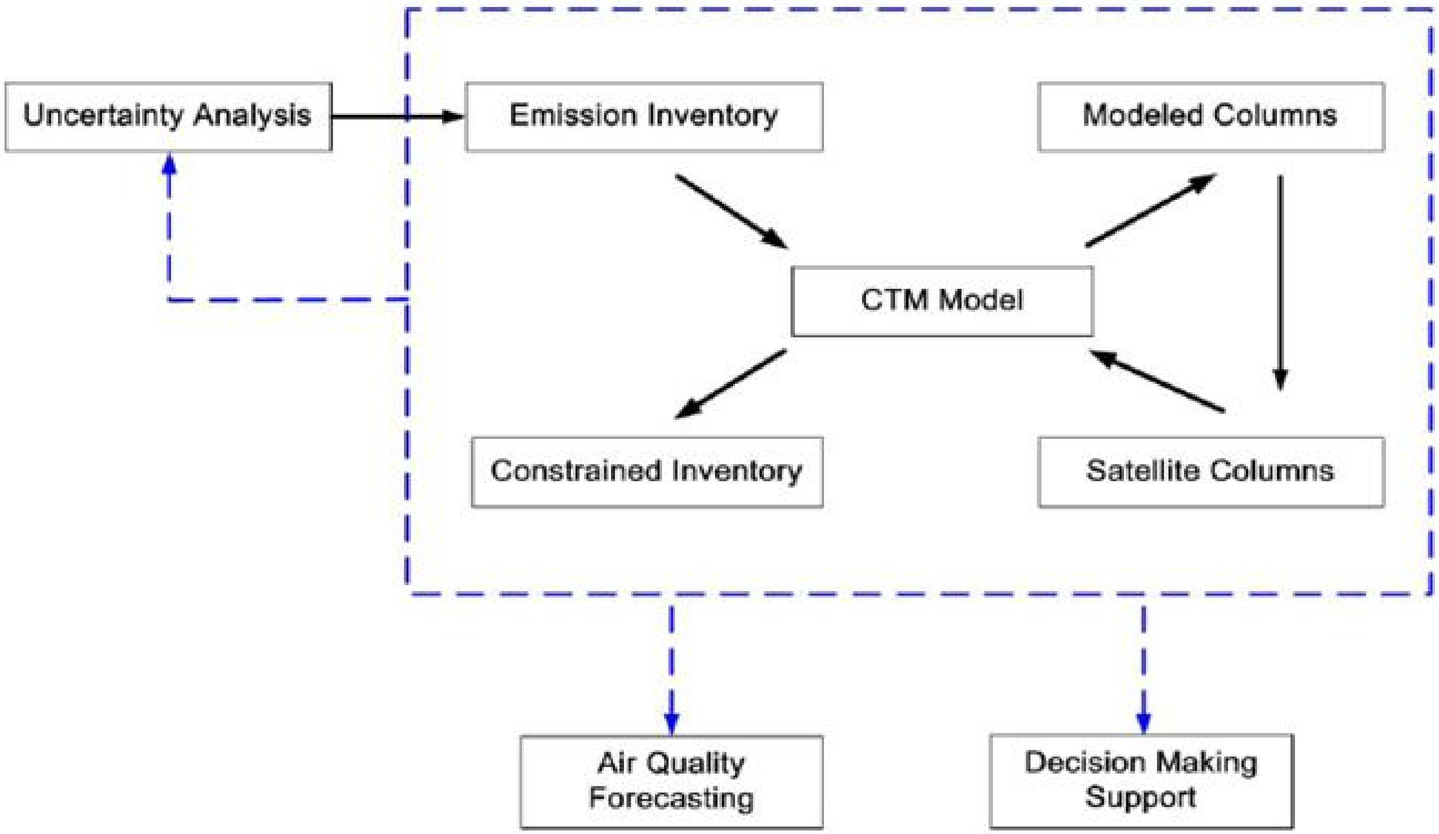
Emissions and Modeling in Support of Air Quality and Climate Impacts – *A Regional-Scale Perspective*

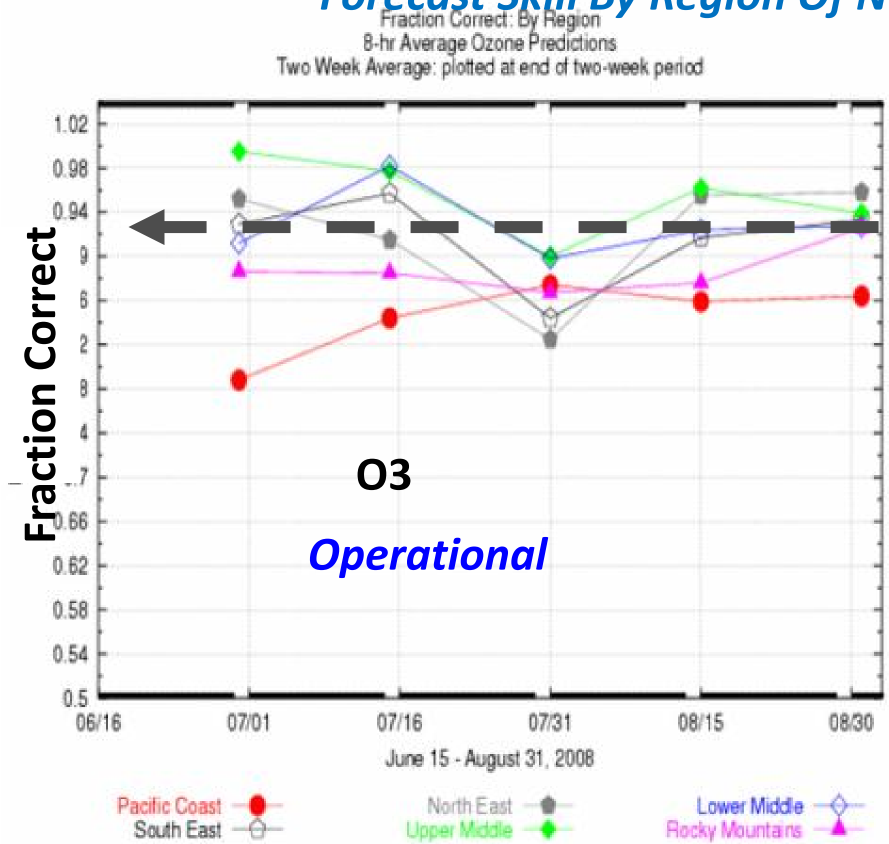
Greg Carmichael, Univ. of Iowa

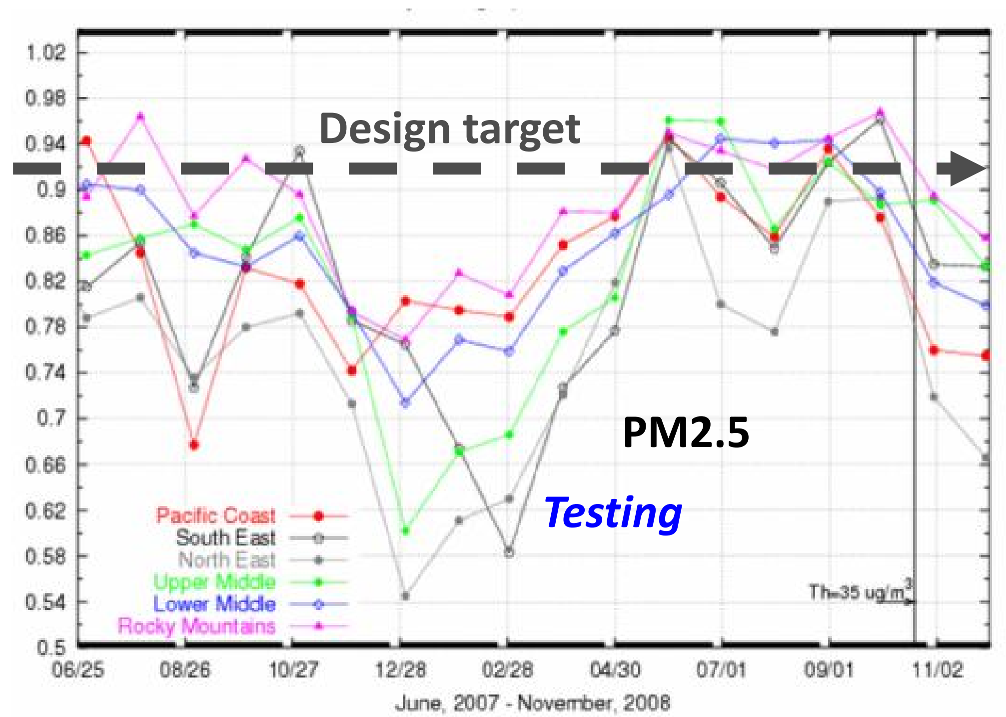


ICAP May, 2012, Italy

Increasing Needs and Expectations for Chemical Weather Forecasts

Forecast Skill By Region Of NOAA's Ozone And PM2.5 Predictions

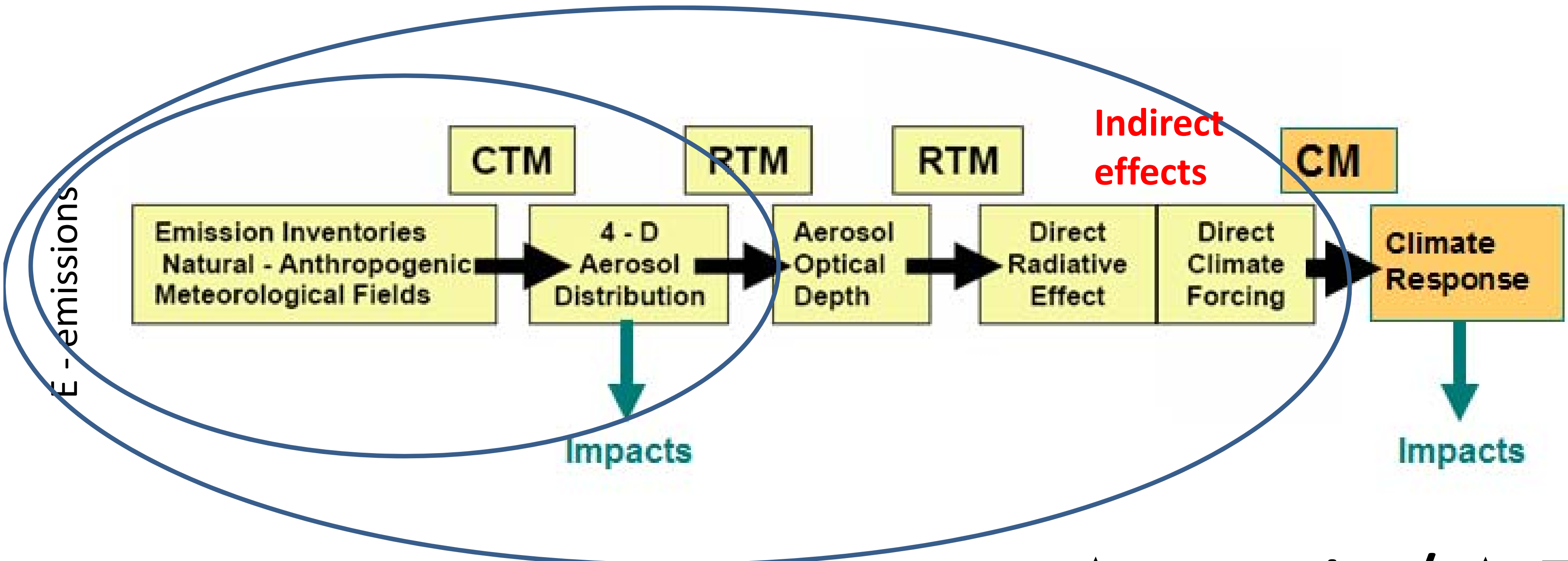




Slide provided by Paula Davidson

Models Play a Critical Role in Linking Emissions to SLCF ($Aerosols$ & O_3) Distributions and Subsequent Radiative/Climate Effects

Keen need/interest in regional analysis!

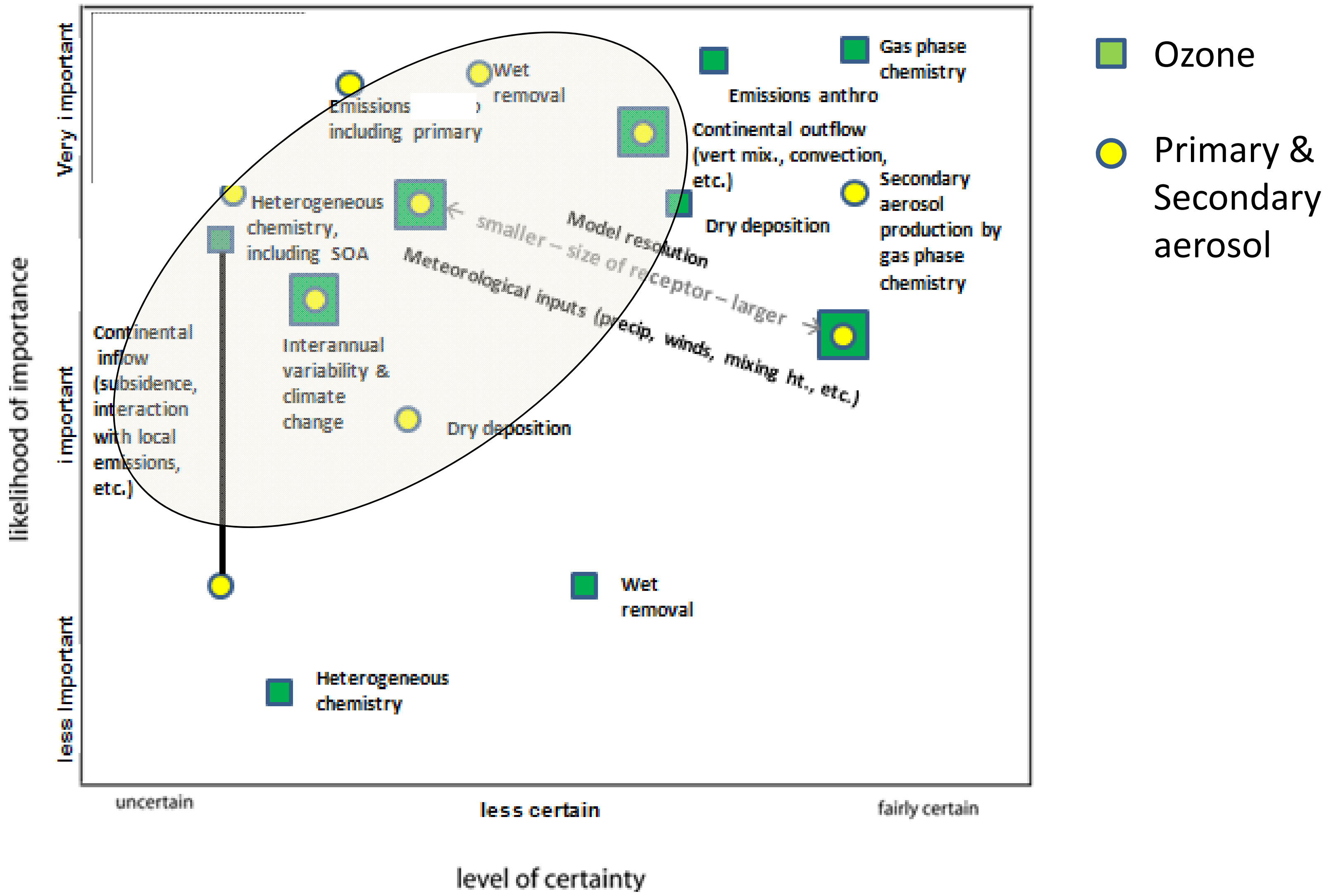


Δ metric / Δ E

Uncertainties

Significant → Increasing

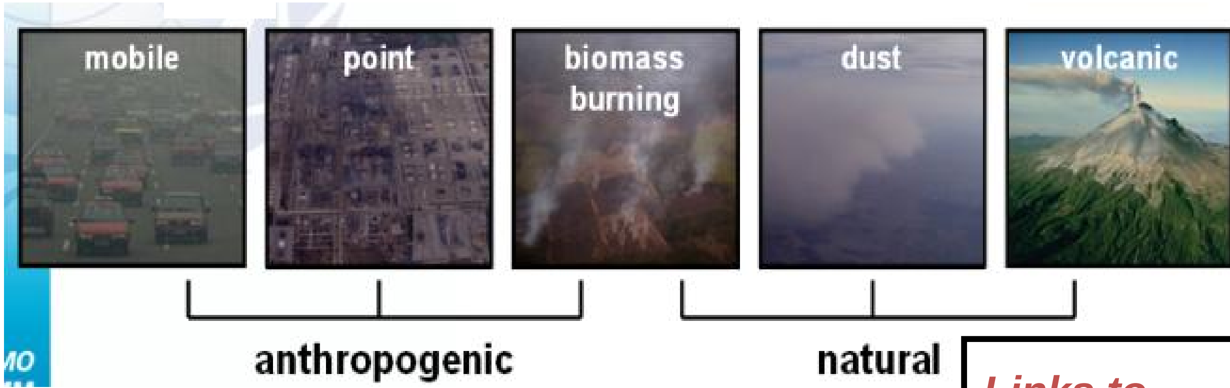
Current Uncertainties in CTM Modeling Source/Receptor Relationships

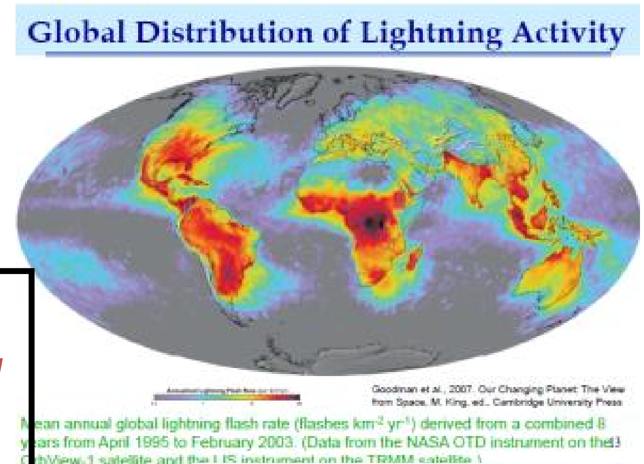


HTAP Report, Feb., 2011

Challenge: Need to Estimate ALL Emissions at Appropriate Scales to Predict Chemical Weather

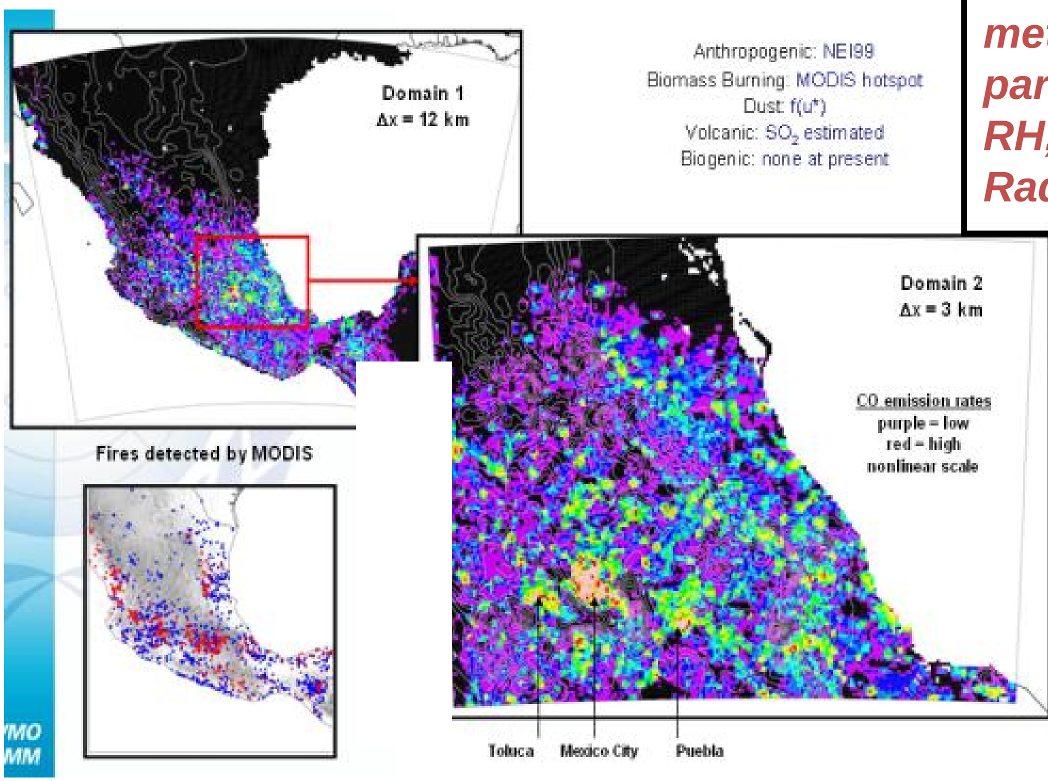
(*and they are constantly changing in space and time)*



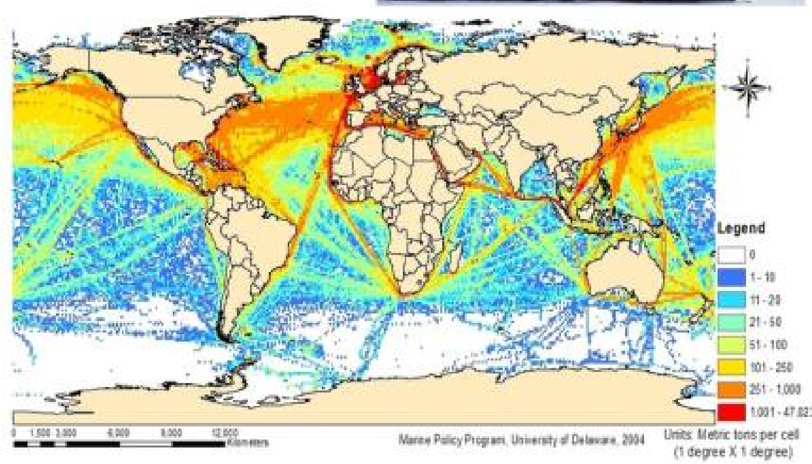


Links to meteorological parameters (T, RH, WS, Radiation, etc.)

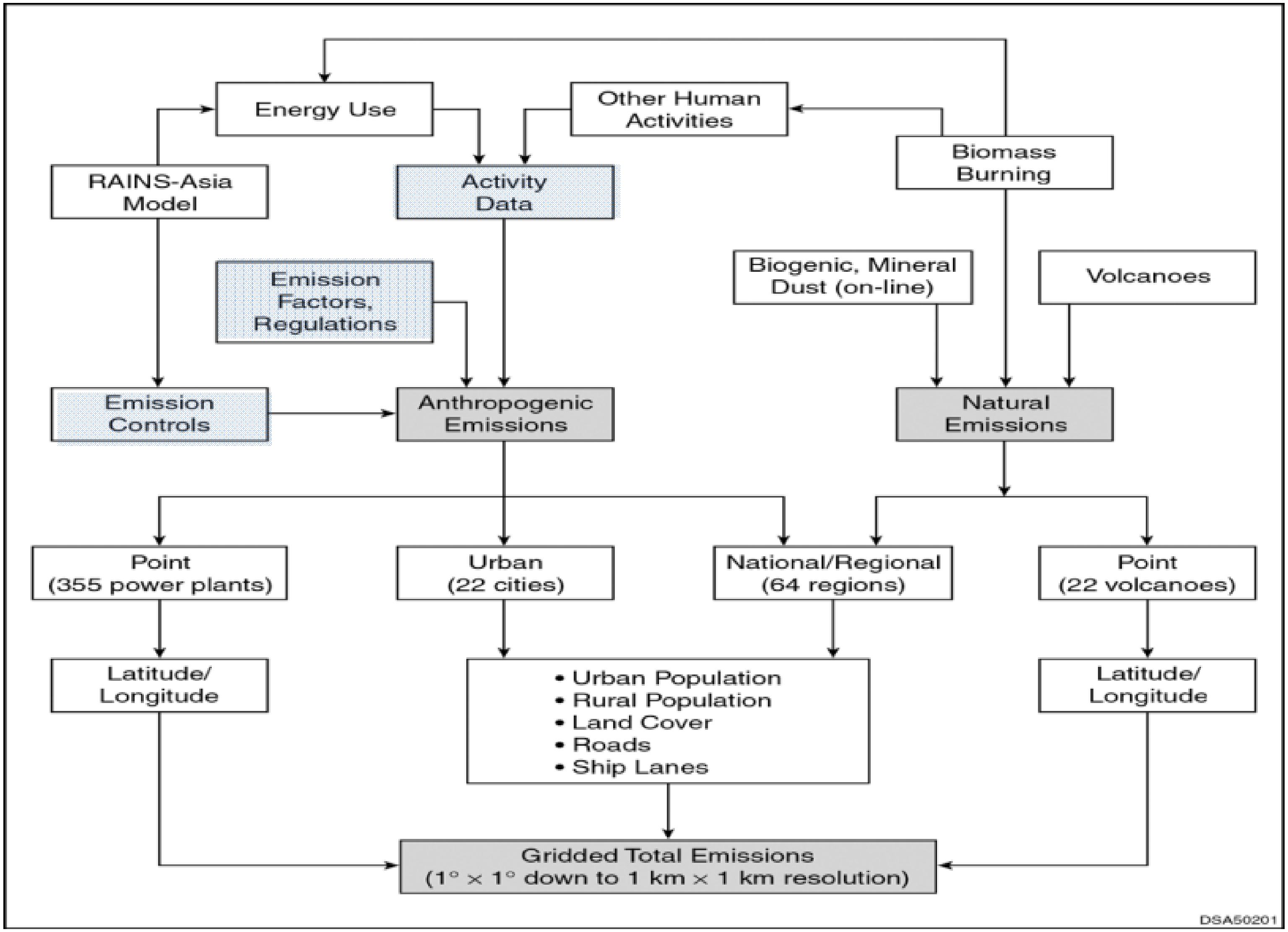
Anthropogenic: NEI99
Biomass Burning: MODIS hotspot
Dust: f(u*)
Volcanic: SO_2 estimated
Biogenic: none at present



SOx Emissions

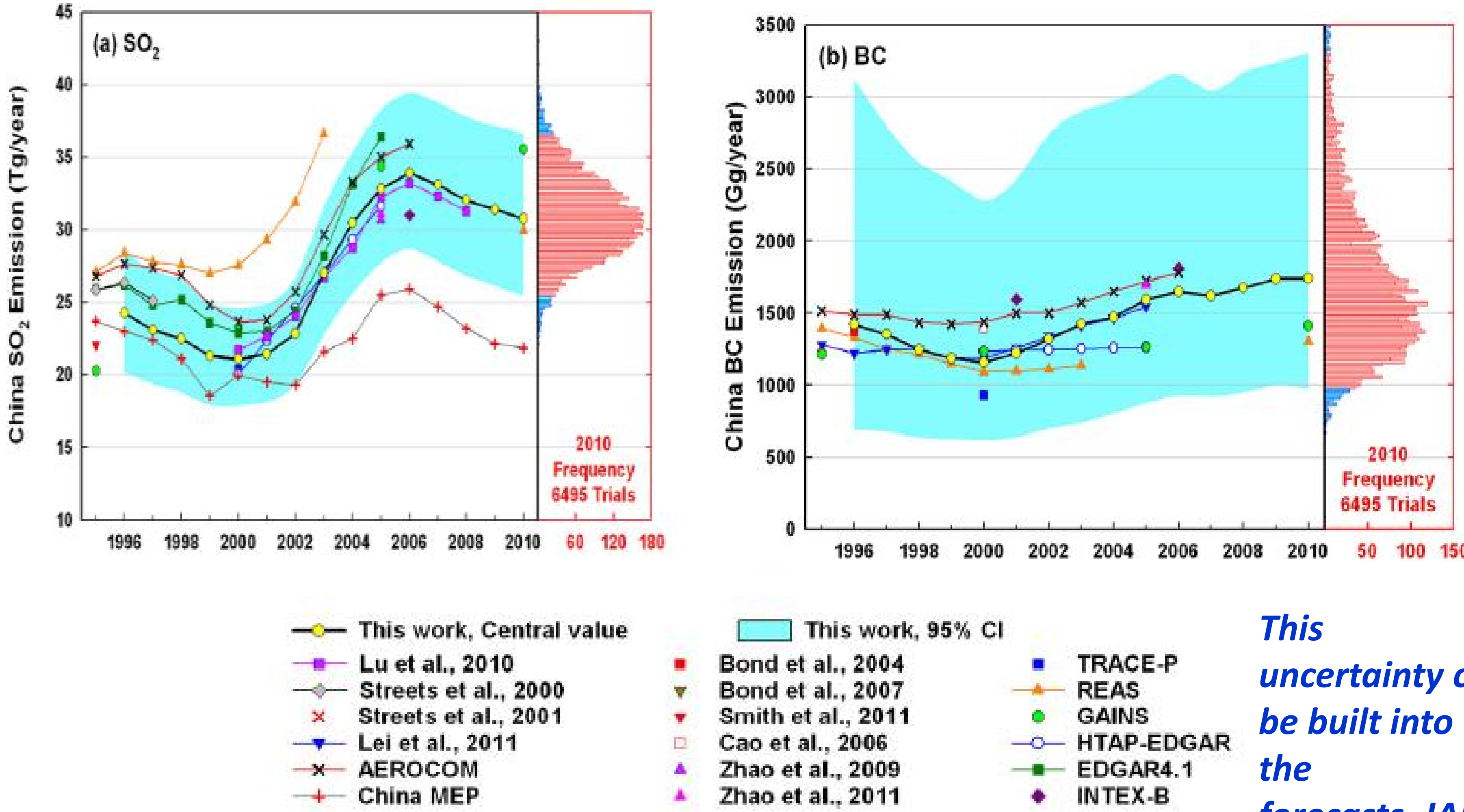


Bottom-Up Emission Inventory Framework



Li et al., ACP, 2012

Emission Estimates Remain Uncertain

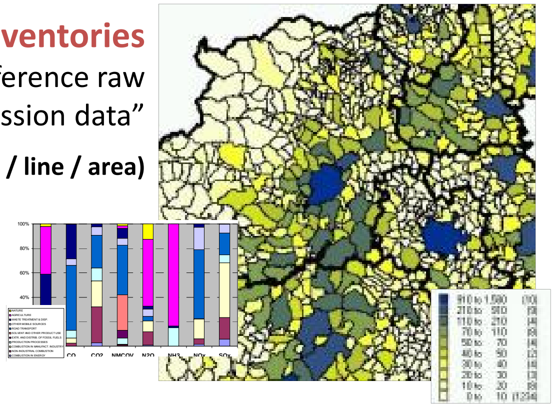


This uncertainty can be built into to the forecasts..IAP

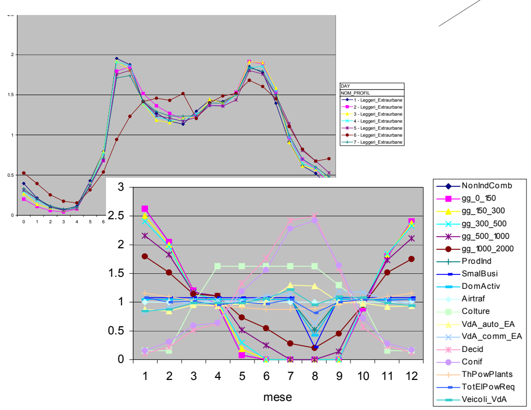
Liu et al., ACP, 2012

Processing For Model-Ready Emissions Adds Additional Uncertainties

Inventories
"reference raw emission data"
(point / line / area)



Modulation profiles
(hourly, daily, monthly)

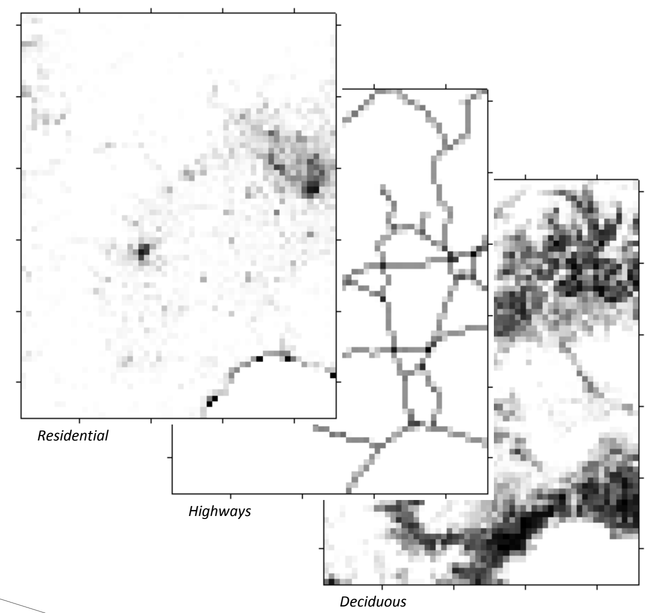


SPACE DISAGGREGATION

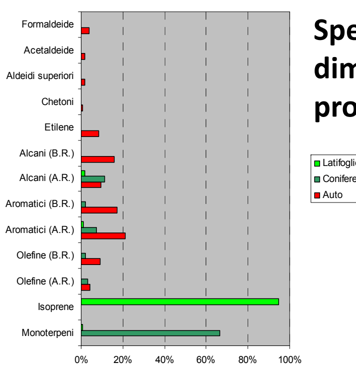
TIME MODULATION

NMVOC & PM SPECIATION & SIZE

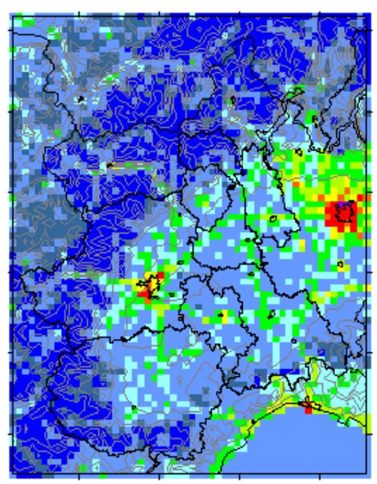
Thematic data



Speciation & dimensional profiles



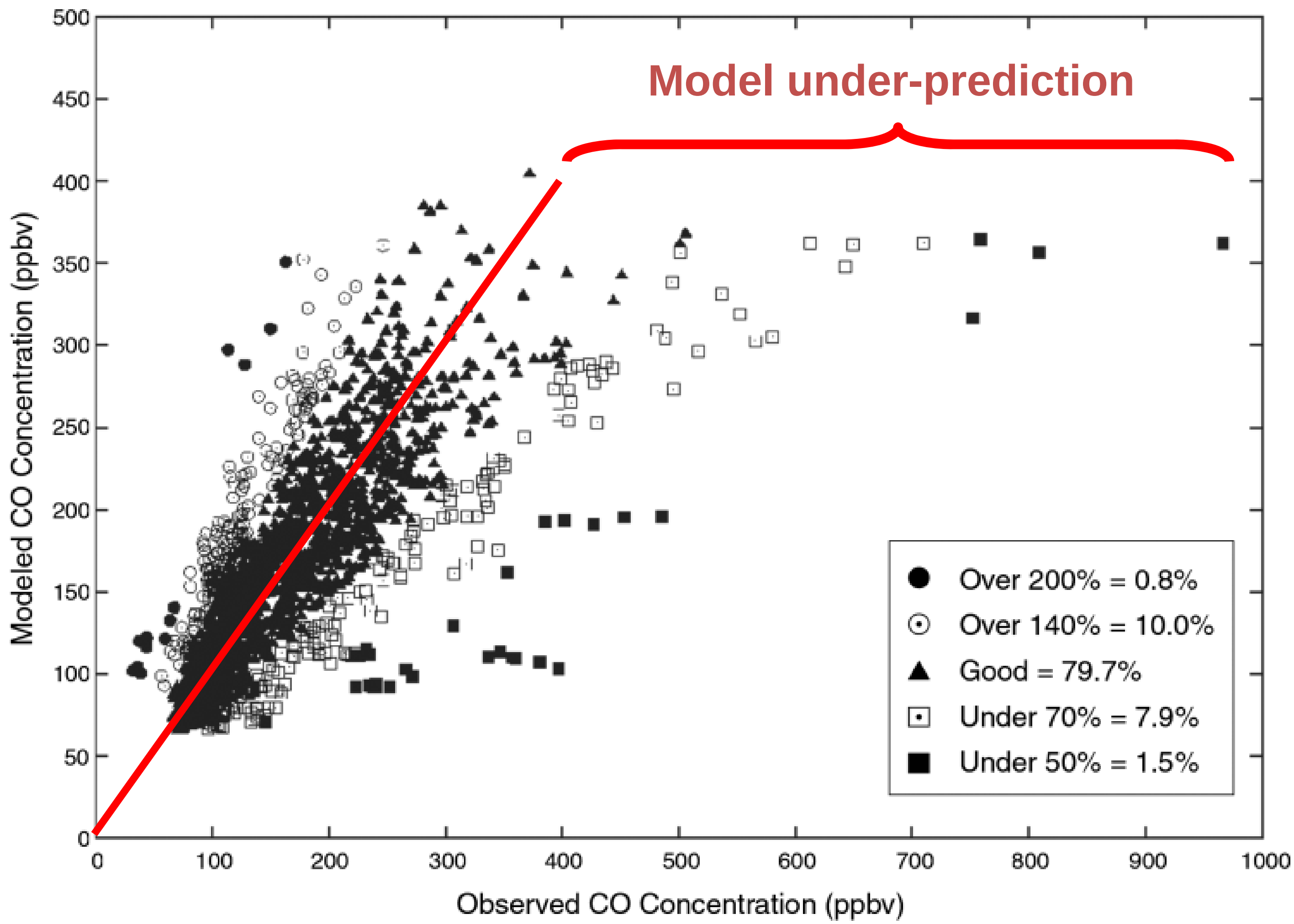
Model-ready input
(hourly, gridded, speciated emissions)



Tong et al., IWAQF, 2011

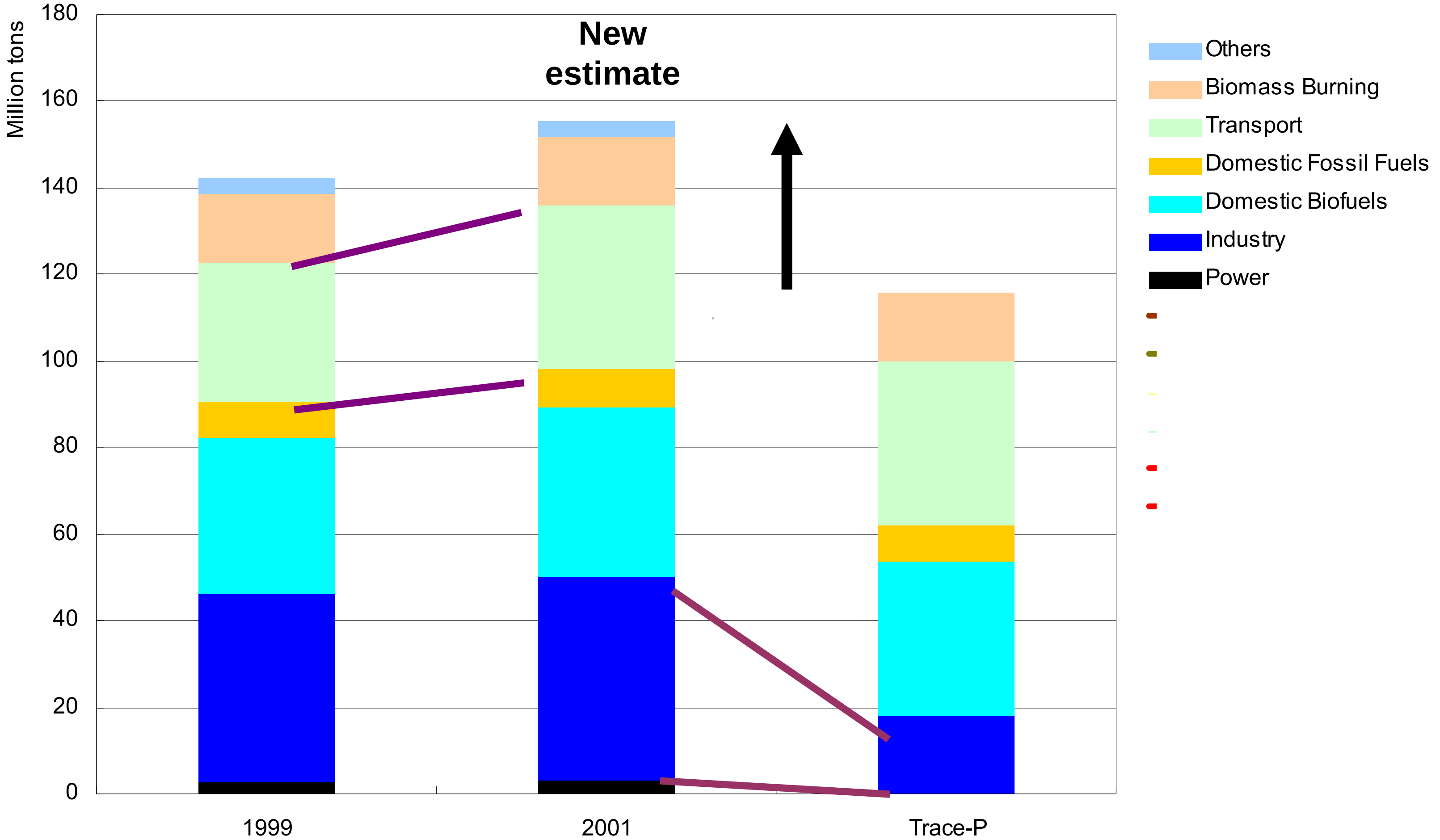
Improving Emissions Through Field Experiments

Post-mission analysis has shown that the inventory seems good for most species, except for high CO and BC observations in the Yellow Sea



(Carmichael et al., JGR, 2003)

Comparison of New CO Inventory with Trace-P

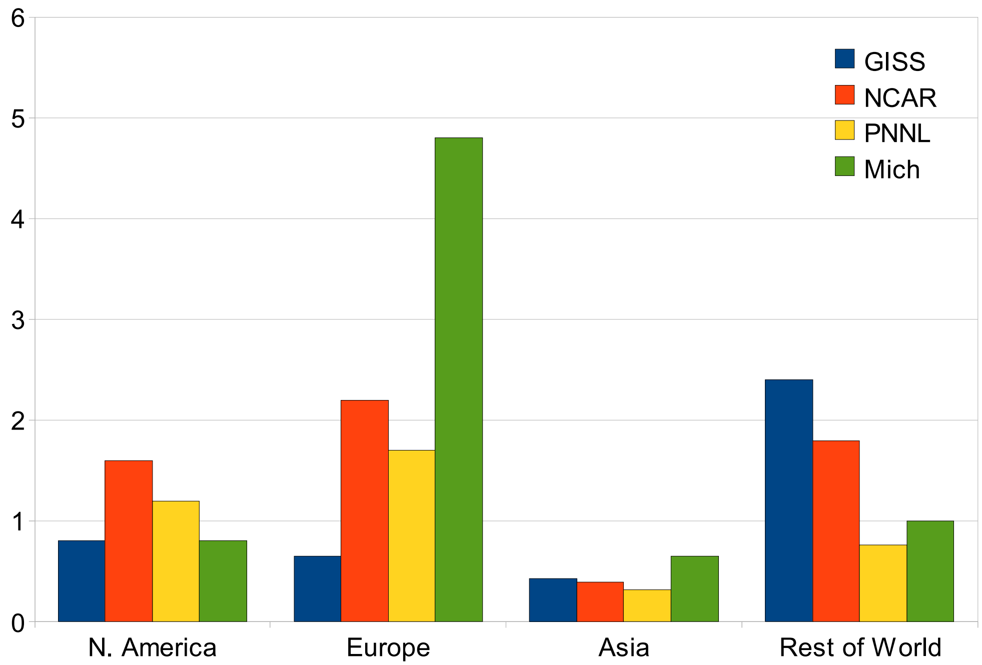


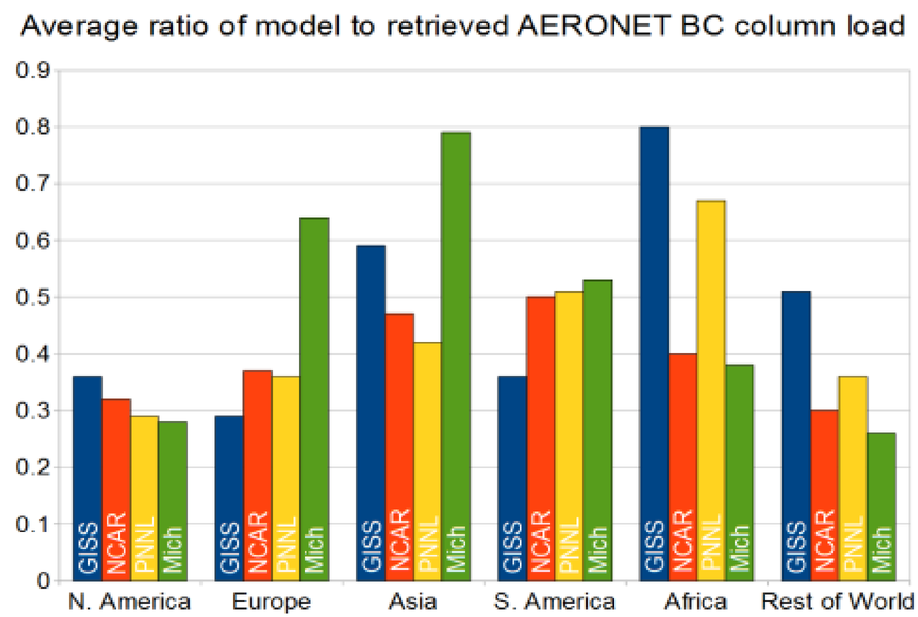
Updated CO Inventory

- 34% higher compared with Trace-P inventory
- 73% of increase comes from industrial sector
- Key reason: low combustion efficiency
- 'Consistent' regional changes
- Implications for BC, OC and VOC?

BC Plays Important Roles in Air Quality and Climate But We Need Improved Capabilities to Predict Its Distributions

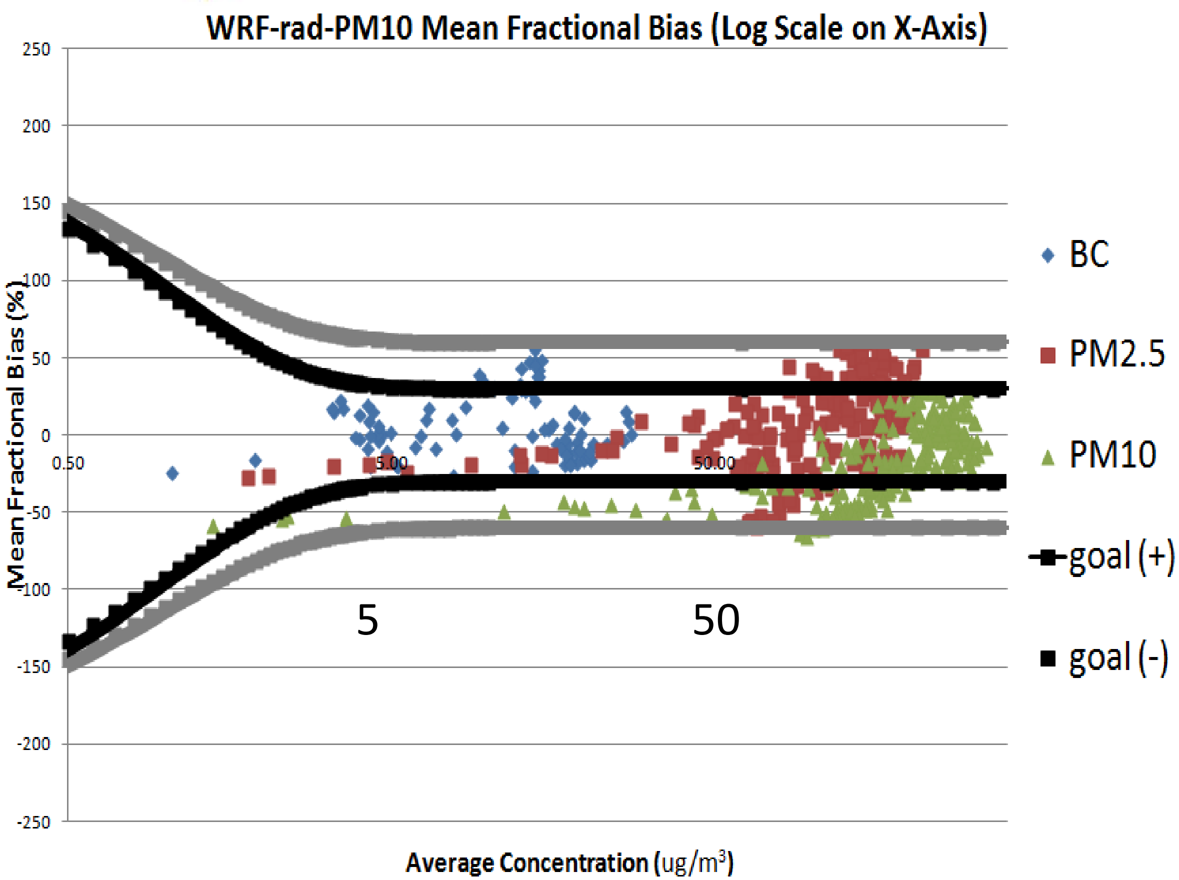
Average ratio between model and observed BC surface concentration (right) and column amount (left) by region

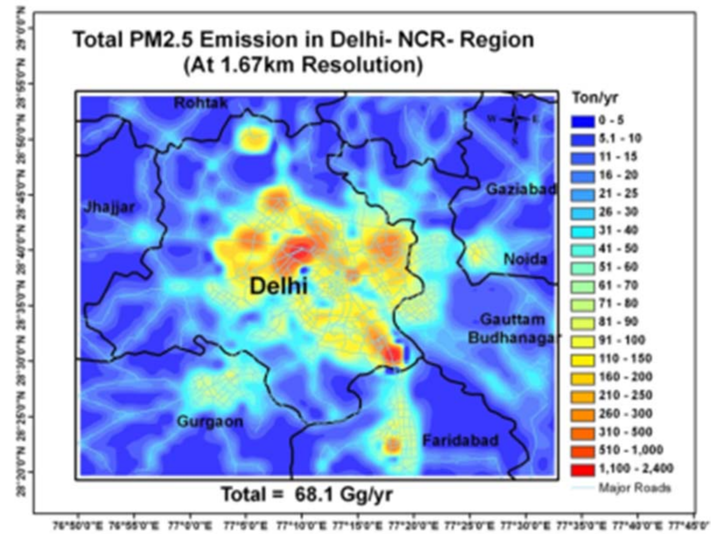




Plotted from Koch et al, 2009

Improving Predictions through Developing and Evaluating New Emission Estimates

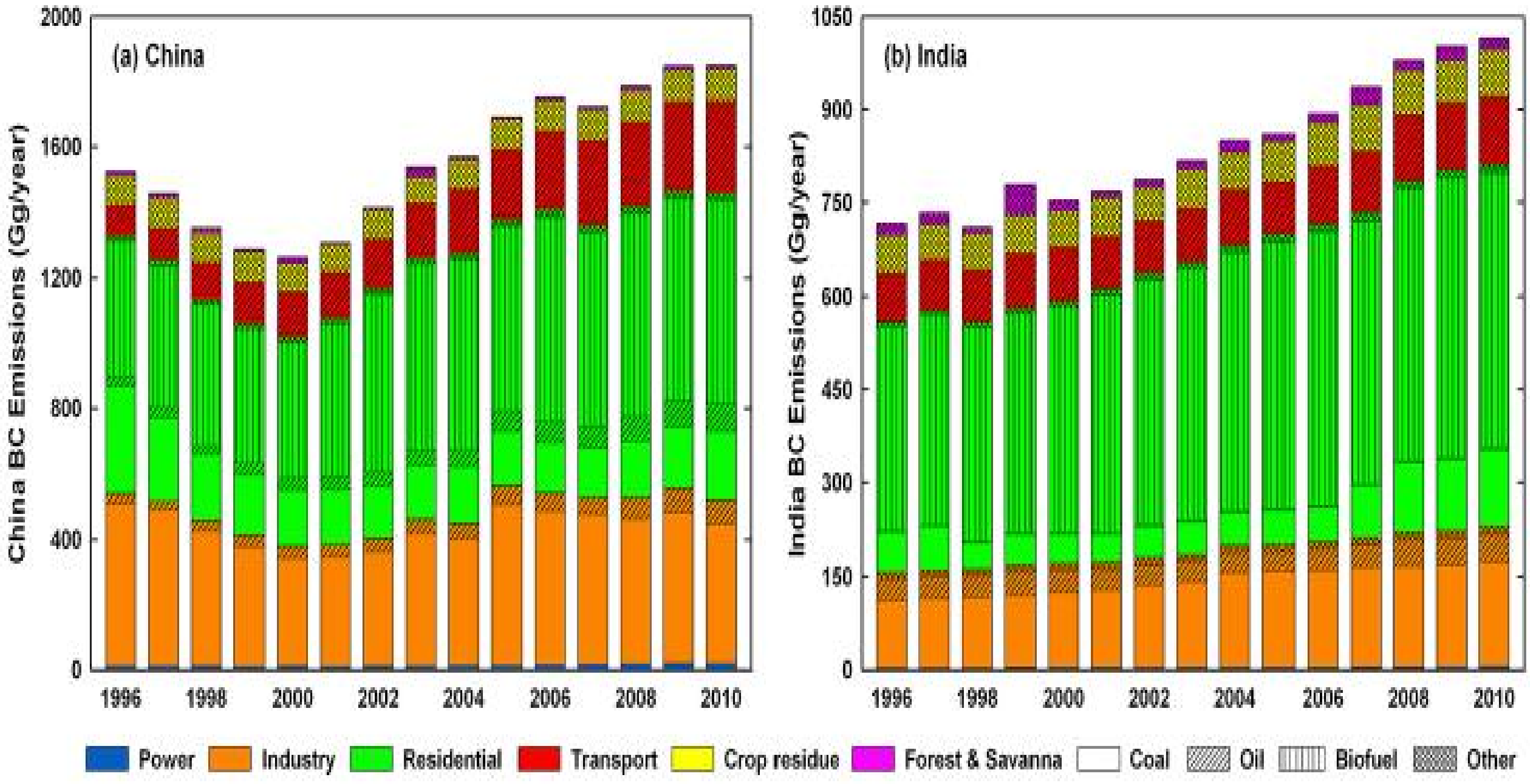




SAFAR Delhi Commonwealth Games – Beig et al.

11 new observation sites

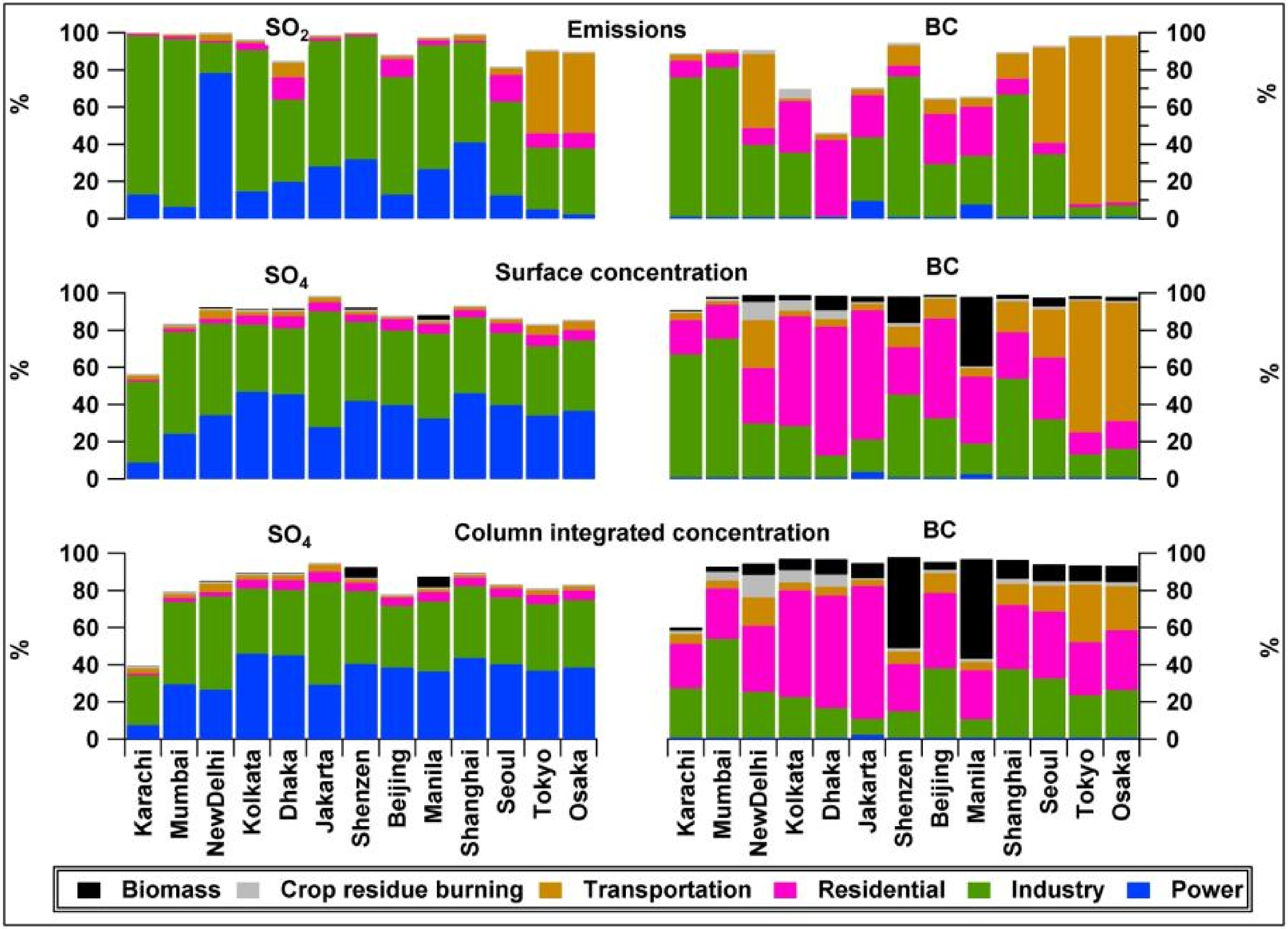
Emission Estimates by Sector & Fuels Provide Valuable Information for Impacts and Policy Analysis



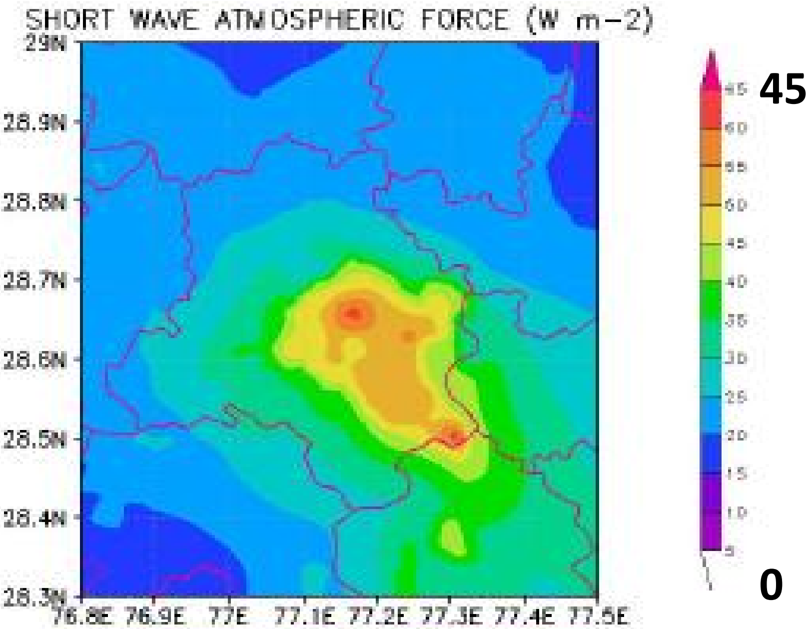
BC emissions by sector and fuel type in **(a)** China and **(b)** India during 1996–2010.

Liu et al., ACP, 2012

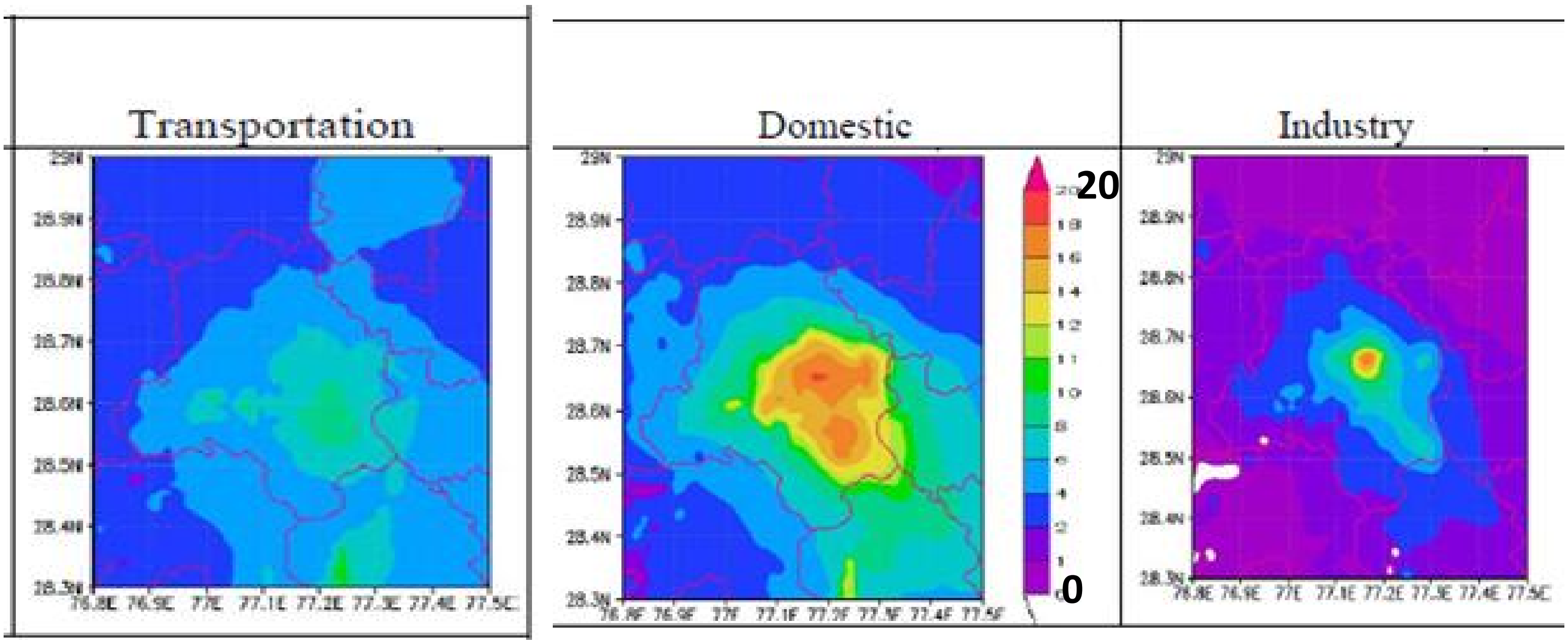
Sector Contribution in Megacities - Varies by Region & Species *(~2001)*



Anthropogenic Radiative Forcing Analysis by Sector in Delhi Shows Warming Due to Transport, Domestic and Industry - Implications for Policy



Anthro Rad Atmos Forcing (W/m²)



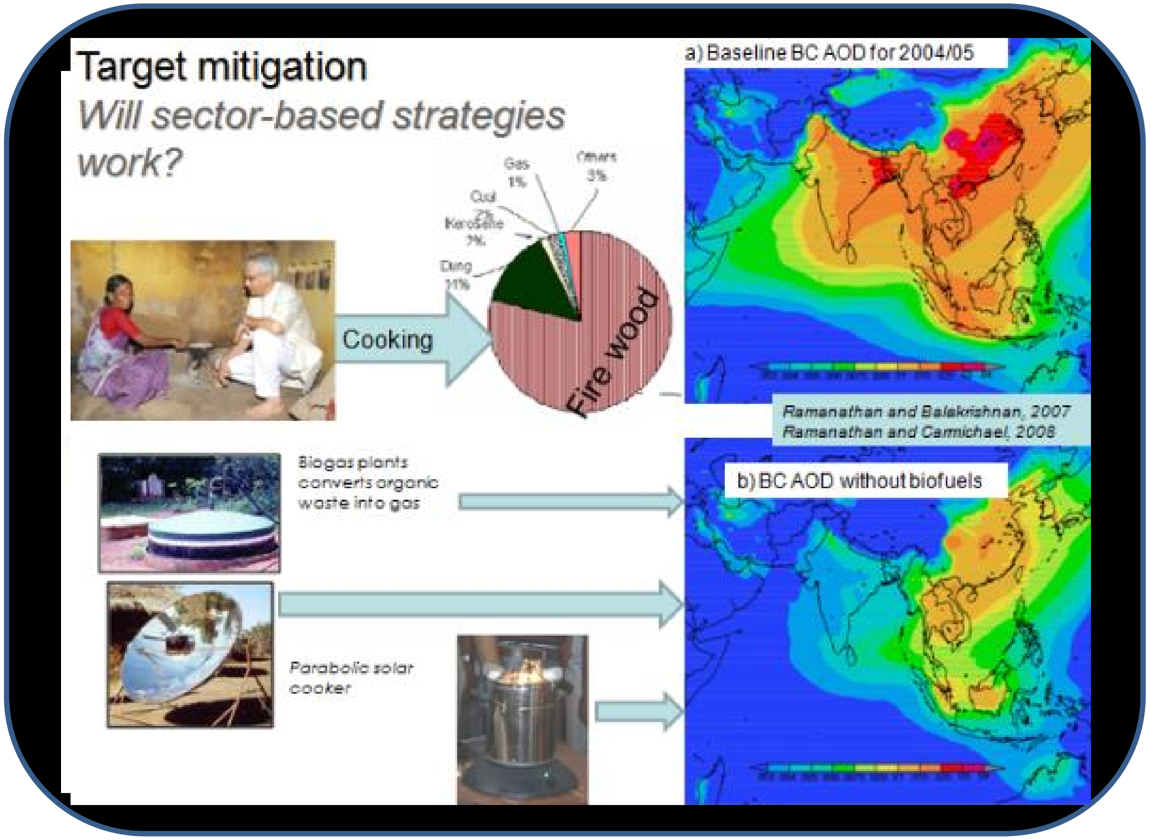
project surya
Fighting Climate Change Now

Technology: Documenting Mitigation in India -- creating a hole in the Atmospheric Brown Cloud

Climbing from the bottom of the energy pyramid

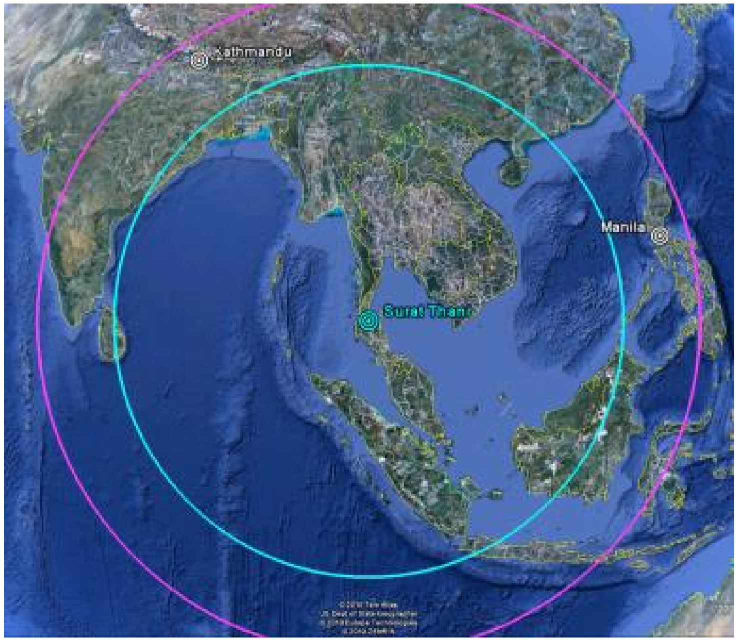
The three billion who live on less than $2 per day can not access or afford fossil fuel. Can we steer them into a sustainable Pathway and enable them to climb the energy pyramid?

Demonstration Phase: 10,000 households

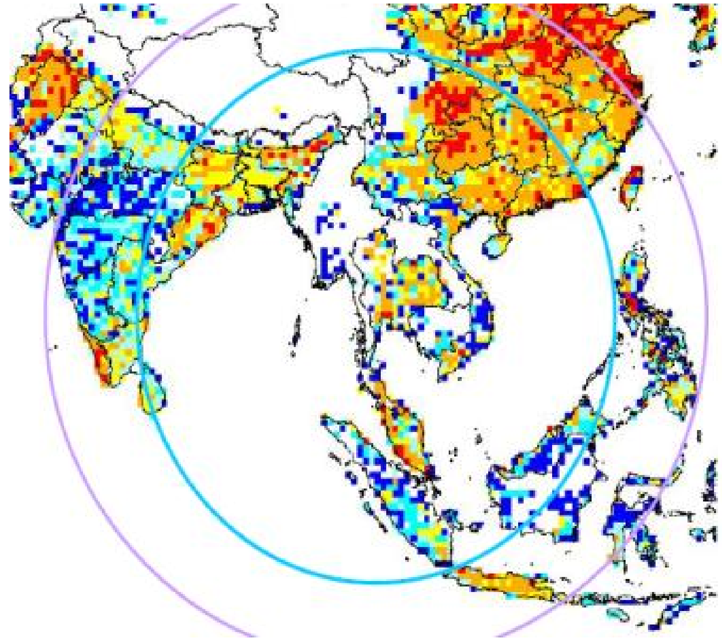


New emission inventory in support of the SEAC4RS mission (ANL)

Proposed operational flight areas



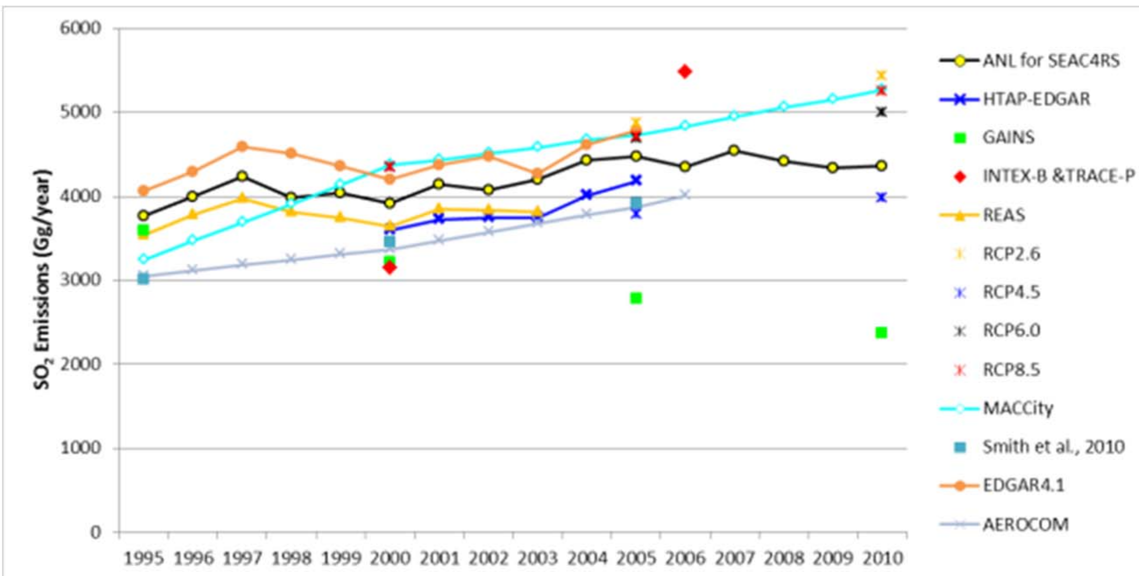
INTEX-B SO_2 EI (product example)



- Following the techniques that were used in the TRACE-P, INTEX-B, and ARCTAS missions, Argonne will support SEAC4RS by developing a new gridded emission inventory for the study region and supporting tools to enable the use of CTMs and subsequent data analysis
- Base year 2010 (or as close as possible)
- Resolution 0.1° × 0.1°
- Species gaseous: SO_2, NO_x, CO, NMVOC, CO_2?, CH_4?, NH_3?
  aerosol: PM_{10}, $PM_{2.5}$, $PM_{1.0}$, BC, OC
- Sectors Power generation, industry, residential, transportation
  Open biomass burning and help with marine emissions

Preliminary SO_2, BC, and OC emissions available now

Trend analysis and comparison with other estimates for regional SO_2 emissions (Gg/year)

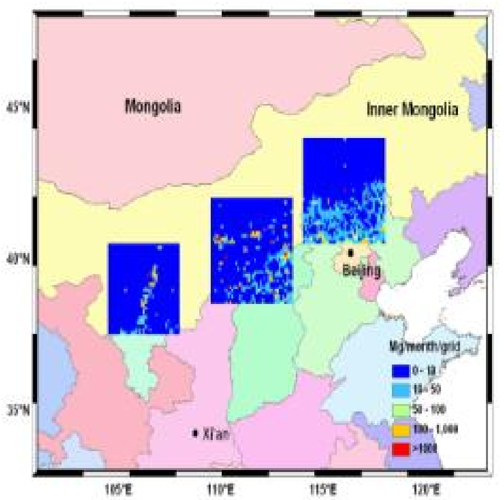


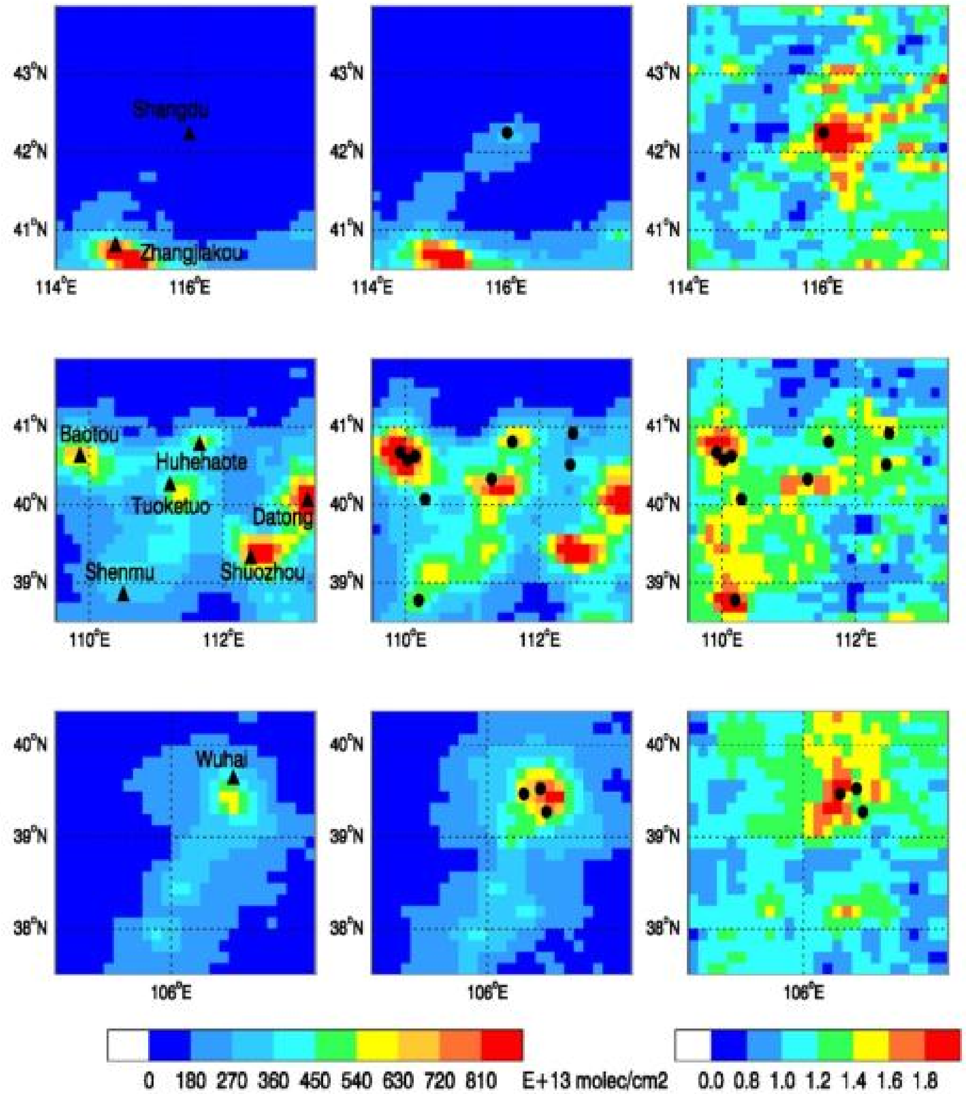
Preliminary 2010 Southeast Asian national emissions (Gg/year)

	SO_2	BC	OC
Brunei	5	0	0
Cambodia	20	11	42
Indonesia	1726	212	656
Lao	16	4	15
Malaysia	355	29	36
Myanmar	29	31	119
Philippines	770	34	77
Singapore	121	2	1
Thailand	982	66	125
Timor-Leste	2	0	1
Vietnam	338	107	330
Sum	***4365***	***496***	***1402***

* International shipping & open biomass burning not included

Opportunity: Satellites can detect enhanced NO_2 columns were observed where there were new coal-fired power plants





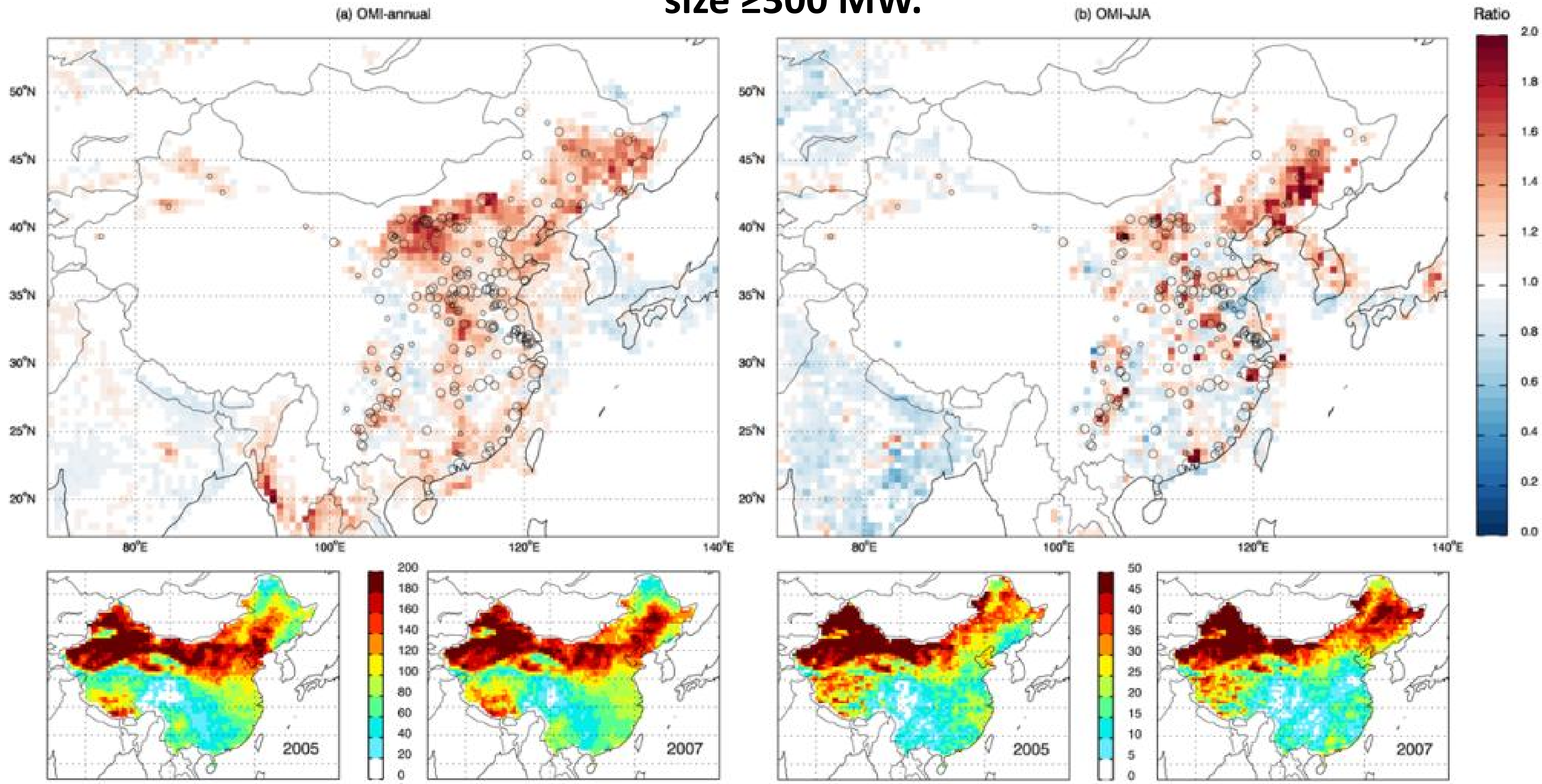
Rural area with only new plants

Urban areas with some new plants

Urban area with new and existing plants

Zhang et al., GRL, 2009

The total capacities of coal-fired power generation have increased by 49% in 2005-2007, with 92% of the total capacity additions coming from generator units with size ≥300 MW.

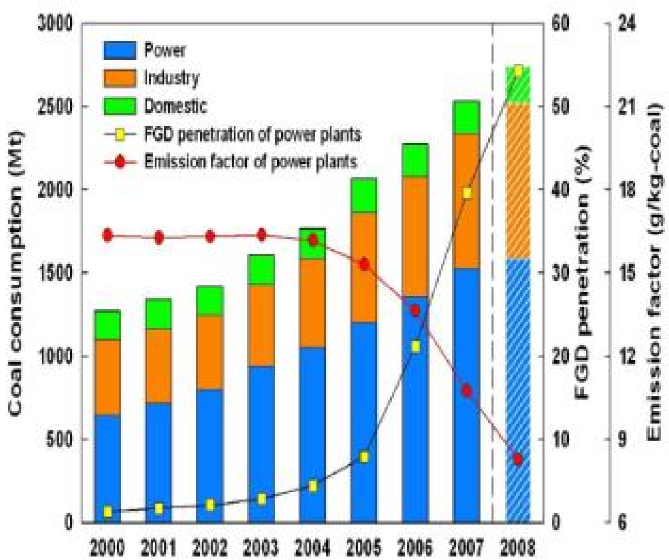


Ratios of average OMI tropospheric NO_2 columns between 2007 and 2005 using (a) annual averages and (b) summer averages.

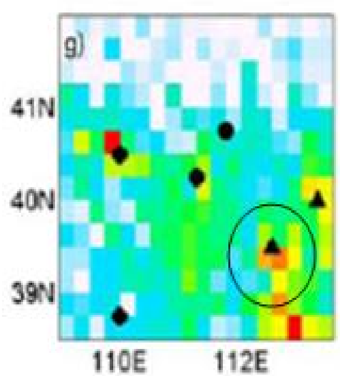
Wang et al., ACPD, 2012

Opportunity: Monitoring of Compliance with Stated Policies

Sample analysis of OMI retrievals for the Shuozhou plant



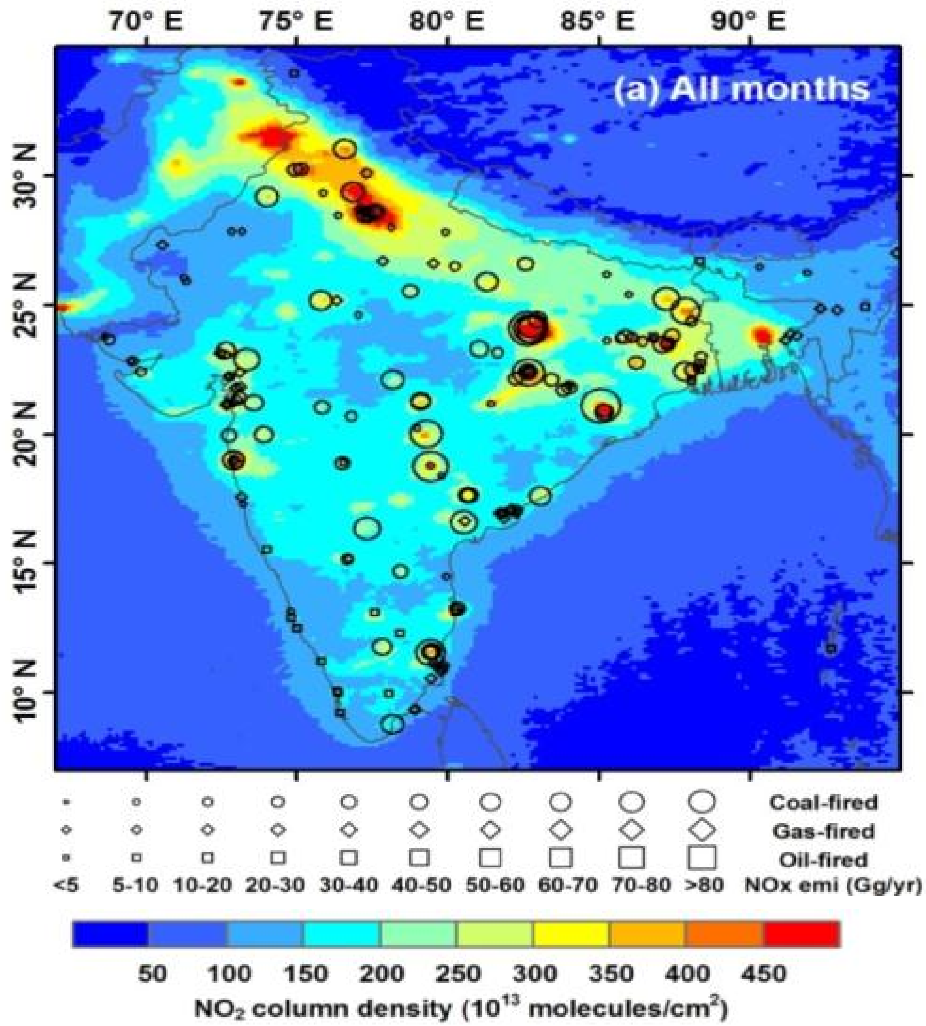
OMI SO_2 retrieval for the Shuozhou area



Analysis of SO_2 and NO_2 retrievals and emission inventories over the period 2005-2008

We conclude that the plant installed the required flue-gas desulfurization equipment in 2008 (*Li et al., GRL, 2010*).

Work Beginning For India

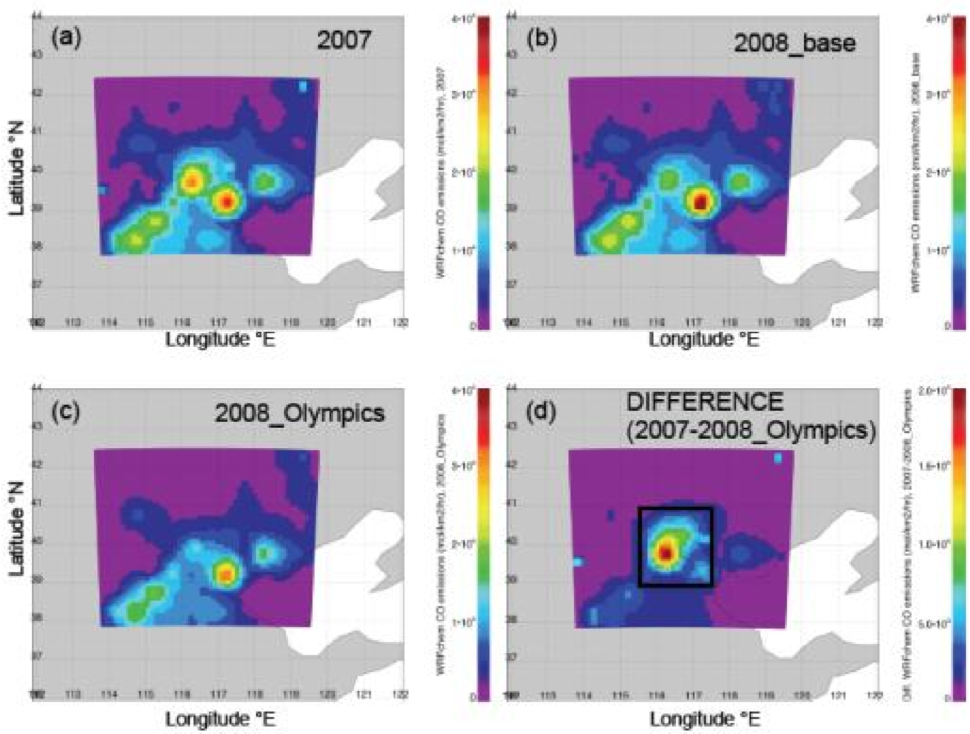


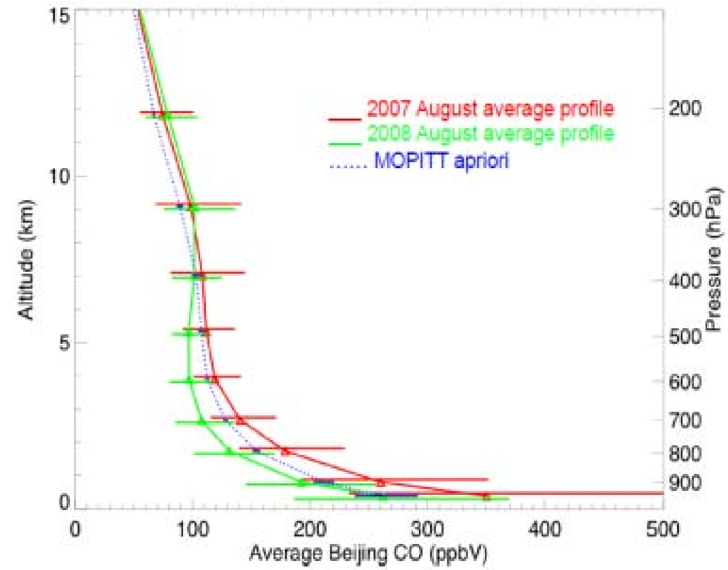
India

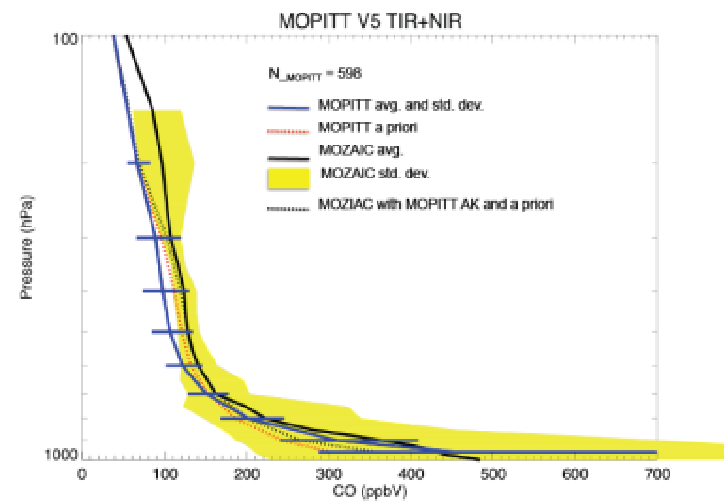
Thermal power plants NO_x emissions vs. OMI NO_2 columns

Streets et al., in progress

New MOPITT Retrievals Using TIR And IR Give More Sensitivity Near Surface



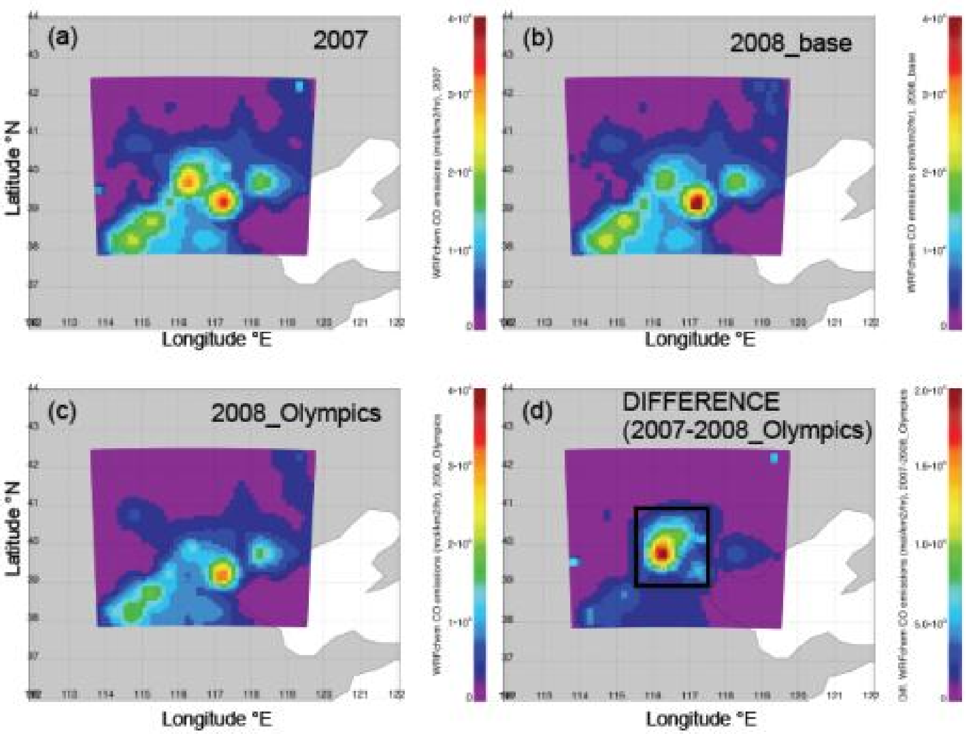




Applying a reported CO/CO_2 emission ratio for fossil fuels, we find the corresponding reduction in CO_2, 60±36 $Gg[CO_2]$/day

Worden et al., GRL, in review, 2012

New MOPITT Retrievals Using TIR And IR Give More Sensitivity Near Surface

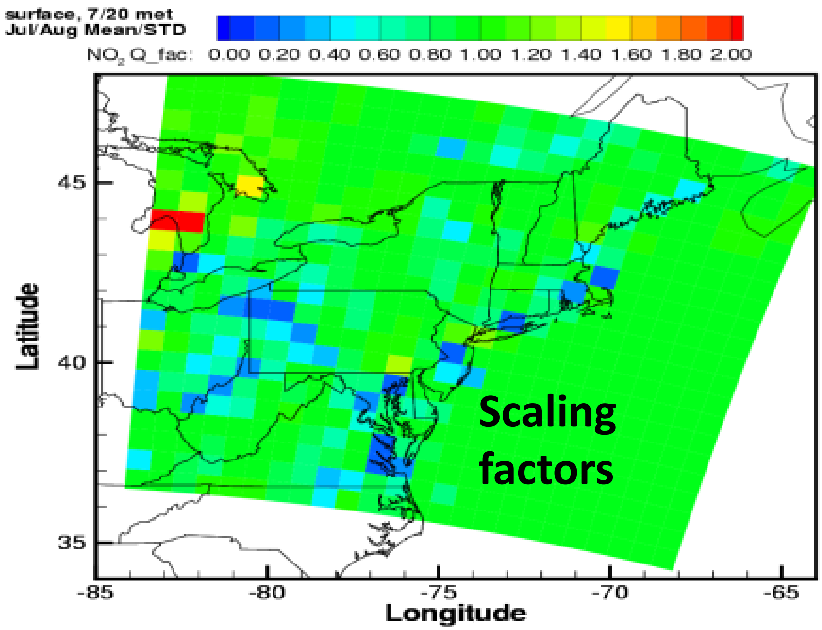


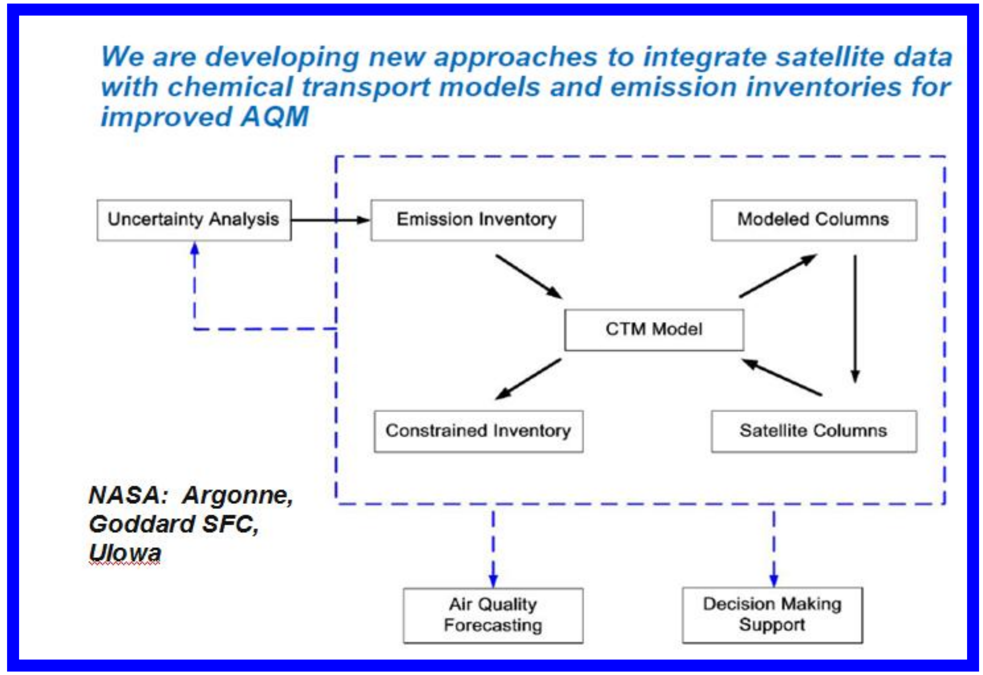
Row#	Estimate type for 39° to 41°N, 115.5° to 117.5°E	Aug. 2007 daily avg. surface layer CO Gg[CO]	Aug. 2008 daily avg. surface layer CO Gg[CO]	Δ(2007-2008) Gg[CO]
1	MOPITT (sampled 80% of area)	16.9 ± 1.1	11.5 ± 0.8	5.4 ± 1.4
2	WRF-Chem sampled[a] & AK	13.9	11.9	2.0
3	WRF-Chem sampled[a] (no AK)	18.0	14.8	3.2
4	WRF-Chem sampled[a] (no AK) for 2008 with 2007 emissions[b]		17.4	0.6
5	WRF-Chem All 29 days[c], (no AK) same grid cells as MOPITT data	17.5	14.6	2.9
6	WRF-Chem All 29 days, (no AK) all grid cells[d]	21.3	17.8	3.5
7	MOPITT estimate corrected for change due to meteorology and temporal/spatial sampling biases: 5.4 Gg x **(1 - 0.19)(1 - 0.09)(1 + 0.17) = 4.7 Gg**			4.7 ±1.4

Applying a reported CO/CO_2 emission ratio for fossil fuels, we find the corresponding reduction in CO_2, 60±36 $Gg[CO_2]$/day

Worden et al., GRL, in review, 2012

Rapid Updates of Emissions Are Needed





4D-Var setup:

Time window:

July , 2004

Control:

Initial ozone, and NOx emissions

Observations:

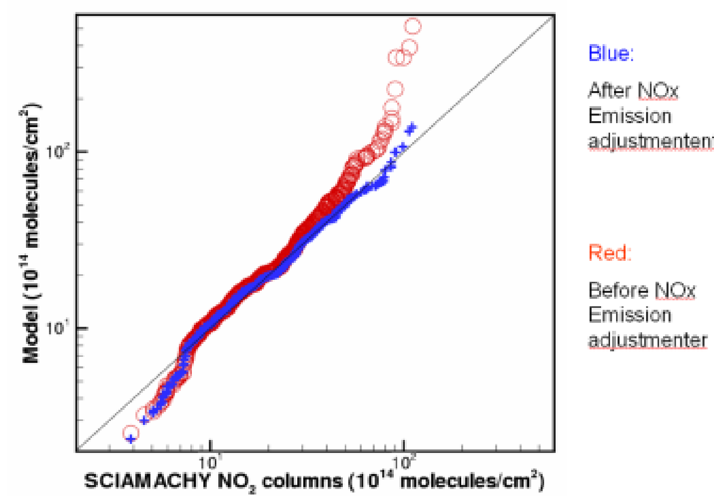
Ozone from different platforms, and SCIAMACHY tropospheric NO_2 columns

Chai et al., AE 2009

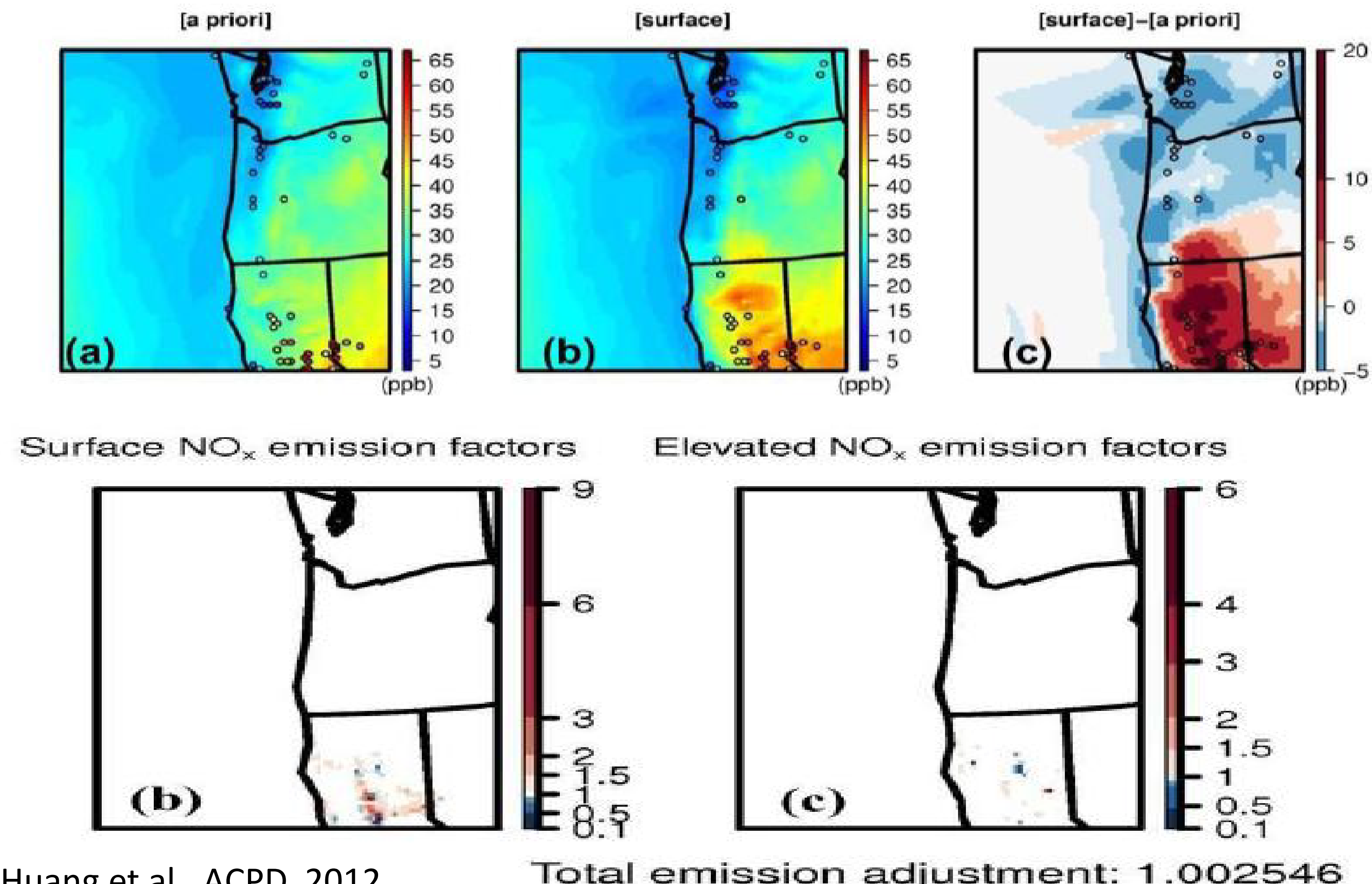
Emission changes over domain
(ratio of new emission over NEI01)

Case	Surface (level 1)	Elevated (2 & above)	Total (all levels)
1 E only	0.934	0.849	0.920
2 E & IC	0.928	0.881	0.908
"OI"	1.318	1.030	1.246

Quantile-quantile plot

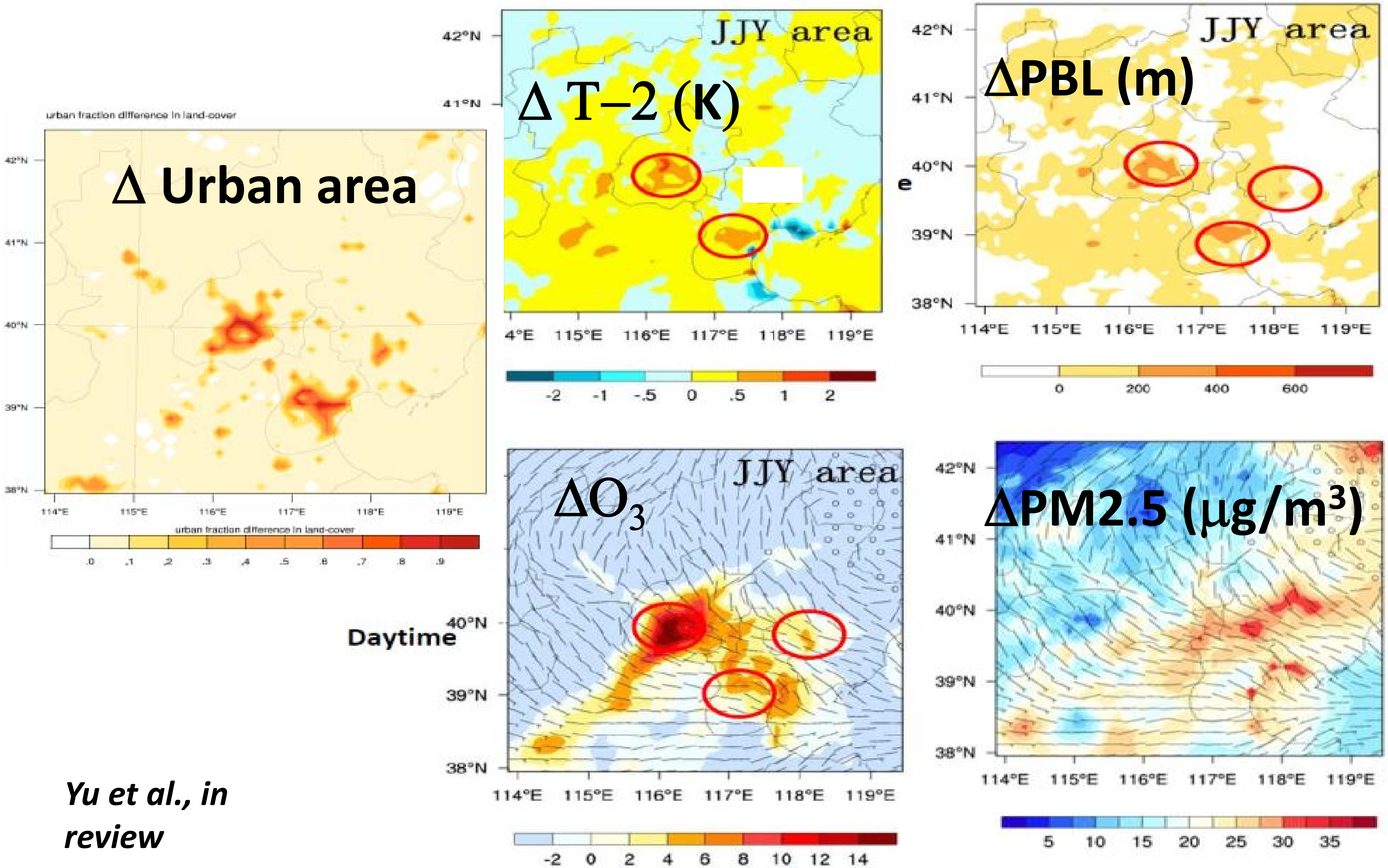


Joint Assimilation of Ozone (i.c.) and NO2 (emissions) Show Influence of Biomass Burning ARCATAS (2008)



Huang et al., ACPD, 2012

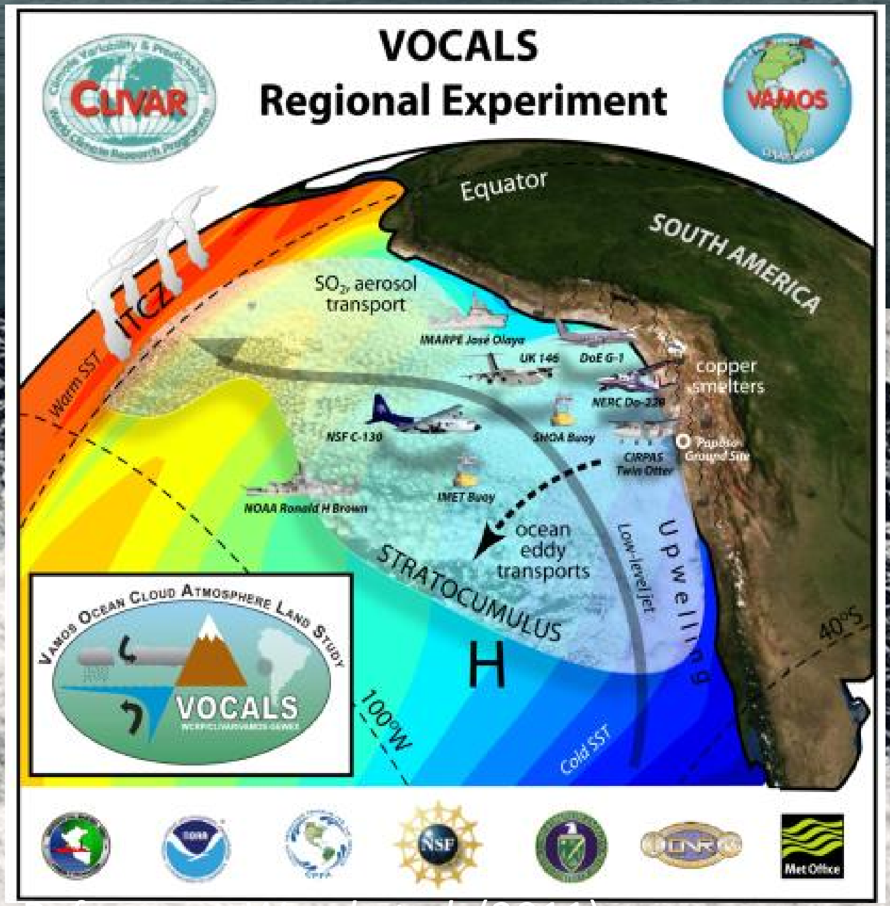
Other Physical Parameters Also Play Important Roles
- Impact of Land Use Changes



Yu et al., in review

The Southeast Pacific
A Climate and Aerosol Modeling Challenge

The world's most widespread, persistent subtropical low cloud regime.



- WRF-Chem v3.3 CBMZ-MOSAIC/MYNN/Lin
- Fine vertical resolution: 75 levels, ~60m Δz < 3km
- Long spin-up: ~3-4 days

Reference: *Wood et al.* (2011)

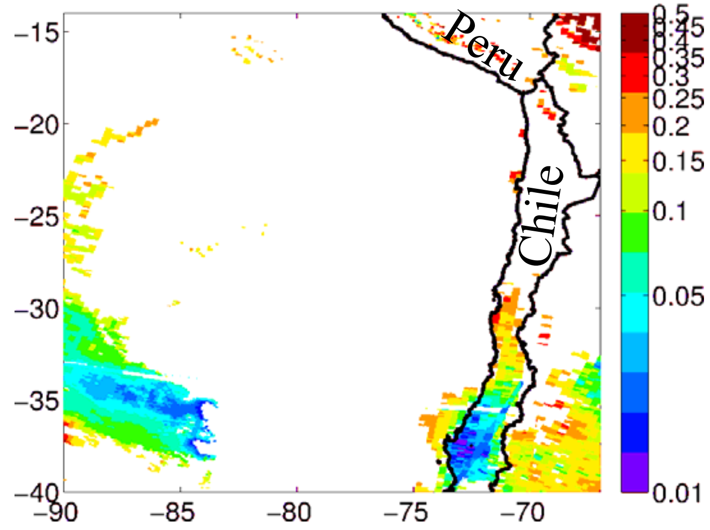
Challenge

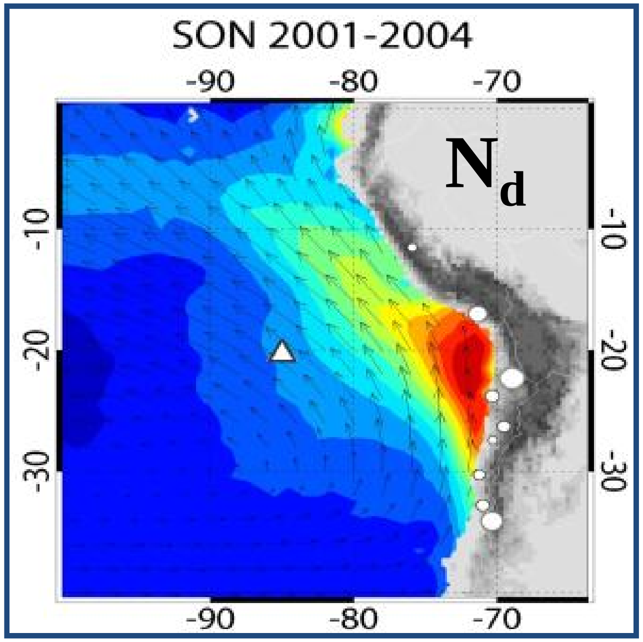
In cloudy regions there is little AOD information – also it provides limited info on size/composition

Idea:

Can we use the cloud retrievals to improve sub-cloud aerosol distributions?

MODIS Terra AOD off Chile & Peru

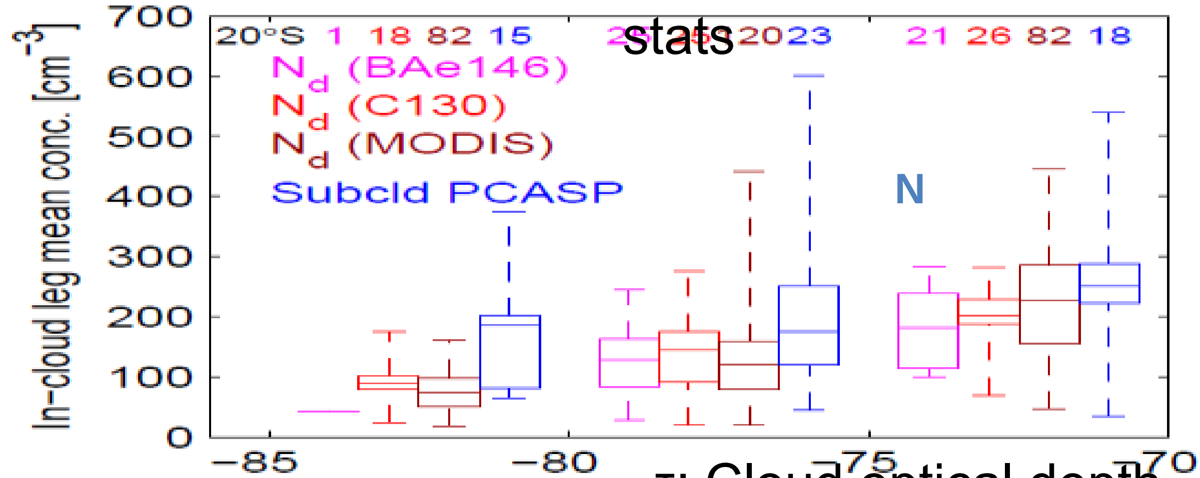




Idea

- **SEP marine Sc N_d satellite retrievals show evidence of aerosol load and agree with observations**
- **Aerosol indirect effects simulated with some skill in WRF-Chem**
- **Hypothesis: variational assimilation with N_d retrievals can improve below-cloud aerosols in models** ***(see aerosols through clouds)***

20º S VOCALS-REx stats



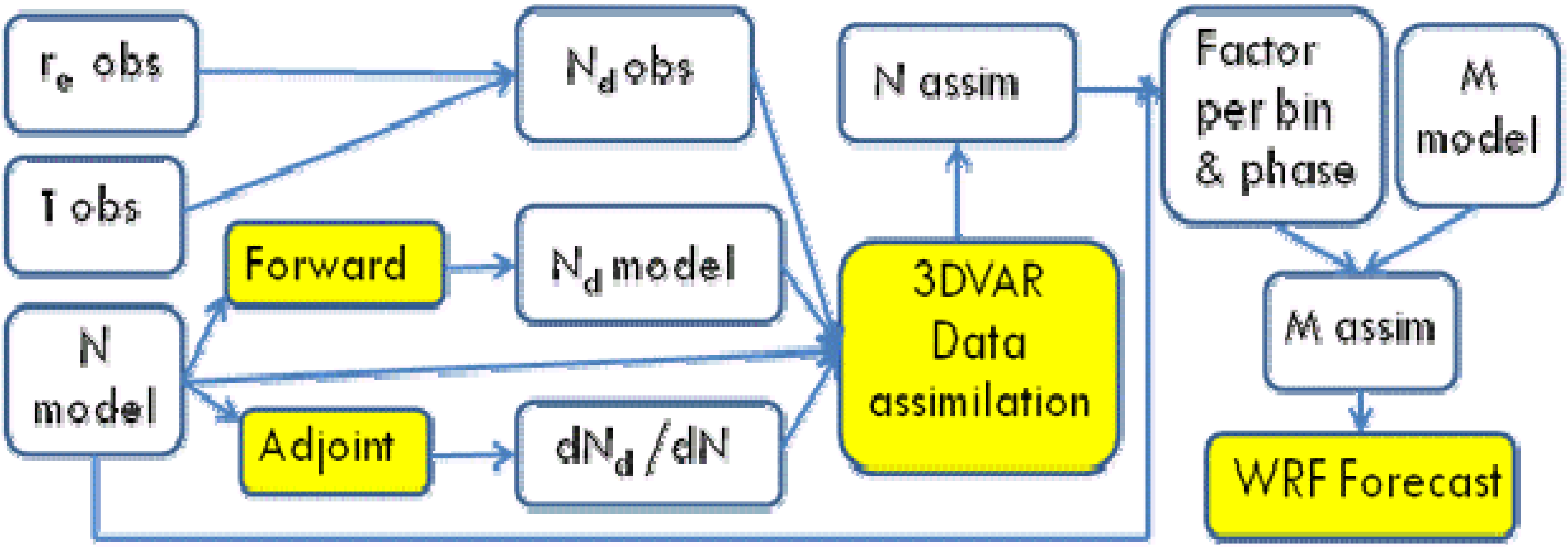
$$N_d = K\tau^{1/2} r_e^{-5/2}$$

τ: Cloud optical depth
r_e: Cloud effective radius
N_d: Cloud droplet #
N: Aerosol #conc.

Refs: Saide et al. (2012), Bretherton et al.(2010), Painemal and Zuidema

Improve 'aerosol': data assimilation

3DVAR data assimilation method to improve **below-cloud** accumulation aerosol using cloud retrievals

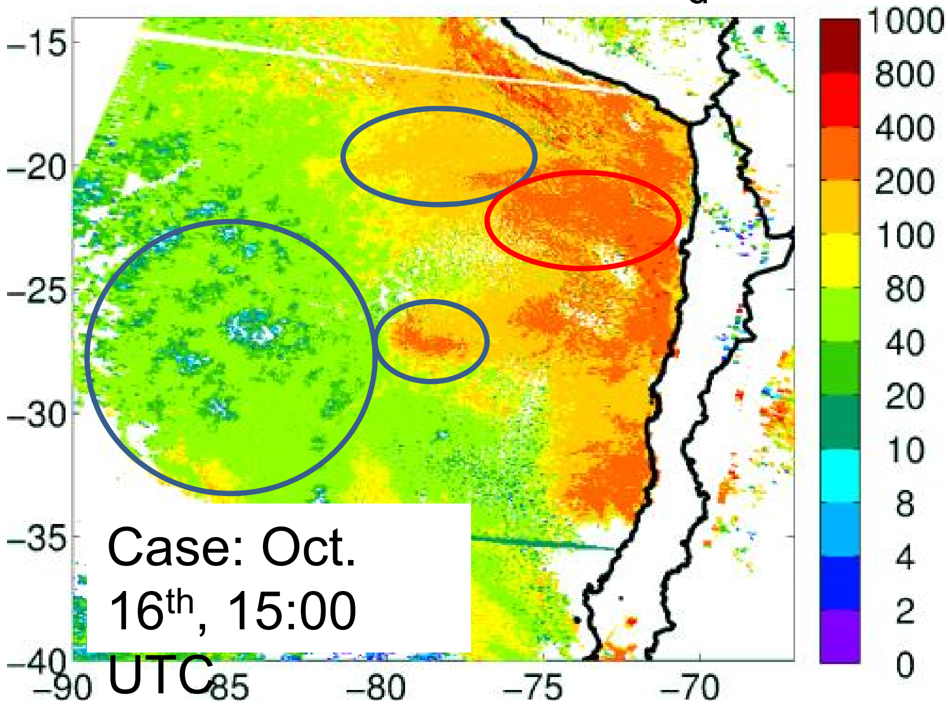


- Sensitivities computed using the adjoint of the WRF-Chem mix-activation routine obtained with TAPENADE (WRF-Chem adjoint)
- 3DVAR assimilation using lognormal errors for different scales

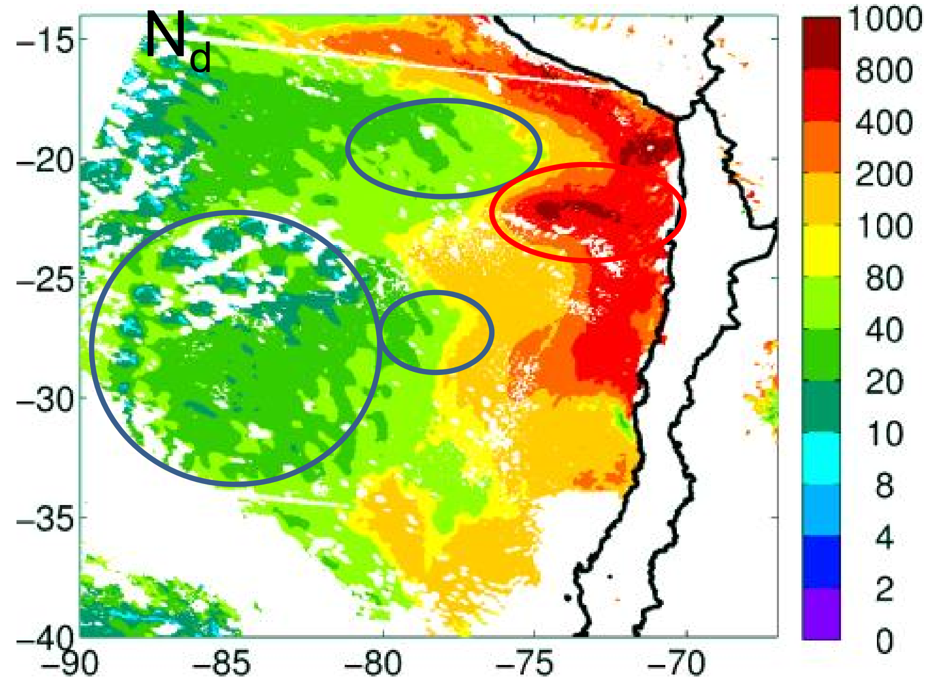
Case Study: Southeast Pacific during VOCALS REx

- Assimilate extensive stratocumulus cloud deck
- Coastal higher Nd, remote zone with lower Nd

MODIS Terra N_d

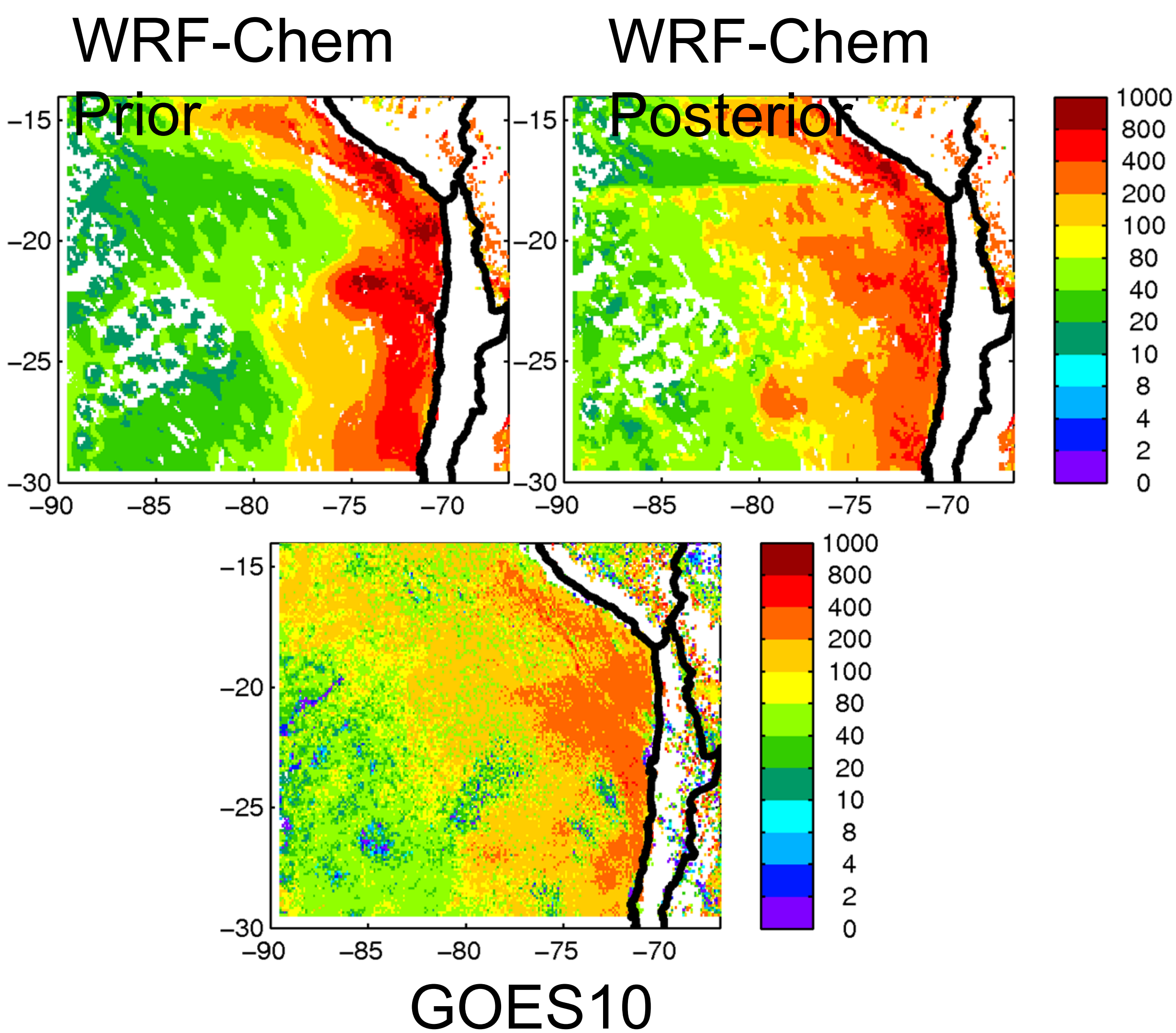


Base WRF-Chem N_d



Impact of Assimilation of MODIS Cloud Info

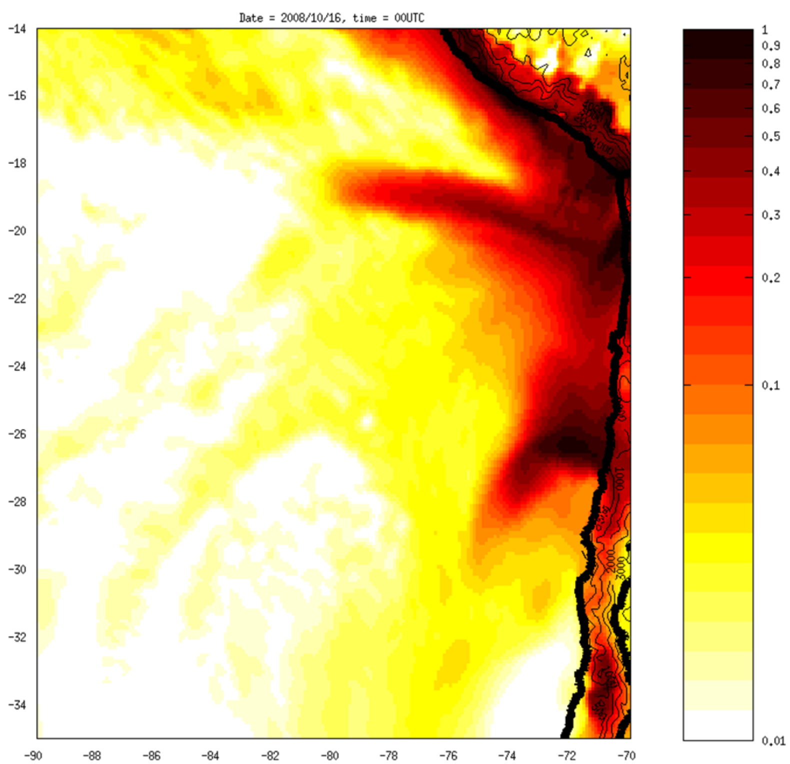
- Large consistent improvements during the first 24 hours



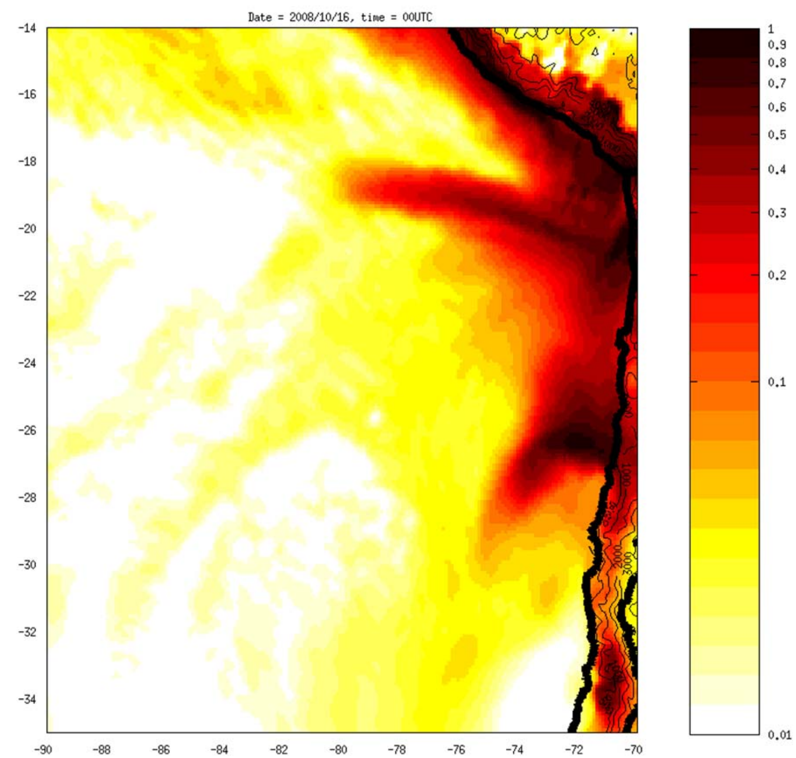
Assimilation results: + & - biases reduced

- Surface level SO4 dry mass (kg/kg), bin 2 of 8 (78-156 nm d)
- Single Assimilation at Oct 16th 15Z, forecast shown from Oct 16th 00Z to 18th 00Z

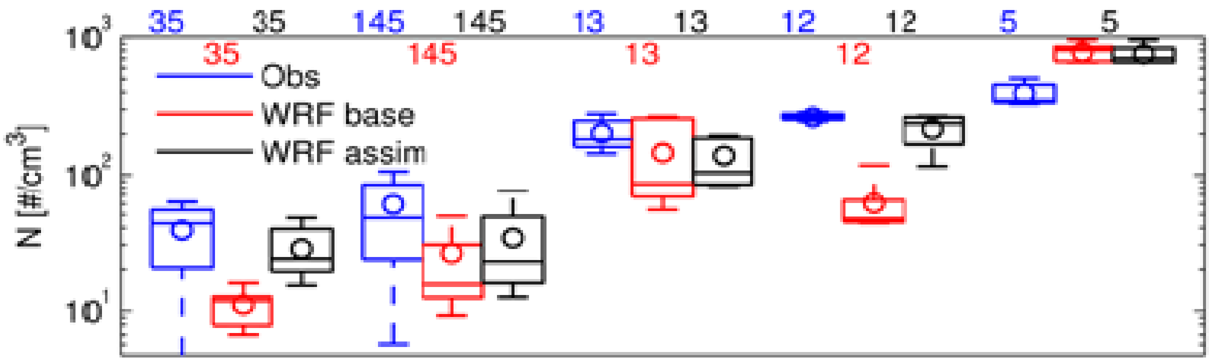
WRF-Chem Prior

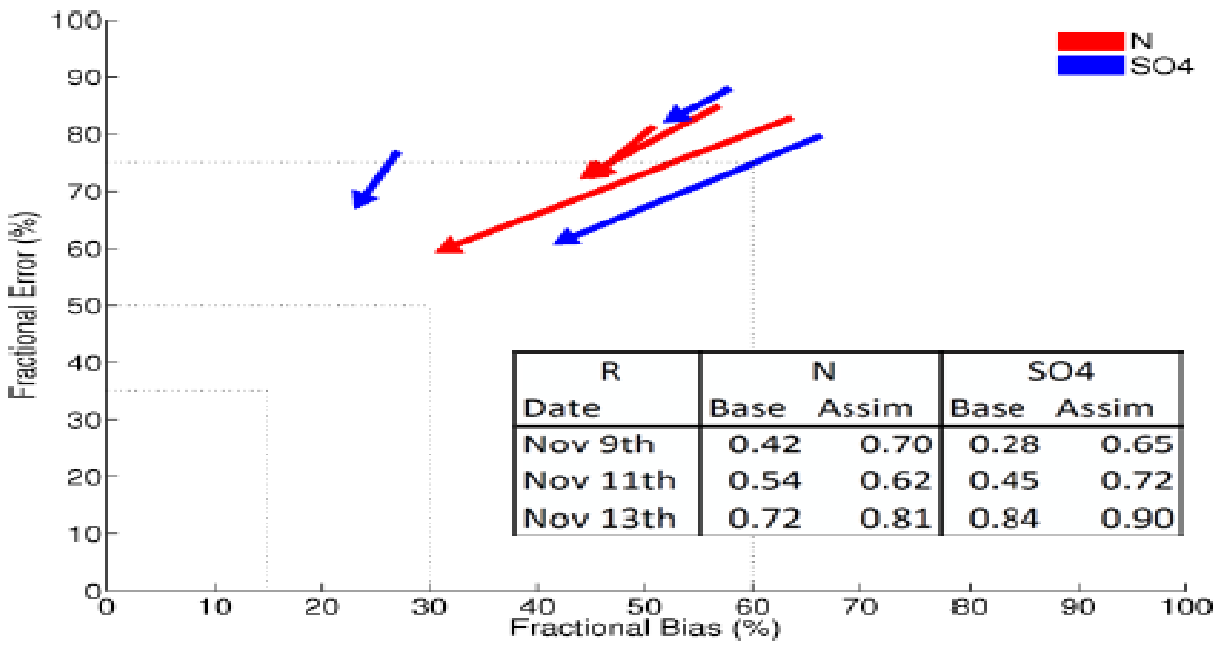


WRF-Chem Posterior



Assimilation improves aerosol number and composition!

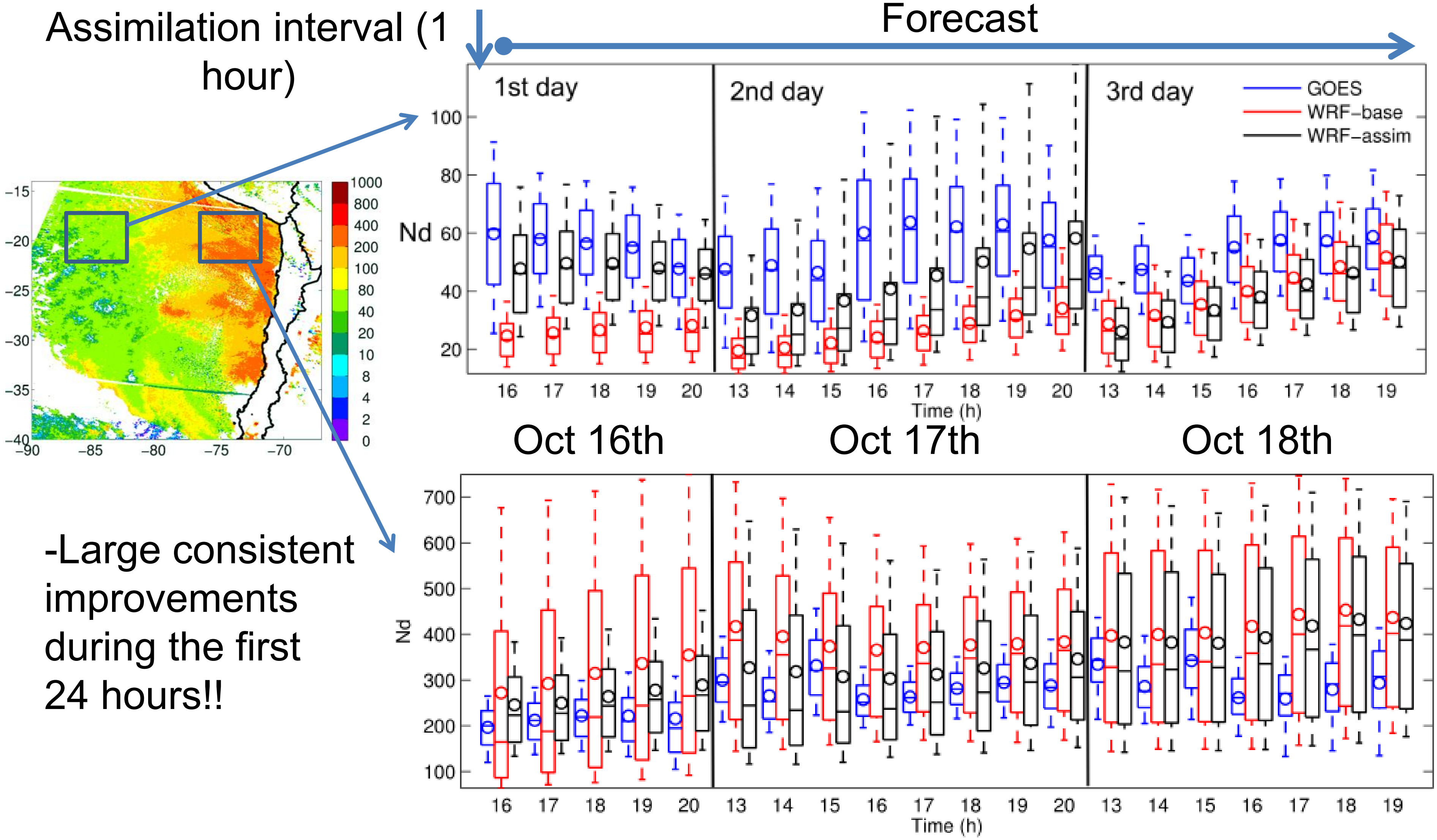




N_d improvement quantified vs. GOES10 5°x 5° coastal & offshore averages

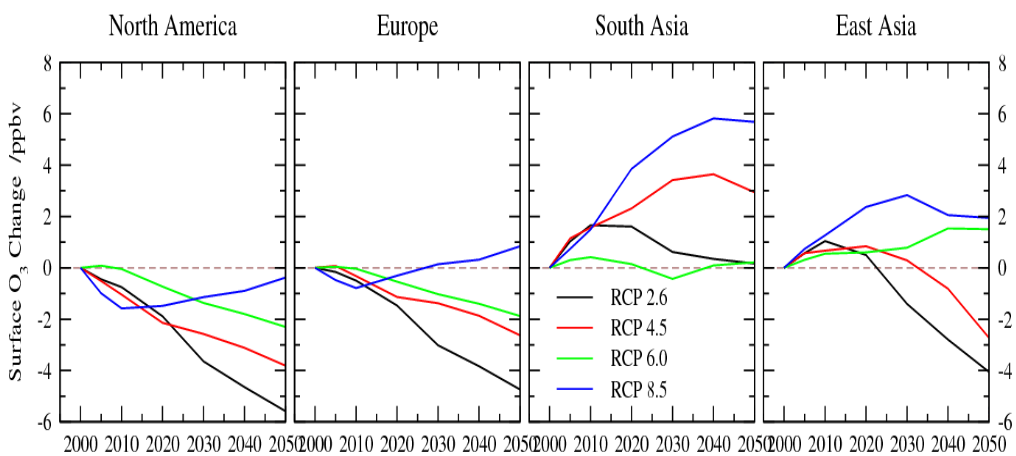
Assimilation interval (1 hour)

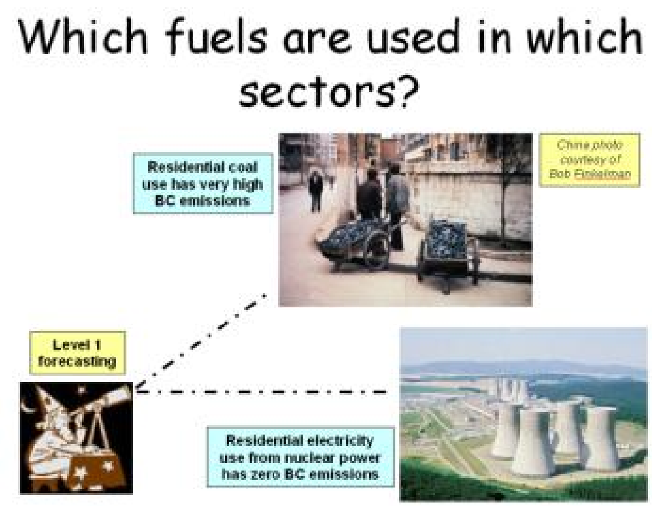
Forecast



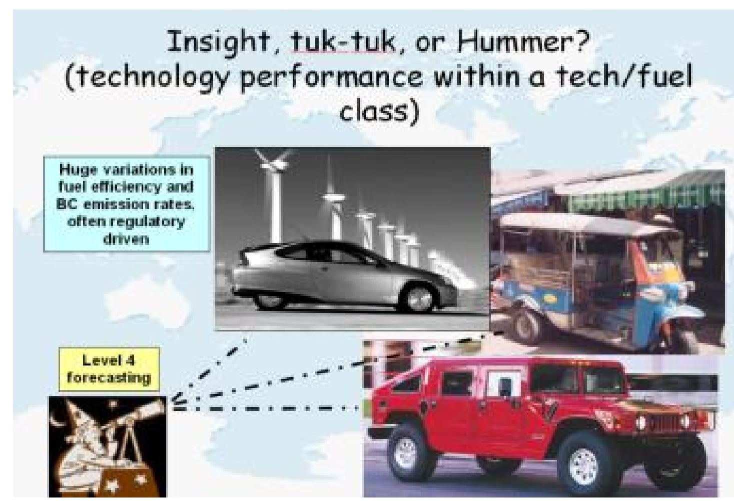
-Large consistent improvements during the first 24 hours!!

Effects of Future Emission Changes



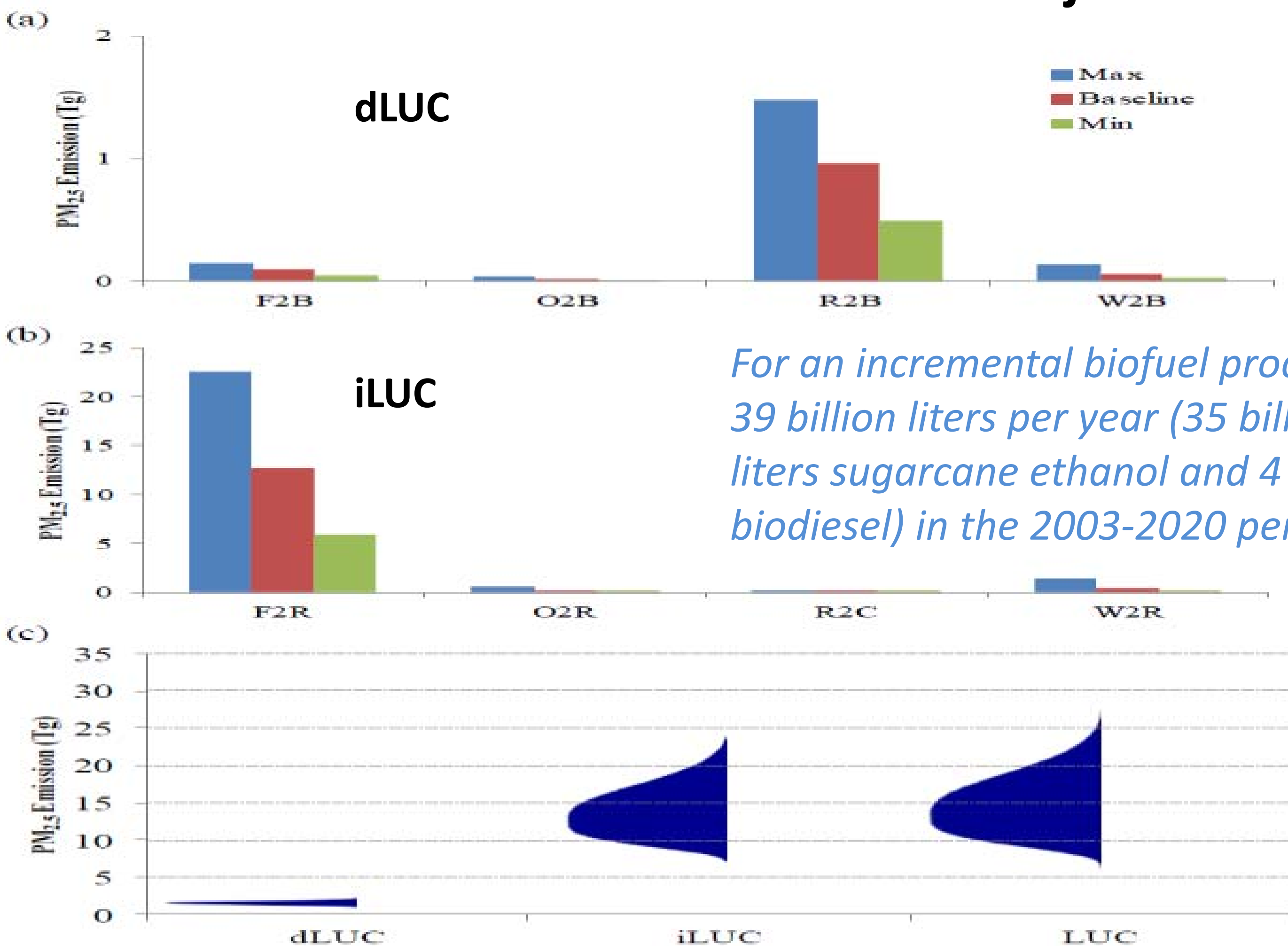


- Anticipated changes in annual mean surface ozone
  - Base on the four RCP scenarios constructed for IPCC-AR5
  - Derive from 6 global models (using linear assumption)
- Findings
  - Big increases of O_3 in Asia matching regional development
  - Relative importance of "imported" O_3 doubles for N.America/Europe
  - Changes in CH_4 make a major contribution to observed O_3 changes



HTAP 2010

Life Cycle Emissions Due to Land Cover Changes Need To Be Considered in Emission Projections



*For an incremental biofuel production scenario of 39 billion liters per year (35 billion liters sugarcane ethanol and 4 billion liters soy biodiesel) in the 2003-2020 period for **Brazil.***

Figure 2. LUC emissions including maximum, baseline, and minimum values, and the distribution of estimates for dLUC, iLUC, and the total LUC emissions. (a) dLUC emissions include emissions from forest to biofuel (F2B), cropland to biofuel (C2B), ranchland to biofuel (R2B), woody savanna to biofuel (W2B), and other vegetation to biofuel. (O2B). (b) iLUC emissions include emissions

Tsao et al., EST in review, 2012

Spatial Distribution of Emissions

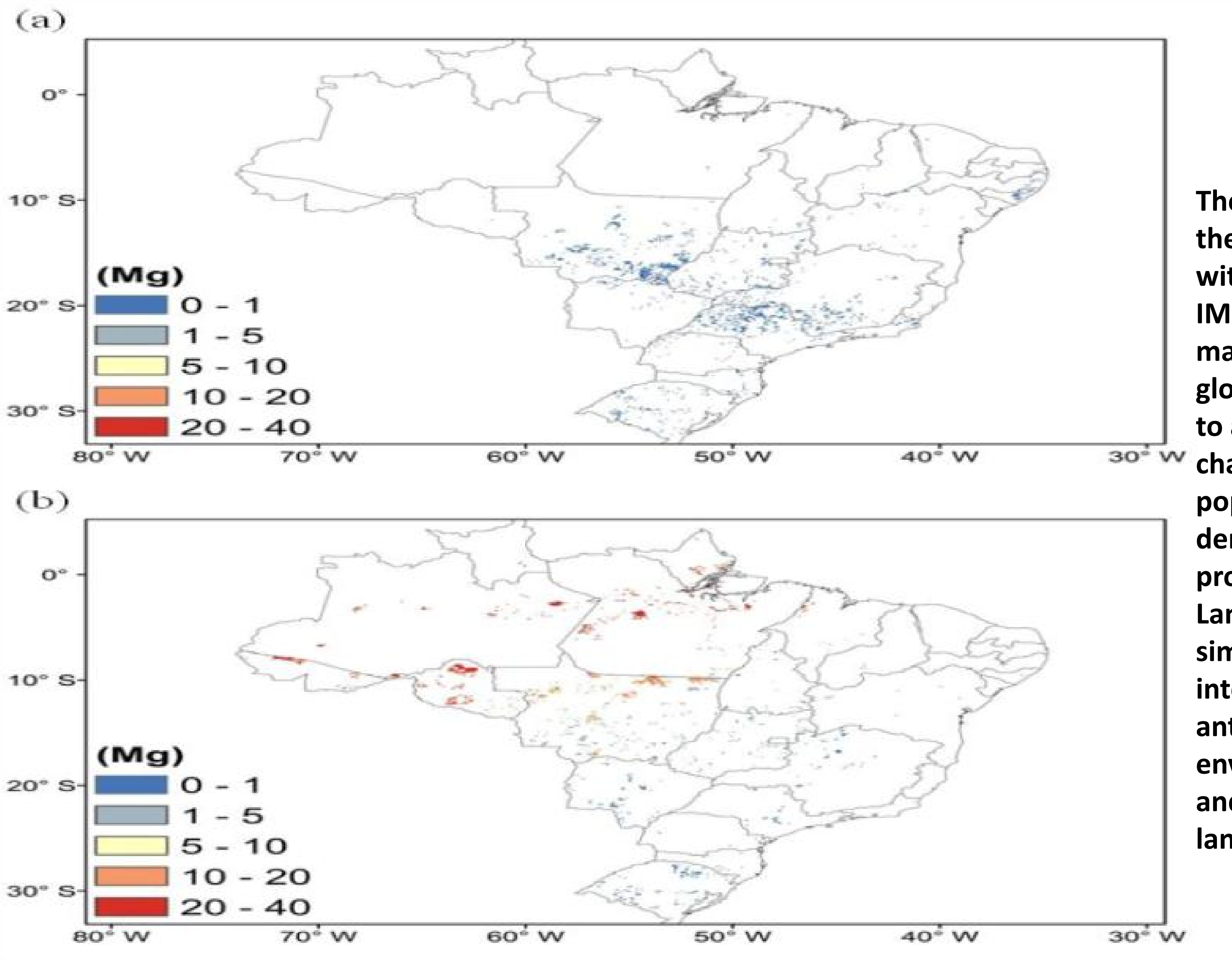
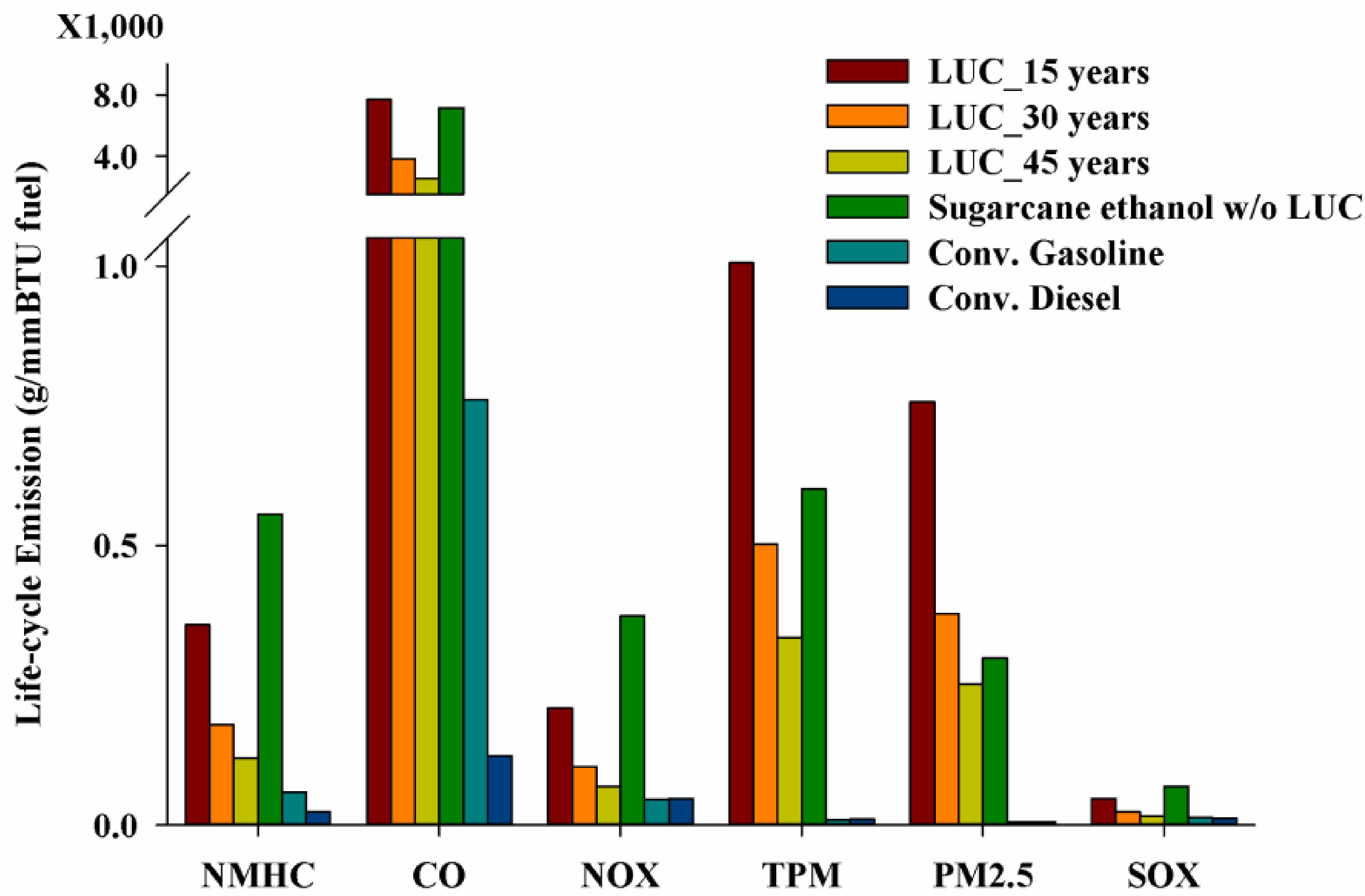


Figure 4. Spatial distribution of $PM_{2.5}$ emission from LUC including (a) dLUC; (b) iLUC

The framework couples the LandSHIFT model with two other models, IMPACT) and LPJ for managed and dynamic global vegetation model, to account for future changes in crop yield, population, food demand, and biomass productivity. The LandShift model simulates the interactions between anthropogenic and environmental drivers and their competition for land resources.

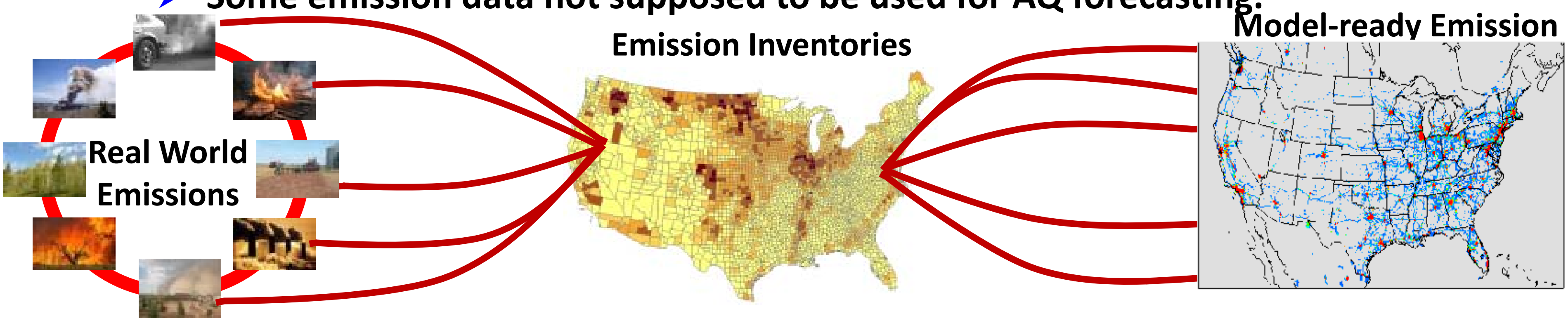


Life-cycle emissions of conventional fossil fuels Compared to 0.005 g (x1000)PM2.5 emitted per mmBTU fuel for both conventional gasoline and diesel).

Limitations of Inventory-Based Approach for AQ/CW Modeling

- **Emission inventories are costly and time-consuming**
  - **Emission Inventories always 2 – 10 years old.**
  - **Frequency of updates driven by regulatory needs, not forecasting needs;**
  - **Large gap between forecasting need and data availability;**

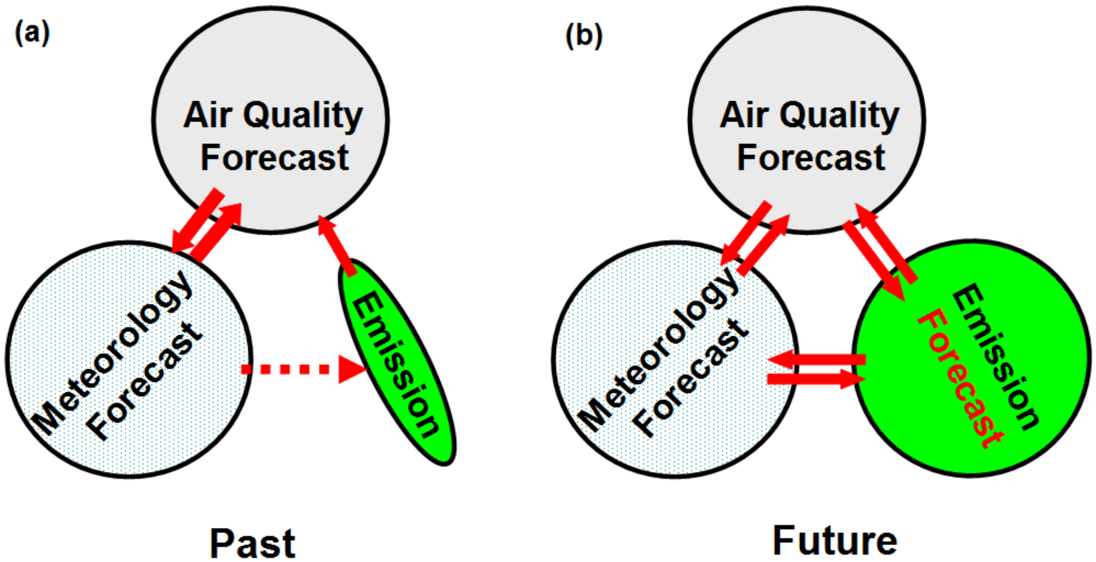
- **Lack of understanding of emission uncertainties**
  - **Information lost when compiling emission inventories;**
  - **Reconstructing such information (e.g.,using SMOKE) introduces extra uncertainties;**
  - **Some emission data not supposed to be used for AQ forecasting.**



Tong et al., IWAQF, 2011

How to Move towards Emission Forecasting?

- **Stage I. Emission activity and process modeling:**
  Reproducing emission inventory data through emission modeling;
  - **Careful review of emission inventory documentation;**
  - **Develop emission models to reproduce emission data;**
- **Stage II. Improving emissions through incorporation of near-real-time data;**
- **Stage III. New emission algorithms and parameterization;**
- **Stage IV. Emission-Meteorology-Air Quality three way coupling;**



Tong et al., IWAQF, 2011

Benefits of Emission Forecasting

- **Capability to forecast emissions of tomorrow;**
- **Bring new emission sources into the domain:**
  - **Wildfires (M. Prank; J. Chen; P. Lee; J. Vaughan);**
  - **Marine isoprene (M. Wang);**
  - **Windblown dust (X. Zhang; M. Cope; D. Tong);**
  - **Lightning (D. Allen);**
  - **Pollen (M. Sofiev);**
  - **Volcanic emission (S. Lu);**
- **Increased transparency of emission data generation:**
  - **Transparency along the data flow from input data to emission algorithm to model-ready emissions;**
  - **Traceability of uncertainties and their propagation;**
  - **Scientifically measureable improvements (data, algorithms, or parameterization);**
- **Less expensive way to update emission inventories;**
- **Increased flexibility for forecasters and air quality managers;**

Tong et al., IWAQF, 2011

MICS-III - Plans

Three topics will be covered

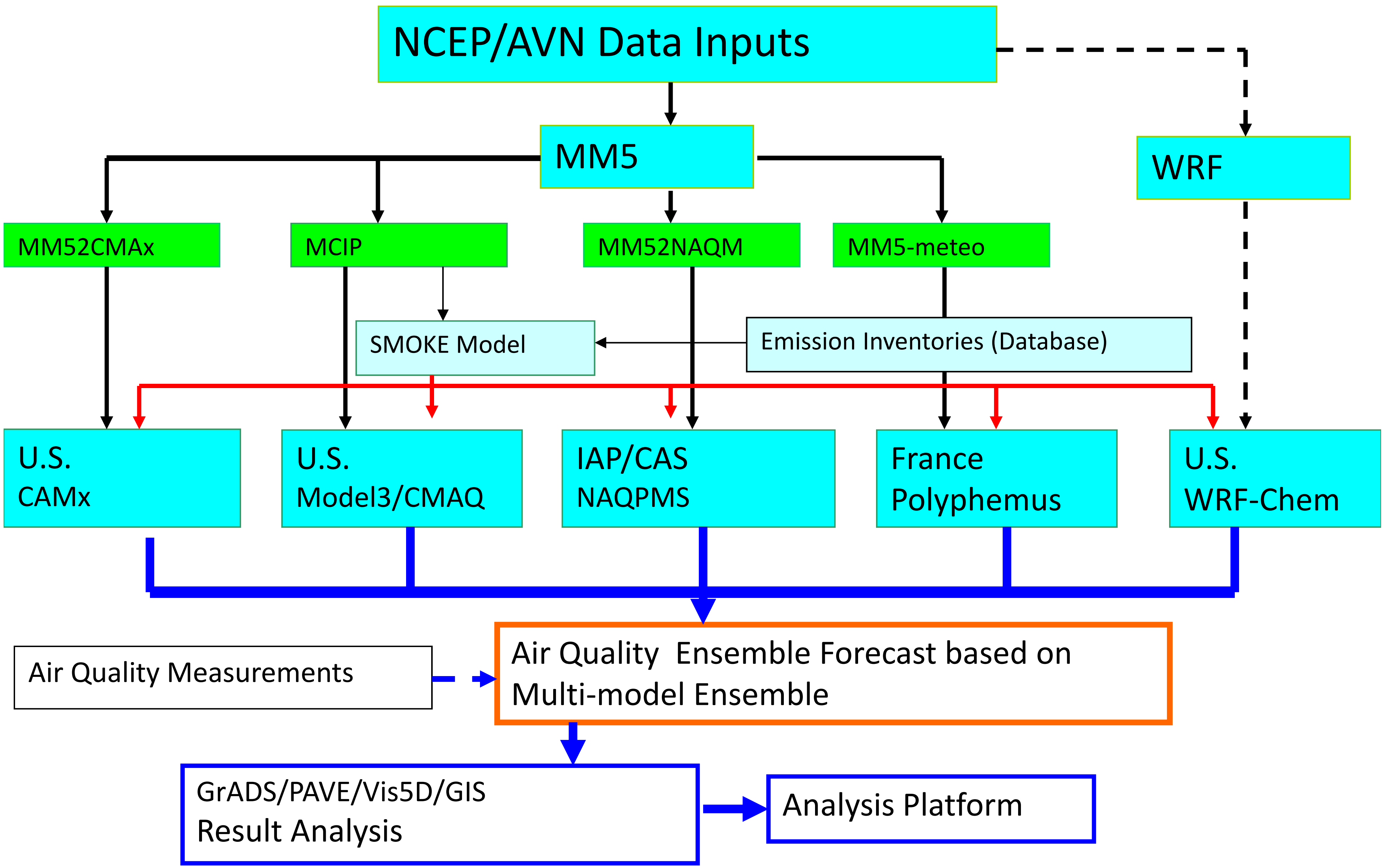
- **Multiscale Model Intercomparison -** To evaluate strengths and weaknesses of current multiscale air quality models for air quality prediction and assessments and provide techniques to reduce uncertainty and improve performance in Asia.
- **Emissions Intercomparison** - Understand present status of anthropogenic emission inventories in Asia by inter-comparison of bottom-up emission inventories and top-down estimates.
- **Air quality/climate -** Link emissions to SLCF (Aerosols & O_3) distributions and subsequent radiative/"climate" effects.

Observations: EANET, National data, special events (Asian & Commonwealth Games, ...)

Participants – expected to be > 20 based on two recent workshops

Announcement/Launch – spring/summer 2012

Design of Emsemble Model System



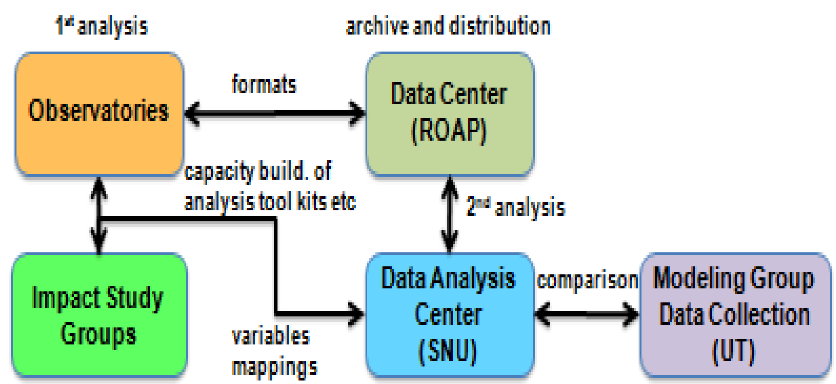
Organization Structure

MICS-Asia ⇄ ABC-Asia

New Modeling Center IAP/ACAP

(Beijing)

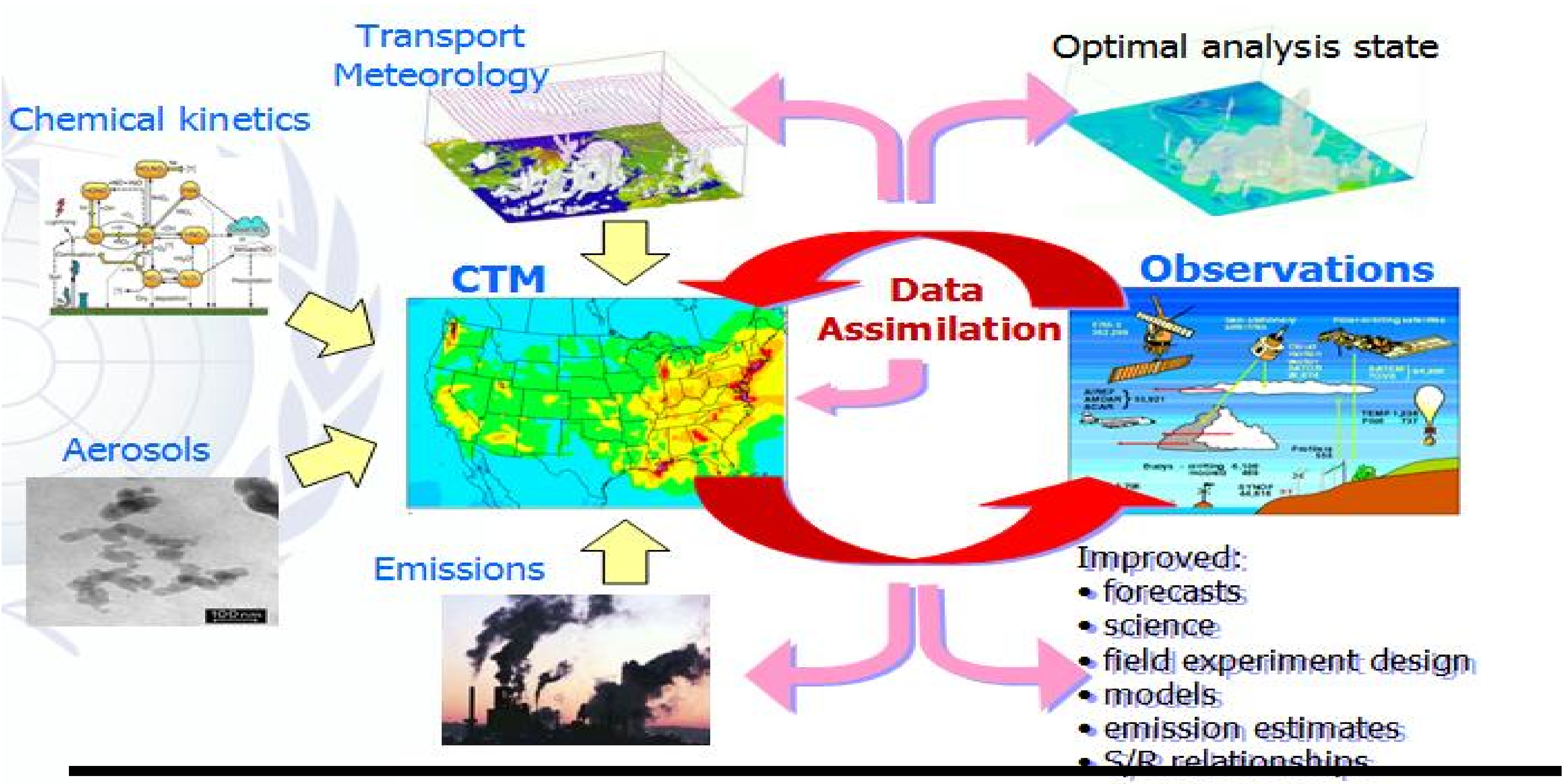
MICS-III



ABC-Asia analysis flow

Coordination with: HTAP, ...

Challenge: Achieving A Closer Integration Of Observations And Models



+ Need to Integrated Air Quality & Met. Model assimilation systems

+ New requirements for NRT data, observing systems, and assimilation systems for chemical applications!!