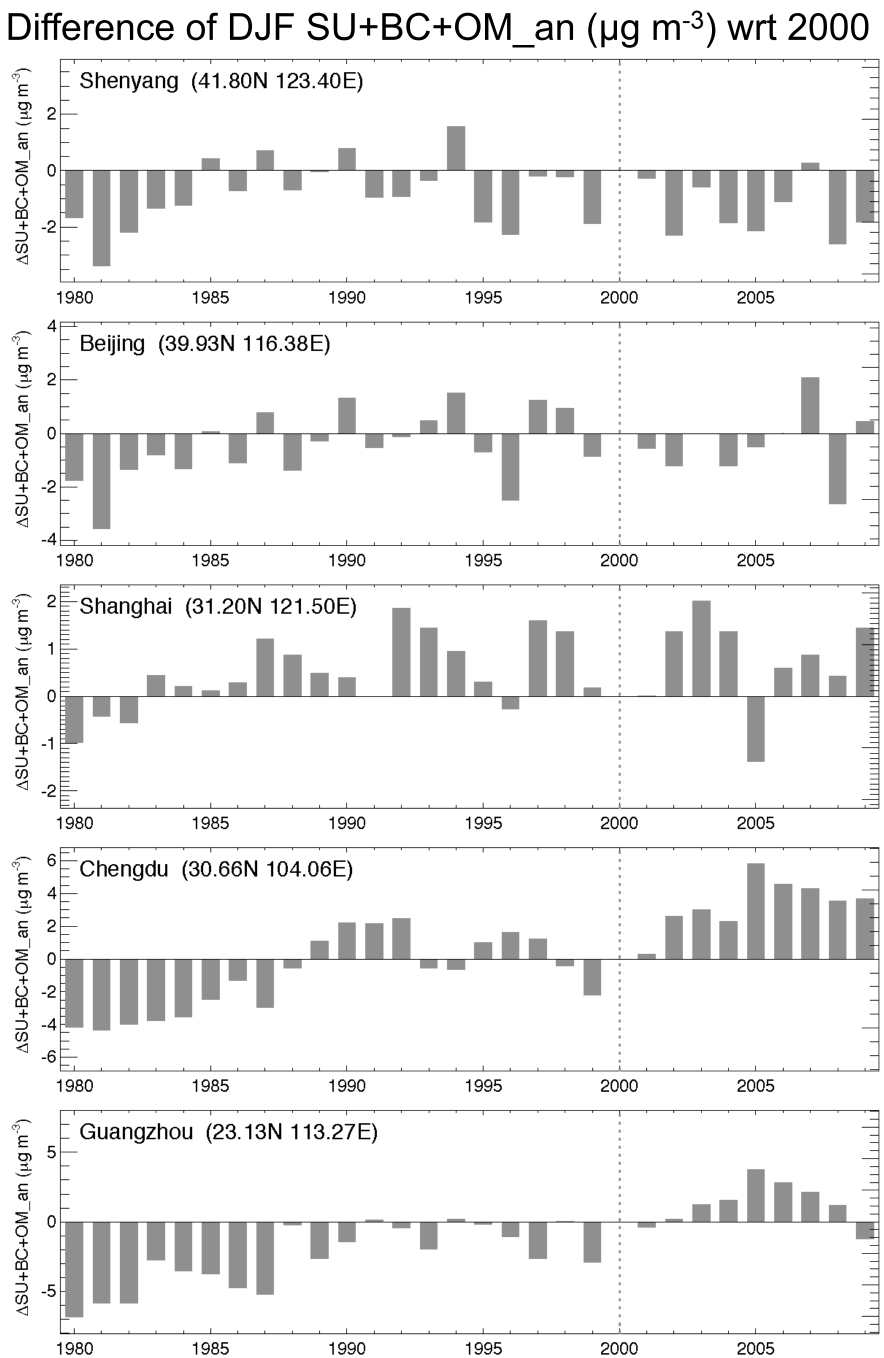


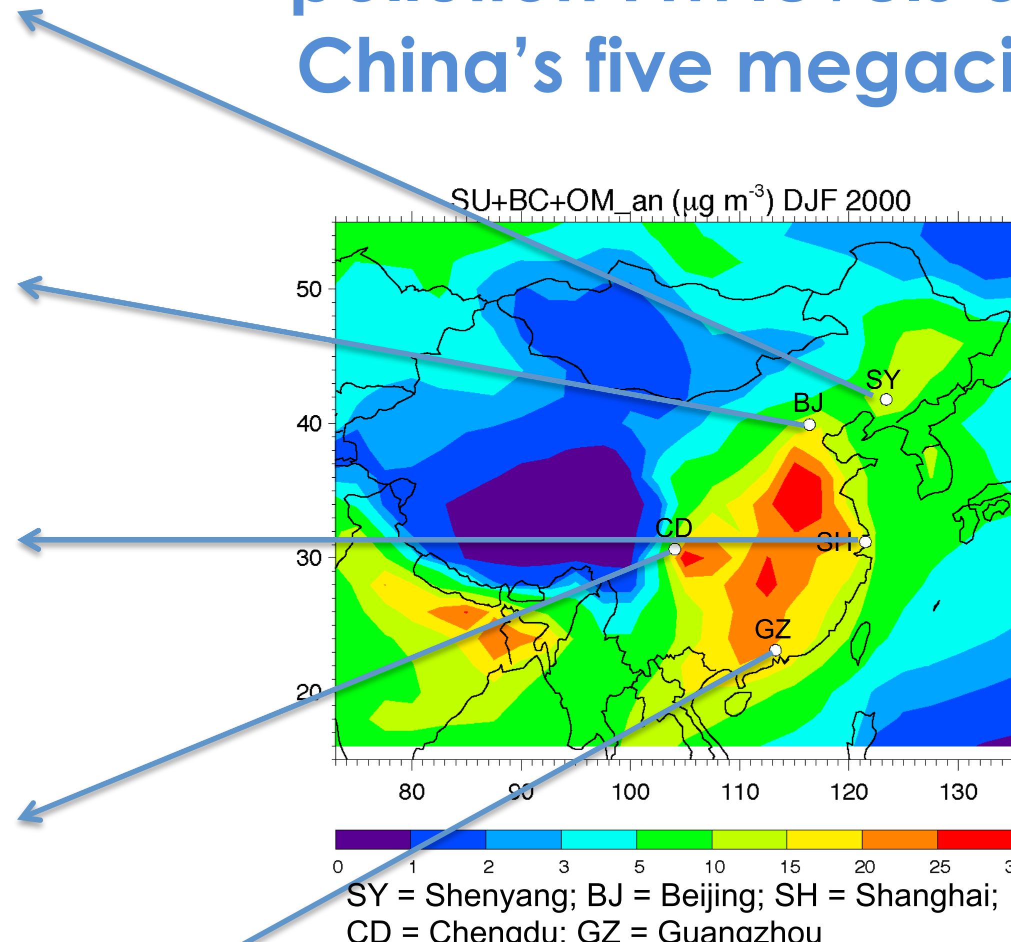
Model experiments and derived information on anthropogenic aerosol concentration change due to change of emissions or meteorology

Experiment	***Emission***
Base 1980-2009	All emissions from anthropogenic and natural sources
Natural 1980-2009	Only emissions from natural sources included
FixedEmi 1980-2009	Anthropogenic emissions fixed at 2000 level

Product	***Information***
P1 = Base - Natural	Change of anthropogenic aerosol due to change of both anthrorpogenic emission and meteorology
P2 = Base - FixedEmi	Change of anthropogenic aerosol due to change of anthropogenic emission
P3 = FixedEmi - Natural	Change of anthropogenic aerosol due to change of meteorology

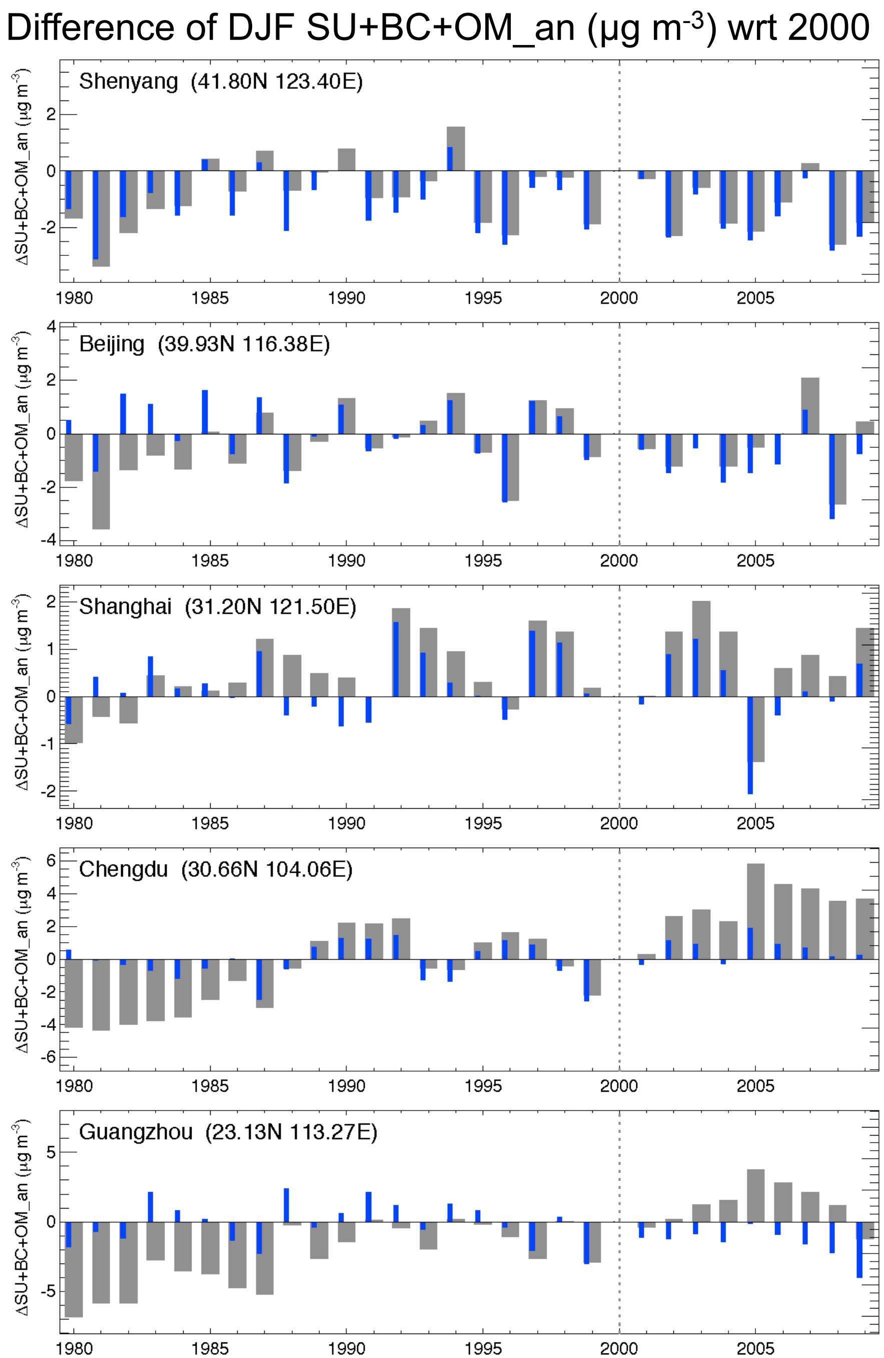
Multi-decadal variations of pollution PM levels over China's five megacities

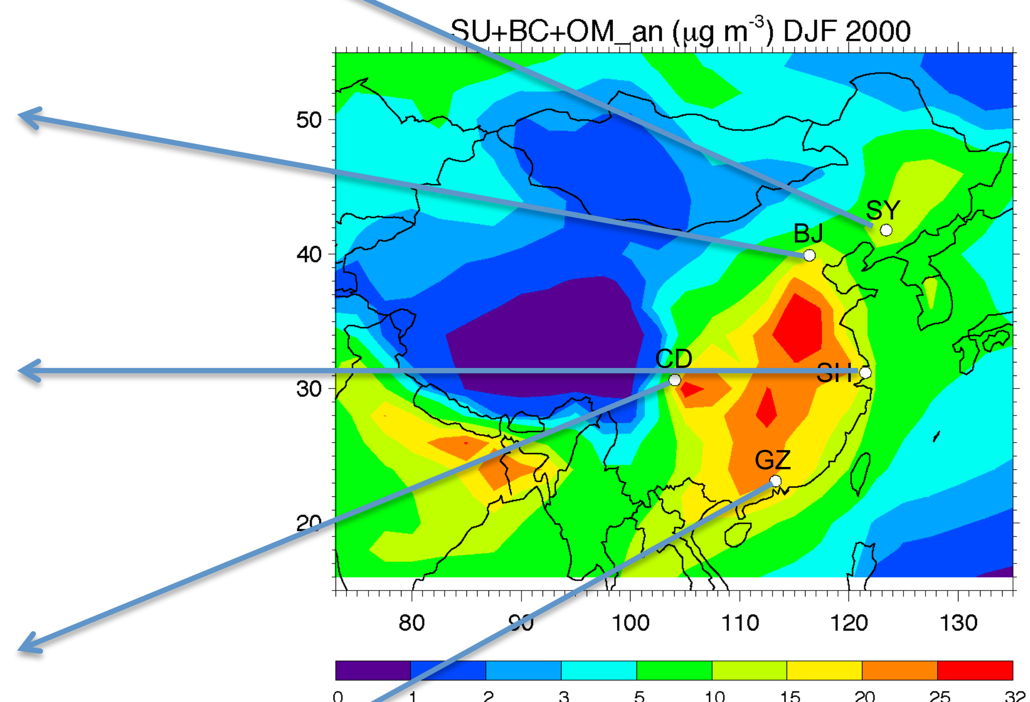




Grey: P1 (Changes due to met & emi)

Multi-decadal variations of pollution PM levels over China's five megacities



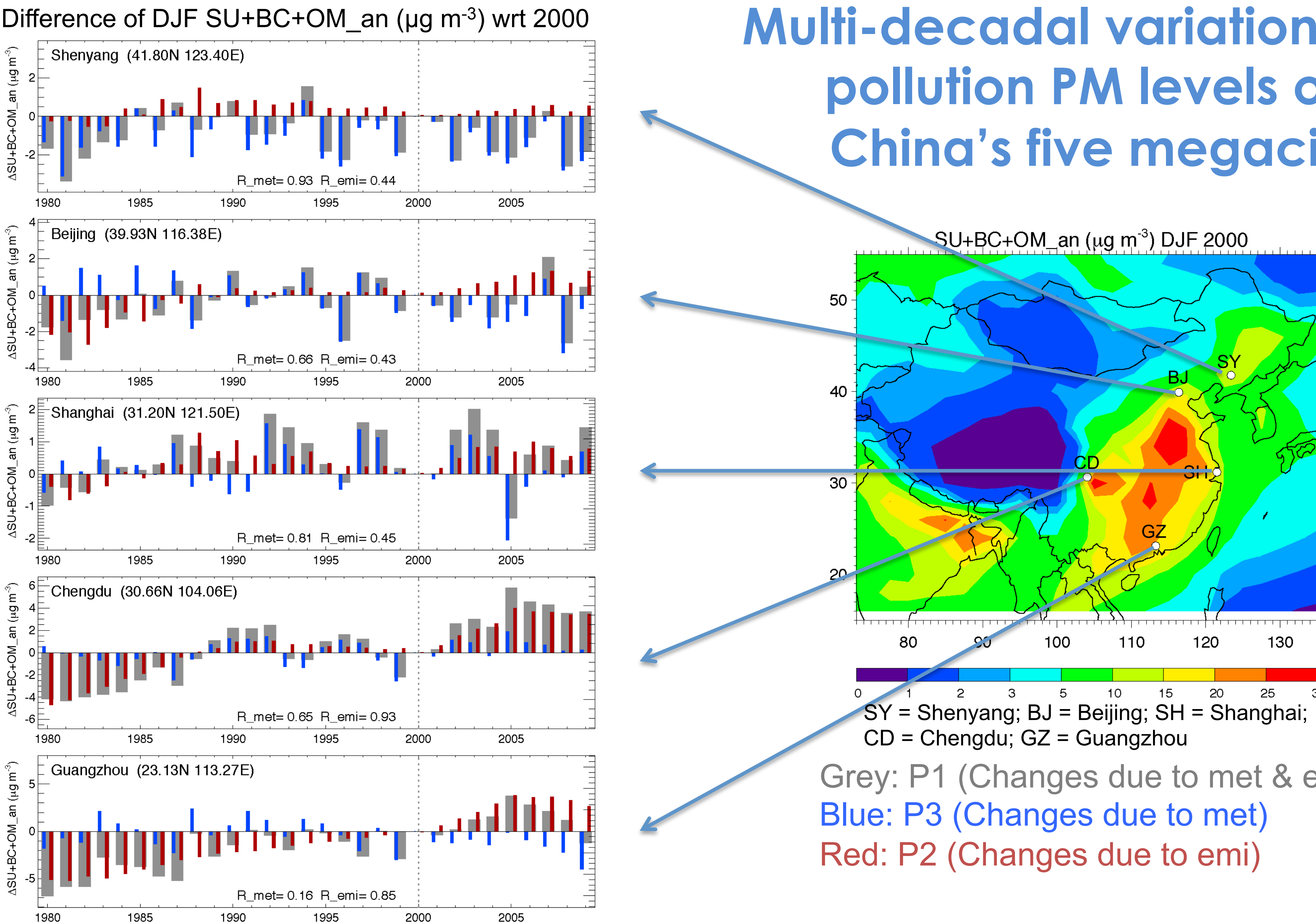


SY = Shenyang; BJ = Beijing; SH = Shanghai; CD = Chengdu; GZ = Guangzhou

Grey: P1 (Changes due to met & emi)

Blue: P3 (Changes due to met)

Multi-decadal variations of pollution PM levels over China's five megacities



SY = Shenyang; BJ = Beijing; SH = Shanghai; CD = Chengdu; GZ = Guangzhou

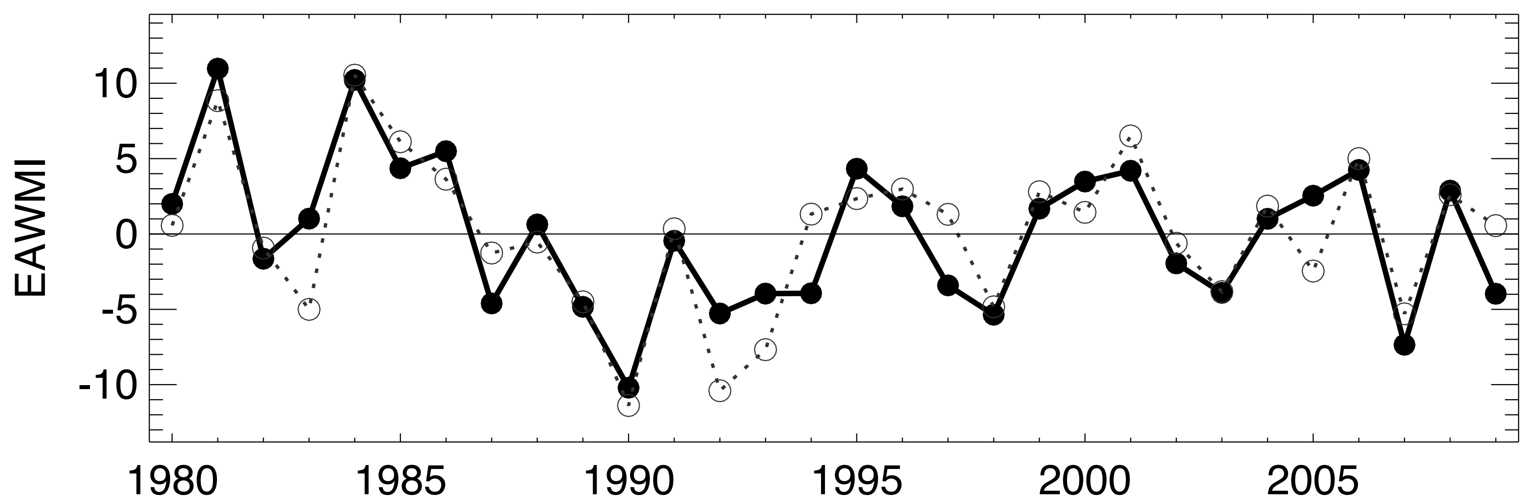
Grey: P1 (Changes due to met & emi)

Blue: P3 (Changes due to met)

Red: P2 (Changes due to emi)

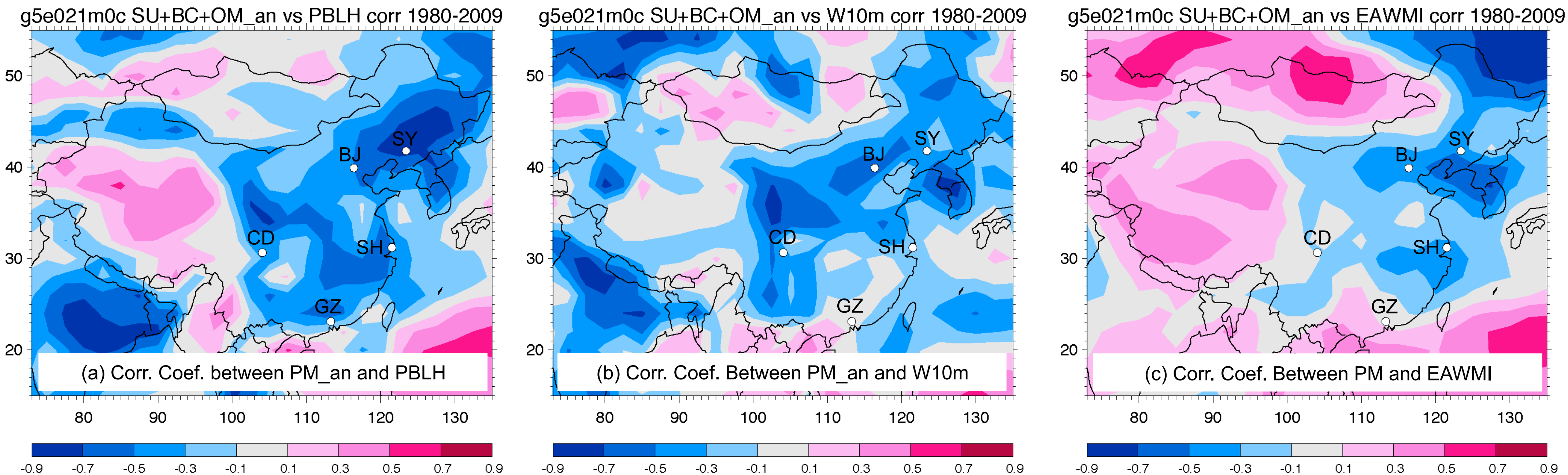
East Asian Winter Monsoon Index (EAWMI)

- There are several “typical” EAWMI calculated from SLP, geopotential height, winds at chosen altitudes, etc.
- We use the Jhun and Lee (2004) index in this work, which is the difference of zonal wind speed at 300 hPa between [27.5-37.5°N, 110-170°E] and [50-60°N, 80-140°E]
- Note that all EAWM indices can only well represent the monsoon characteristics over part of the East Asia, because the large domain of East Asia with complex and different climate zones



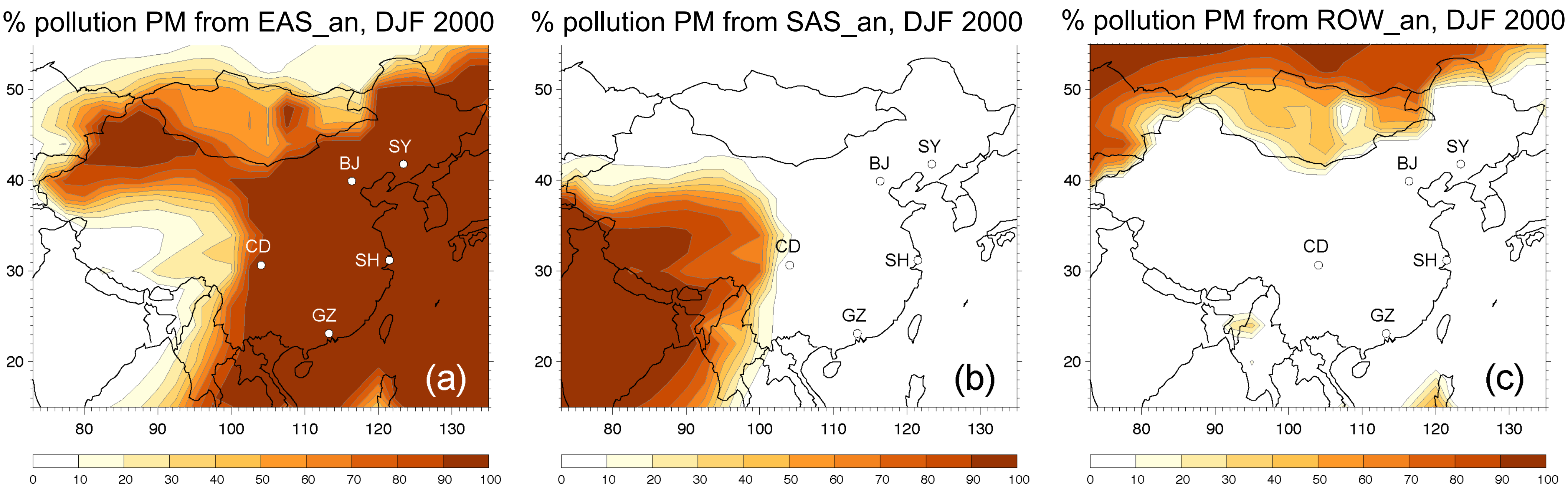
Black: Jhun and Lee, 2004. Grey: Li and Yang, 2010 (based on zonal winds at 200 hPa)

Relationships among pollution PM, PBLH, winds, and EAWMI: model results with fixed anthropogenic emission (meteorology-induced changes of pollution PM), winter 1980-2009



- PBLH and near-surface winds (indicated by W10m) are the most influential meteorological variables affecting pollution PM concentrations
- Pollution PM (as well as PBLH and W10m) are positively correlated to EAWMI except in western China (Tibet Plateau)

Why is PM in western China not responding to EAWM strength and local met fields?

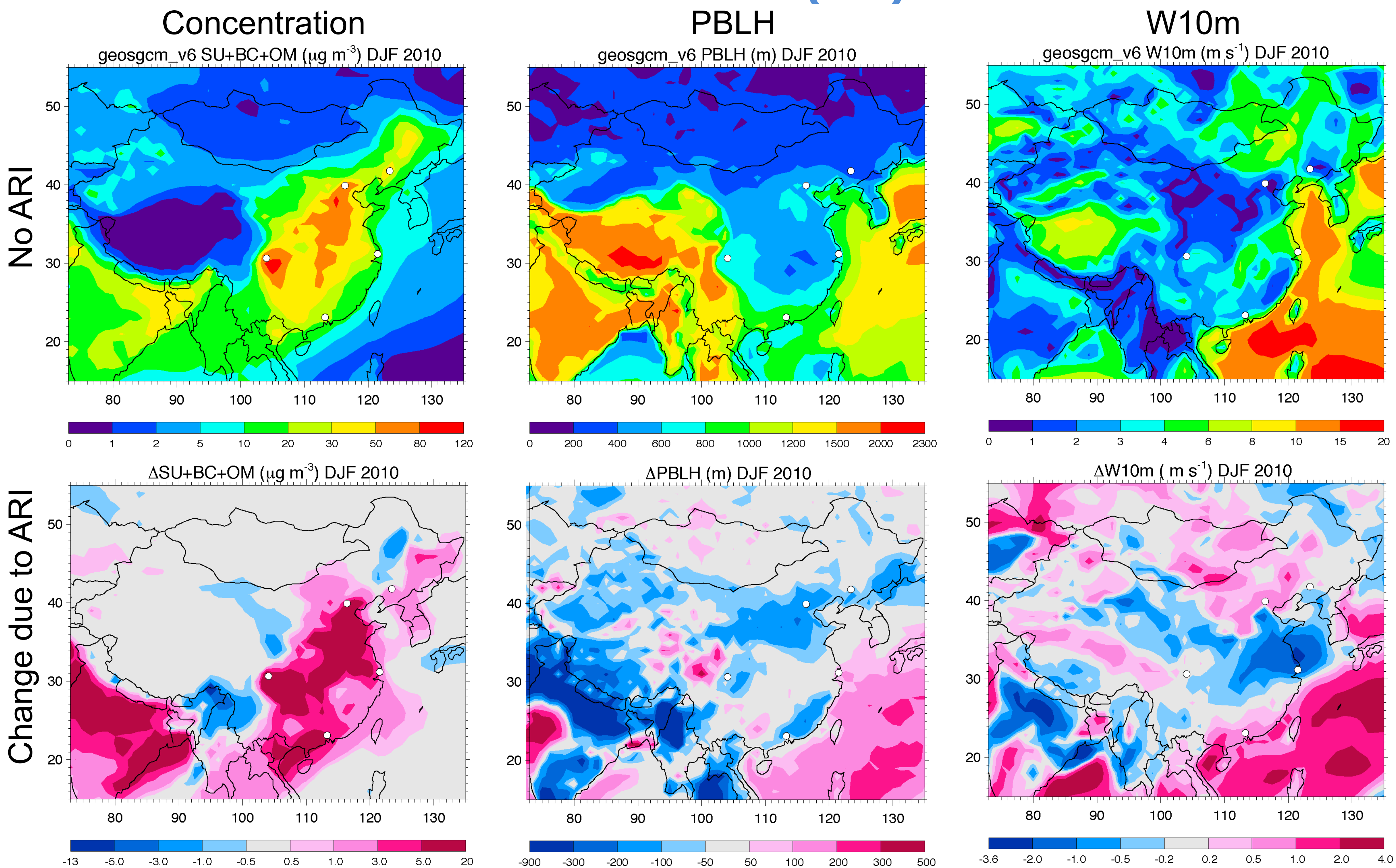


This is because in western China, especially over the Tibet plateau, the PM level is mostly controlled by the trans-Tibet transport of pollution from South Asia, in contrast with eastern China where regional pollution sources have entire control of the pollution PM levels.

Aerosol effects on meteorology through aerosol-radiation interaction

- Simulation of winter 2010 using the GEOS-5 AGCM with GOCART aerosol grid-components that interact with radiation (i.e., the so-called semi-direct effects)
- Driven by prescribed sea surface temperature

GEOS GCM simulations: Changes due to aerosol-radiation interaction (ARI)

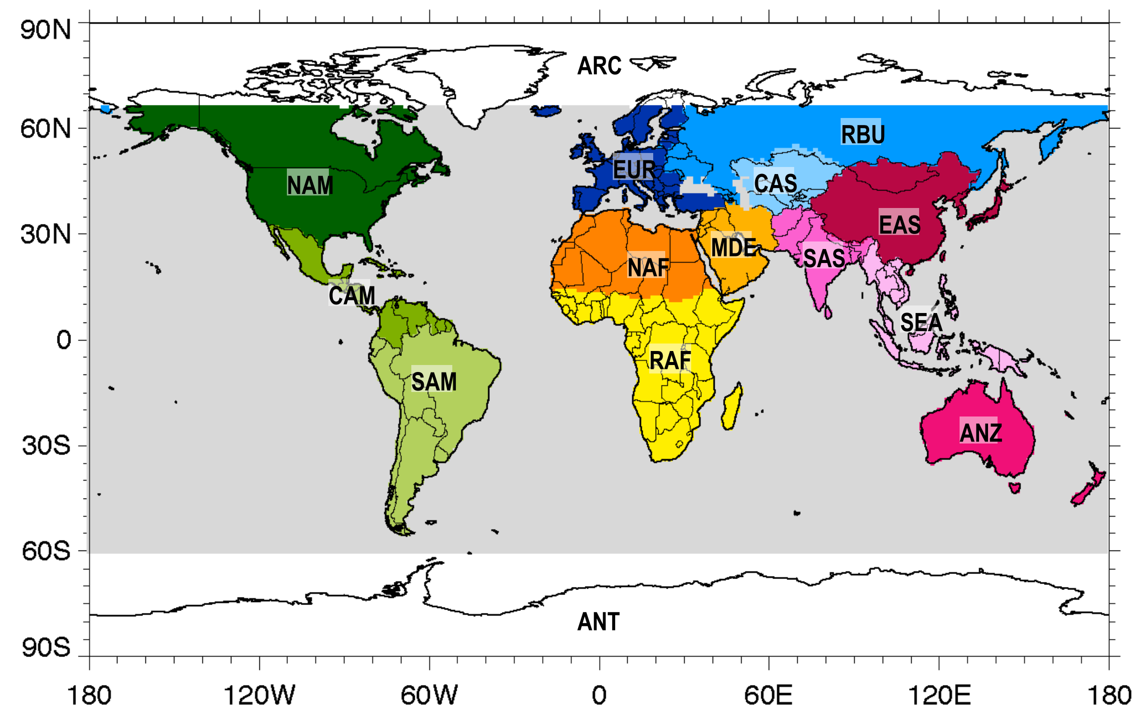


Summary for A)

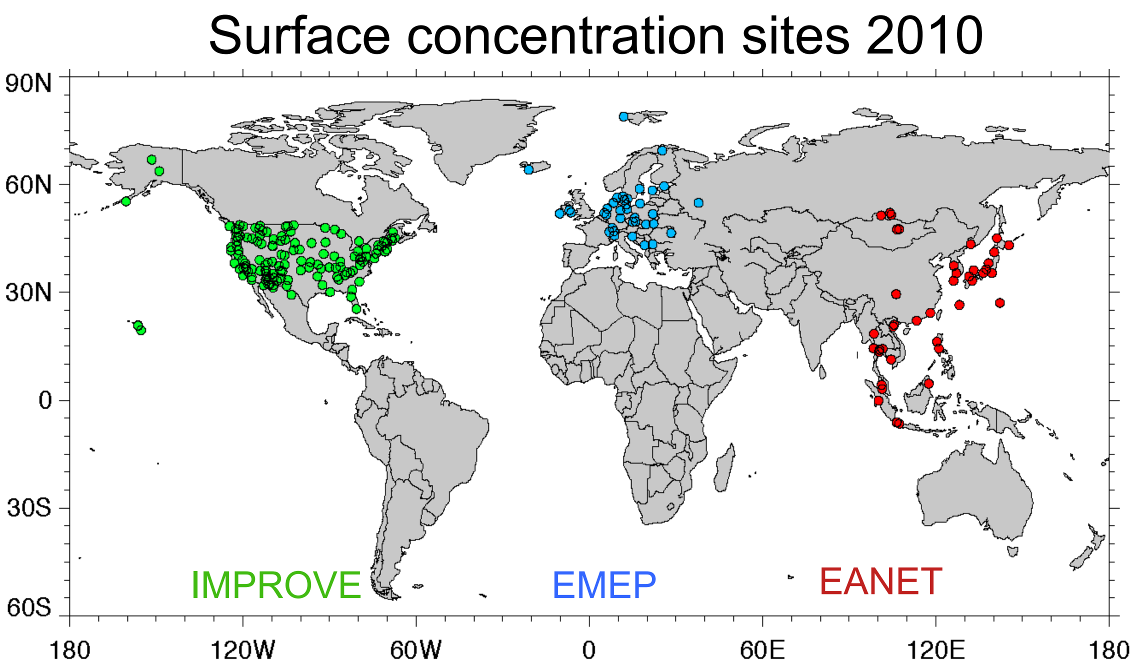
- Wintertime pollution in megacities – emission or meteorology?
  - Shenyang: Meteorology is most responsible for the change of pollution PM level
  - Beijing and Shanghai: Both meteorology and emissions are responsible
  - Guangzhou and Chengdu: anthropogenic emission is mostly responsible
- What are the most important meteorological variables affecting pollution levels?
  - PBLH and near surface winds (using W10m as an indicator)
  - Both PBLH and W10m are positively correlated with the EAWMI in eastern China
  - => Weaker EAWM associated with shallower PBLH, lower wind speed, and higher pollution PM in eastern China
- What is the effects of pollution on meteorology that may cause further worsening of air quality?
  - AGCM experiment has shown a "positive feedback loop" – through ARI, absorbing aerosol causes shallower PBLH and weaker winds to trap more pollutants in pollution regions at the surface

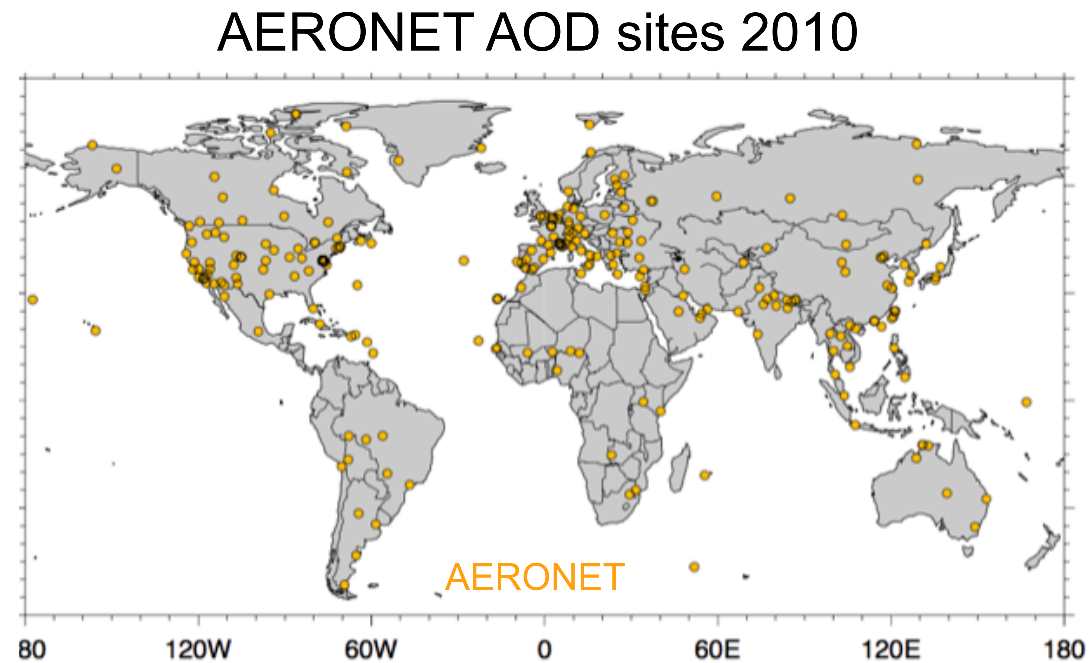
B) Hemispheric transport of air pollution: Source attribution of aerosols in different regions

- HTAP and AeroCom coordinates the HTAP multi-model experiment on assessing how pollution generated in one region may affect pollution levels in downwind region(s)
- Method:
  - BASE simulations with all sources
  - A series of simulations with anthropogenic emissions from one particular region reduced
  - The difference can be used to estimate the concentrations (or other quantities) from regional or extra-regional sources

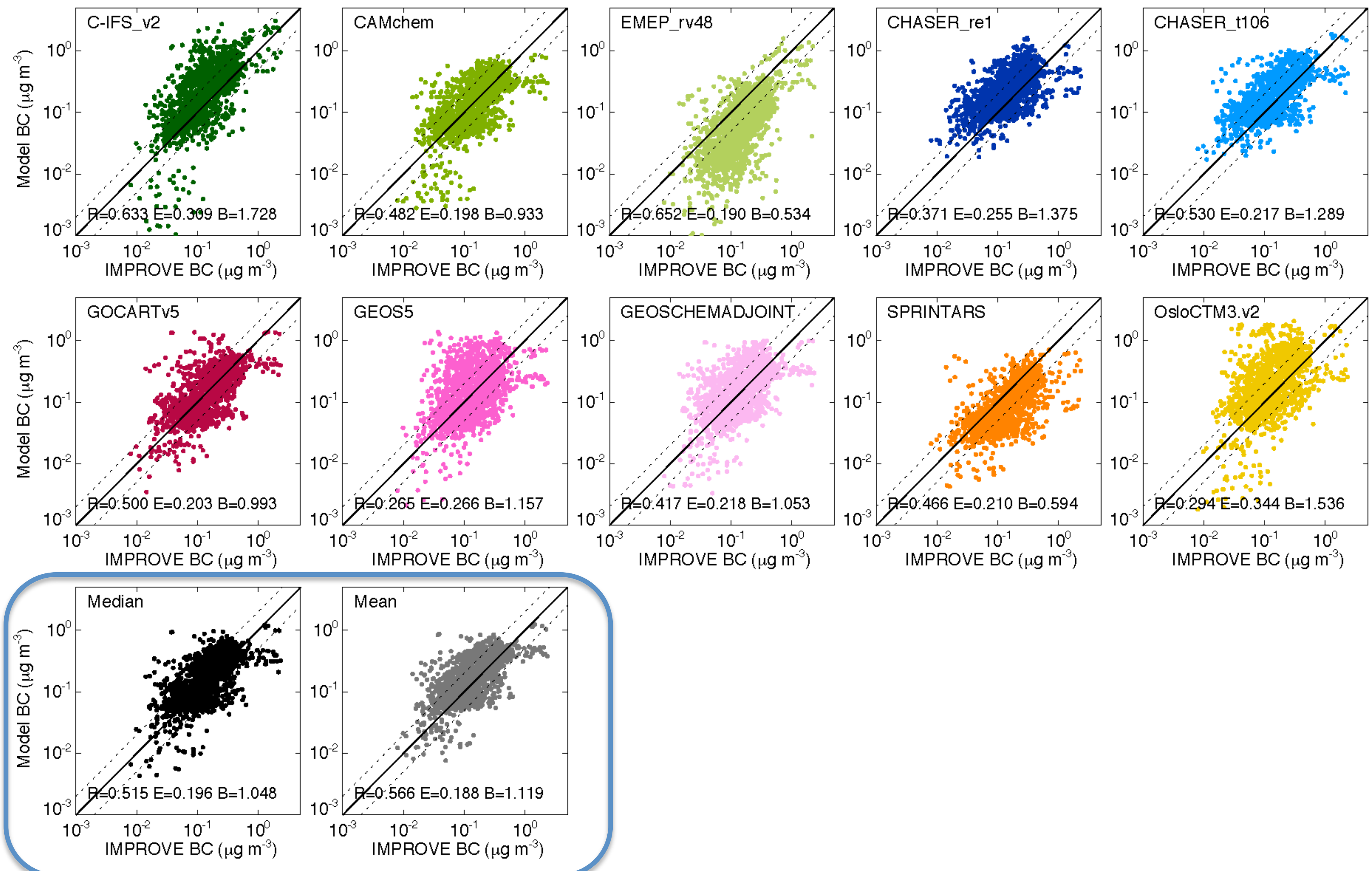


Surface sites of aerosol concentrations or AOD measurements for model evaluation

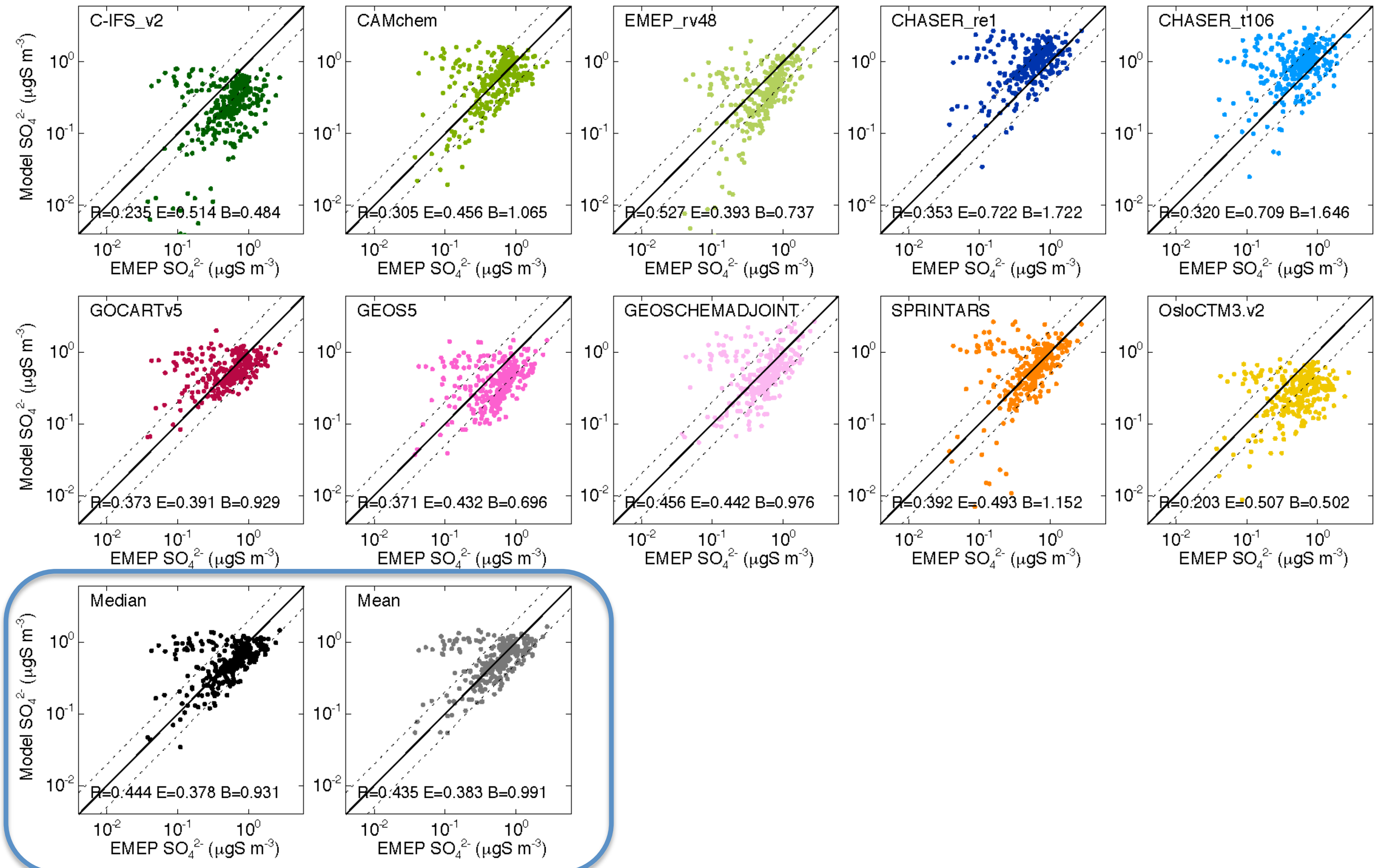




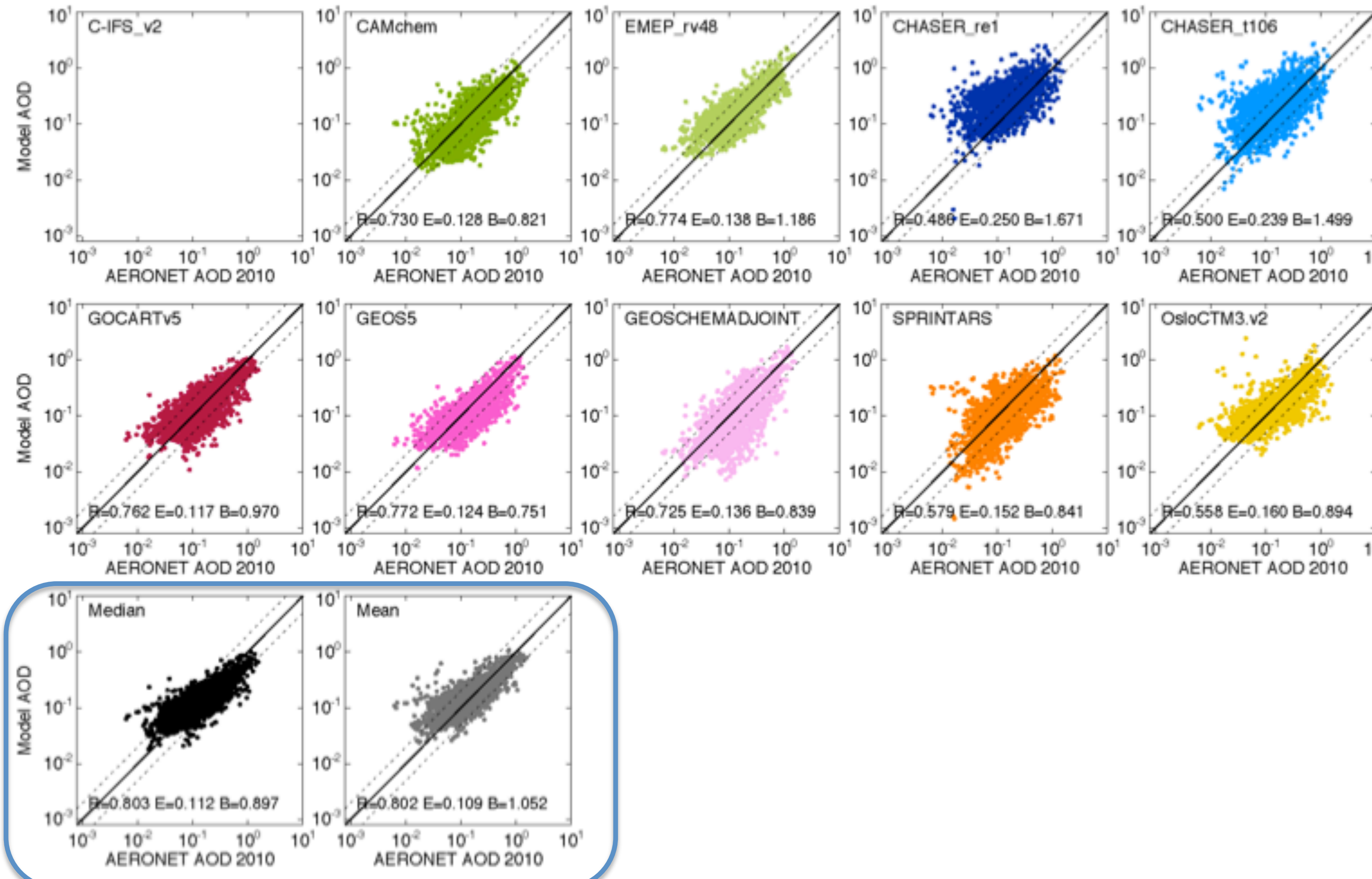
Comparisons of BC surface concentrations in USA



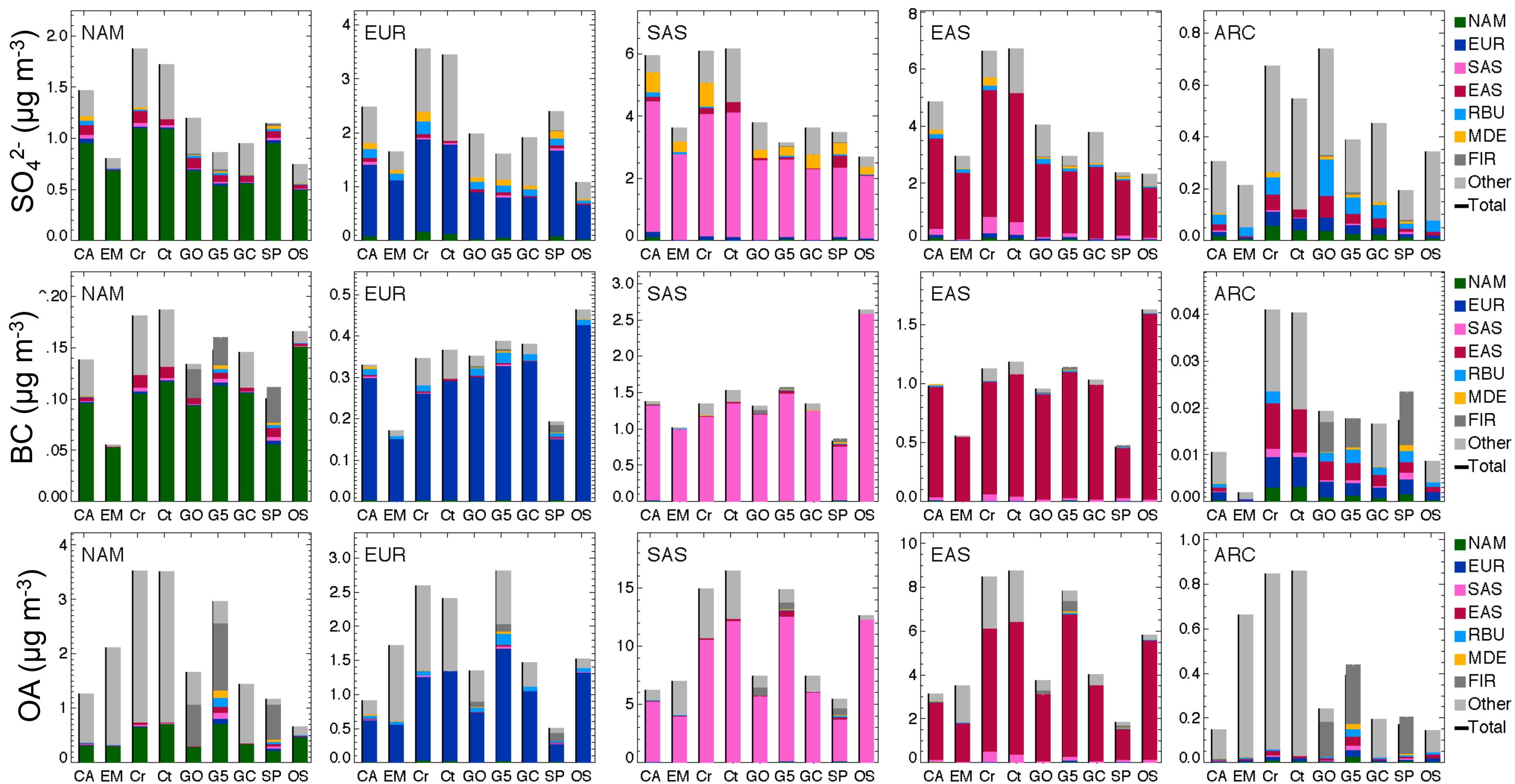
Comparisons of sulfate surface concentrations in Europe



Comparisons with AERONET AOD, monthly average, 2010



Source attribution – Surface concentrations from regional vs. extra-regional pollution sources



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OPPORTUNITIES, CHALLENGES, AND WAY FORWARD

Opportunities

- Aerosol has a wide range of effects, from pollution to climate change, and many of those effects are still not well understood (e.g., aerosol-monsoon interactions)
- There have been unprecedented rich atmospheric observations of aerosols from satellite, ground-based, and in-situ observations that are publically available to provide unlimited research opportunities
- There have also been number of global and regional models publically available to the community to use for aerosol research

Challenges

- No data or models are perfect – many times they are difficult to manipulate or understand
- Satellite data have large spatial and temporal coverage but they are limited in retrievable physical quantities.
- In-situ data are more detailed in aerosol characteristics but they are limited in spatial or temporal coverage
- Models are getting more and more sophisticated, but many processes are not observable to be evaluated with observations. They can also be computationally demanding

Way forward

- Take synergistic approach between modelers and observationalists, understand how to use the data and model
- Work with your colleagues and reach out to and be involved in the larger community (good example: AeroCom and AeroSAT)
- Think globally, act locally – Build a view of big pictures but focus on solving one problem at a time