Constraining urban-to-global scale estimates of black carbon distributions, sources, regional climate impacts, and co-benefit metrics with advanced coupled dynamic - chemical transport - adjoint models

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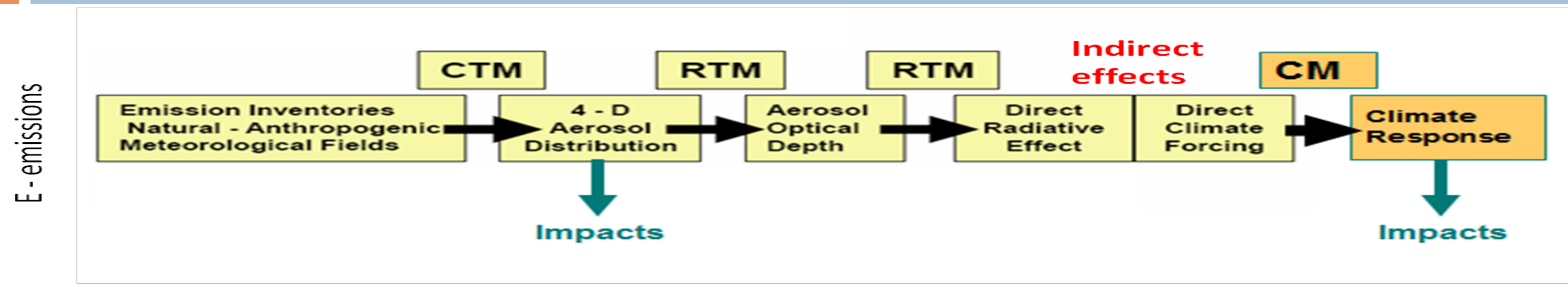
NOAA: Georg Grell*

**supported by EPA STAR BC*

Large uncertainties in linking emissions of BC and other SLCF agents to impacts across scales

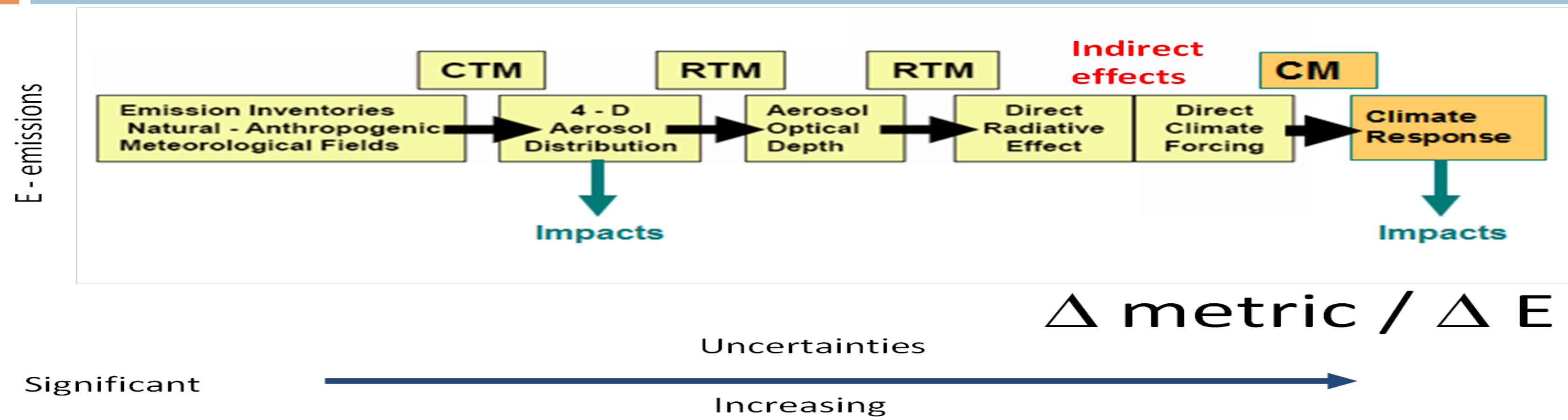


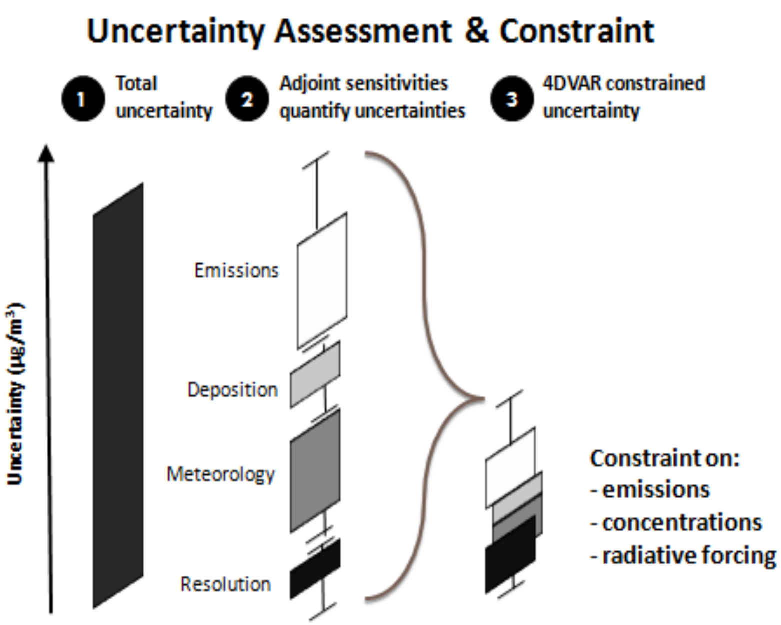
Δ metric / Δ E

Uncertainties

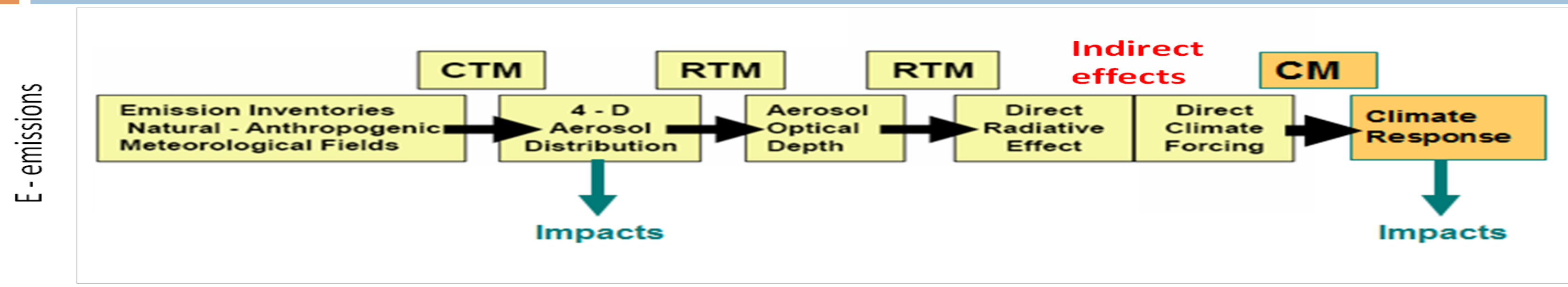
Significant → Increasing

Large uncertainties in linking emissions of BC and other SLCF agents to impacts across scales





Large uncertainties in linking emissions of BC and other SLCF agents to impacts across scales

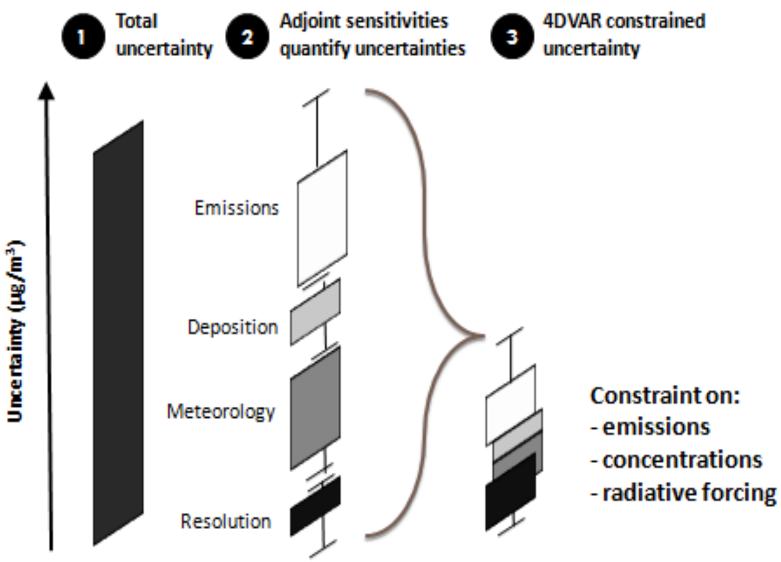


Δ metric / Δ E

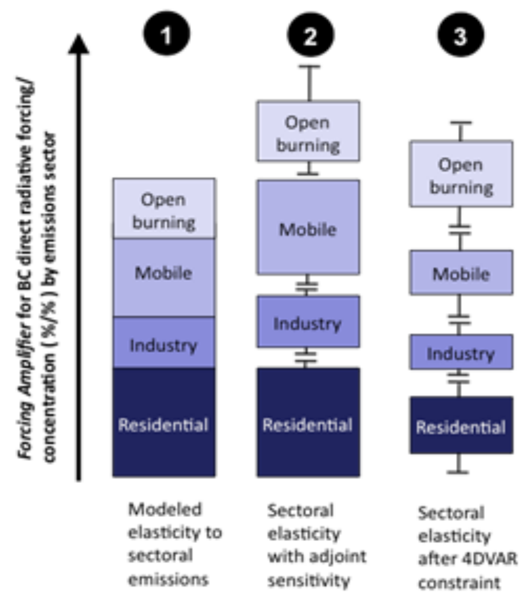
Uncertainties

Significant → Increasing

Uncertainty Assessment & Constraint



Co-Benefits Metrics



California: regional BC transport w/intense forest fire episodes and complex meteorology

- Constrain uncertainty in BC emissions & vertical distributions using ARCTAS observations
- U.S. application of sectoral BC co-benefits metrics

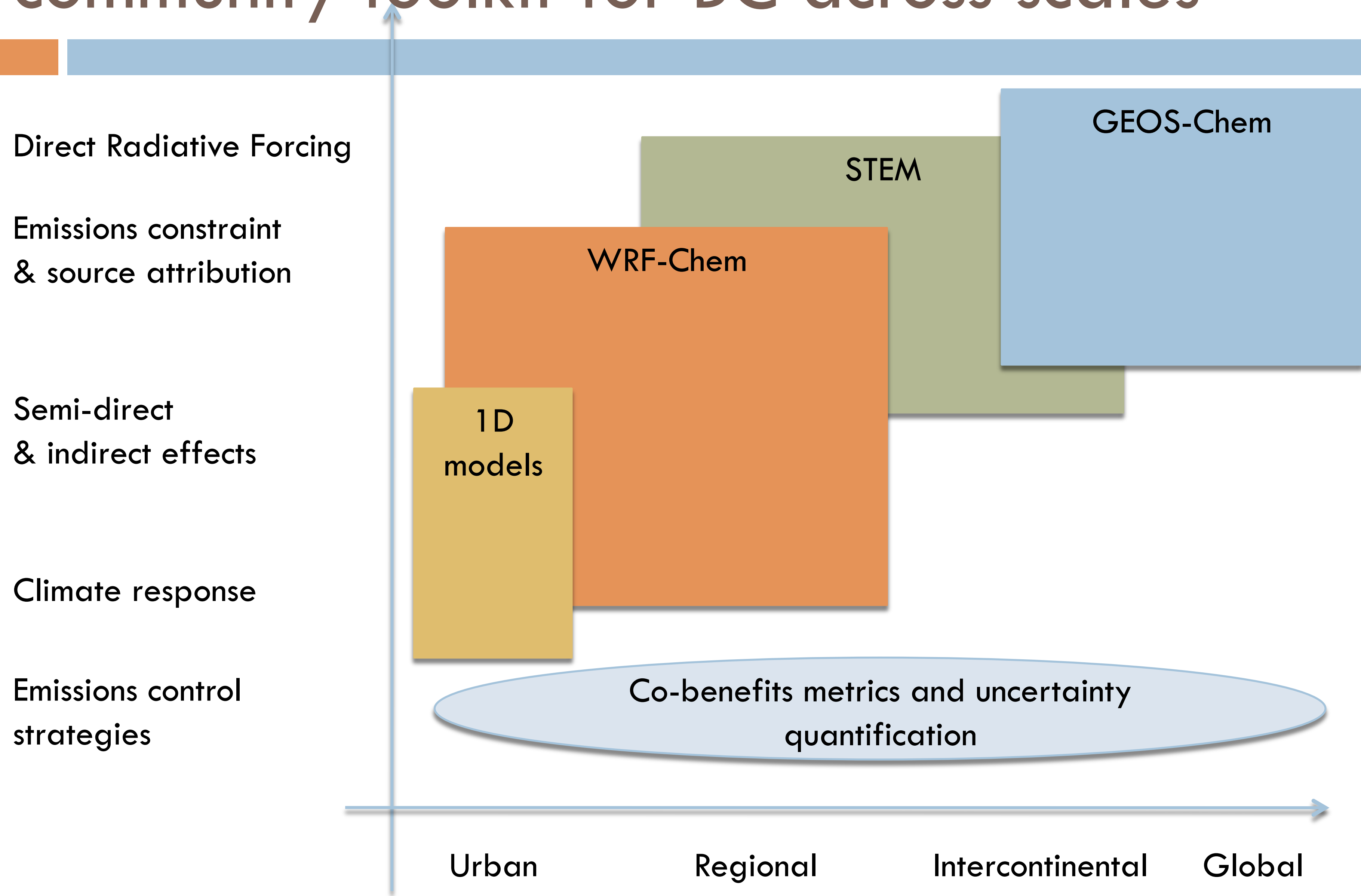
India: high urban & regional BC burdens, strong direct & indirect radiative forcing

- Constrain large, highly uncertain emissions inventories
- Sectoral BC co-benefits metrics across urban to regional scales

Arctic: long-range BC transport critical to global climate

- Constrain and compare uncertainty in BC emissions & long-range transport in regional & global models
- National/sectoral co-benefits metrics @ GCM scale

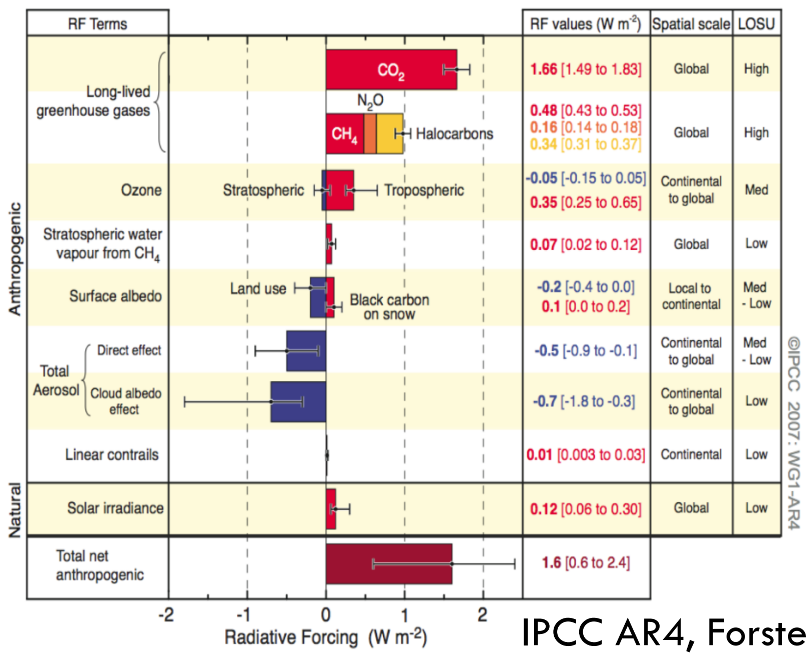
Developing a comprehensive open-source community toolkit for BC across scales



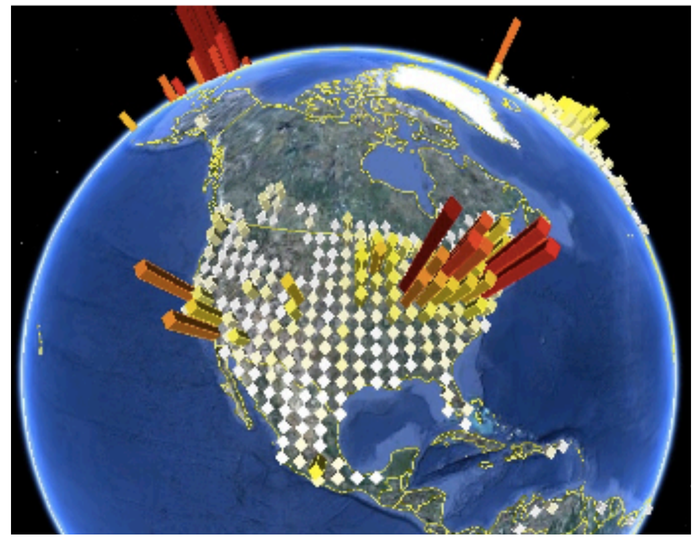
Aerosols & Radiative Forcing

Global Abundance

Local Causes & Effects



IPCC AR4, Forster *et al.*, 2007

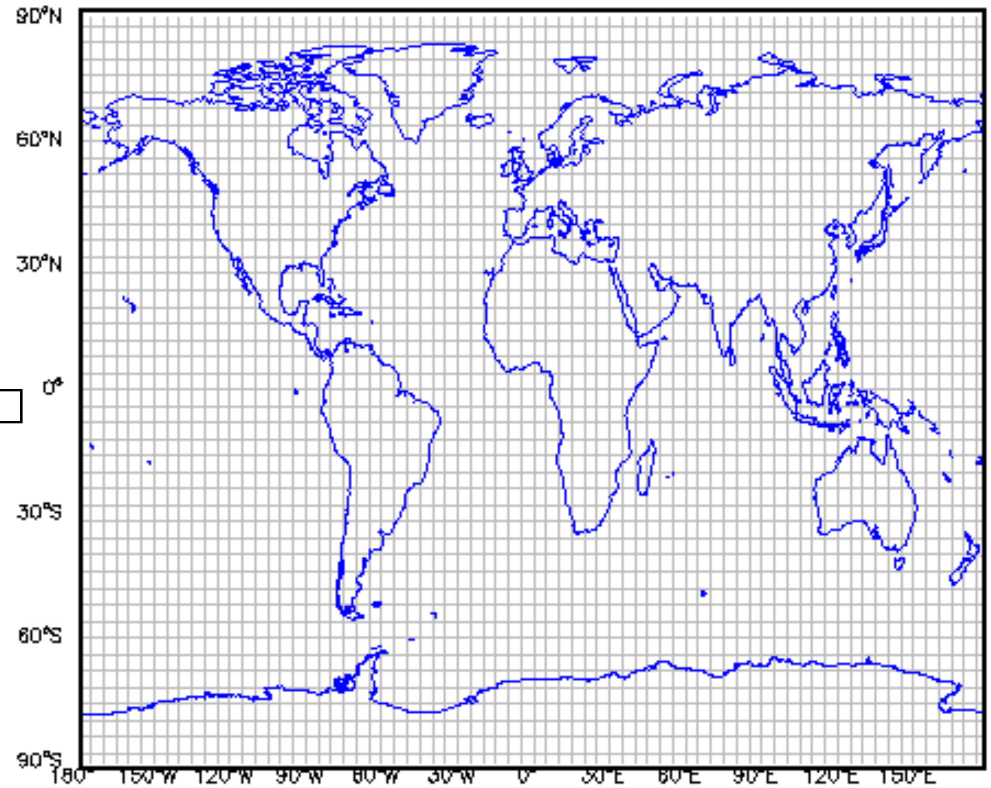


• Perturbing emissions & recalculating RF -> regional assessment (e.g., Koch et al., 2005; Fuglestvedt et al., 2008; Unger et al., 2010)

• Adjoint modeling provides an efficient means of estimating the RF from each emitted species, sector and location (Henze et al., submitted; Bowman and Henze, submitted).

Global aerosol direct radiative forcing sensitivities from **every sector & region**

$$\delta E_1$$
$$\delta E_2$$
$$\vdots$$
$$\delta E_{10^5}$$



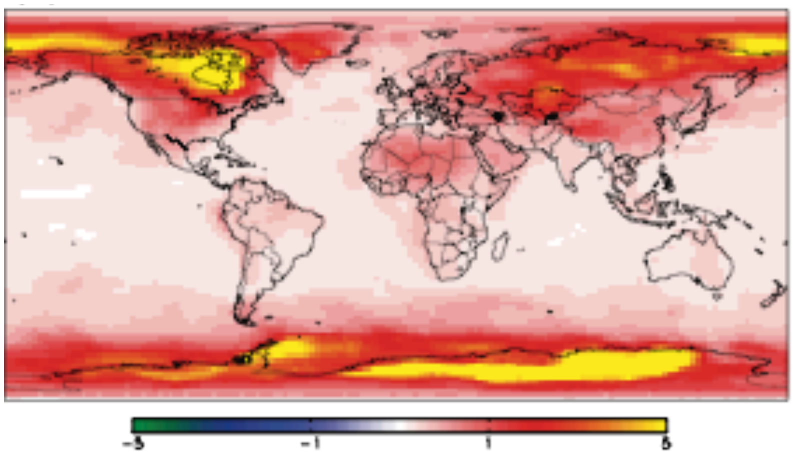
$$\delta RF$$

Calculated very efficiently with the
GEOS-Chem adjoint (Henze et al., 2007) + **LIDORT** (Spurr, 2002)

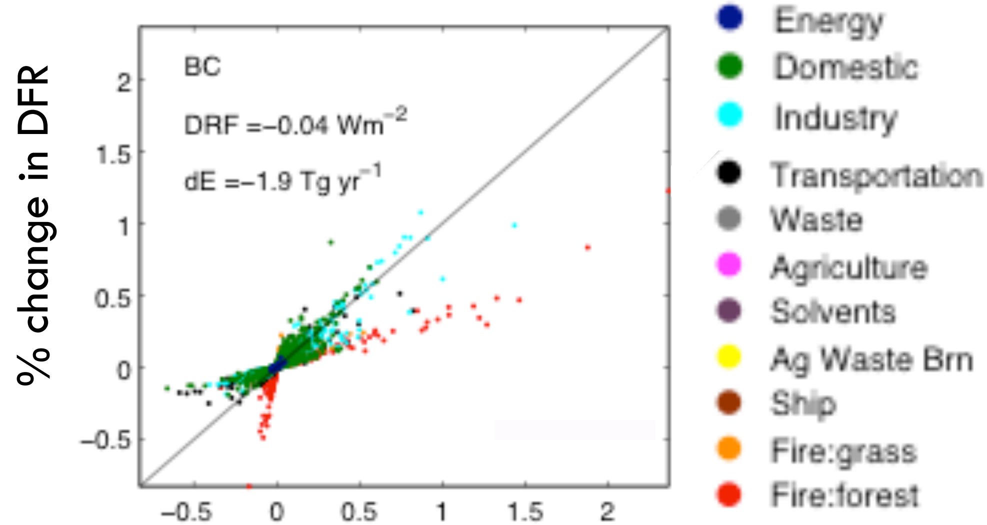
Direct Radiative Forcing efficiencies

How does variability in DRF efficiency impact aerosol direct forcing across changes to emissions sources and sectors in future scenarios?

change in DRF per
change in BC emission



W m^{-2} / (kg m^{-2} yr^{-1})



% change in BC emissions
for 2050 – 2000 RCP 4.5

Moving forward: what are the indirect forcing impacts and local-regional-global climate responses?

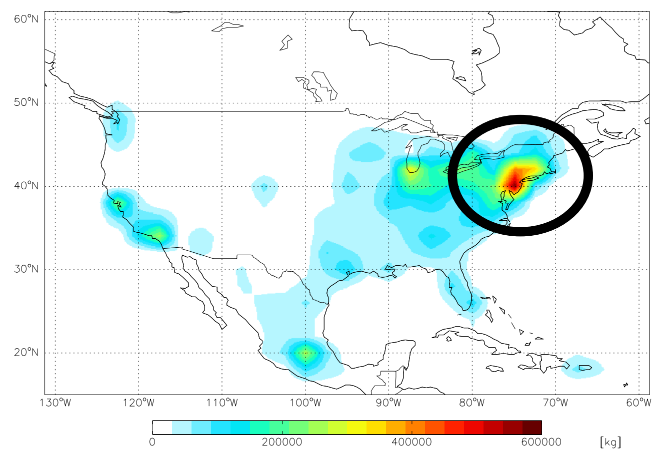
How best to quantify spatiotemporal variability in direct + indirect + semi-direct RF & net climate response?

To date: offline calculation by zonal range and forcing agent (Shindell *et al.*, 2009):

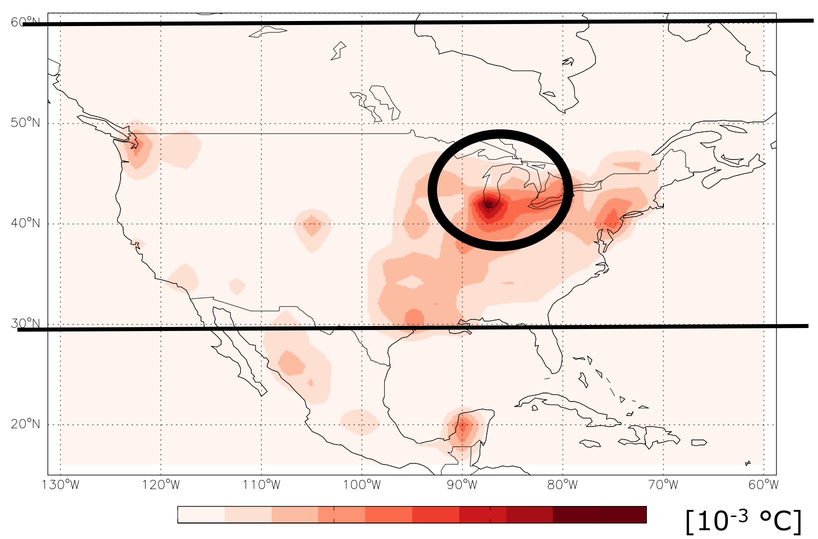
$$\frac{\Delta T_s^{NL}}{\Delta RF^{NL}}\left(\frac{\Delta RF^{NL}}{\Delta E_i}\right)=\frac{\Delta T_s^{NL}}{\Delta E_i}$$

0.15 °C / Wm^{-2} *CTM adjoint*

BC Emissions Rates

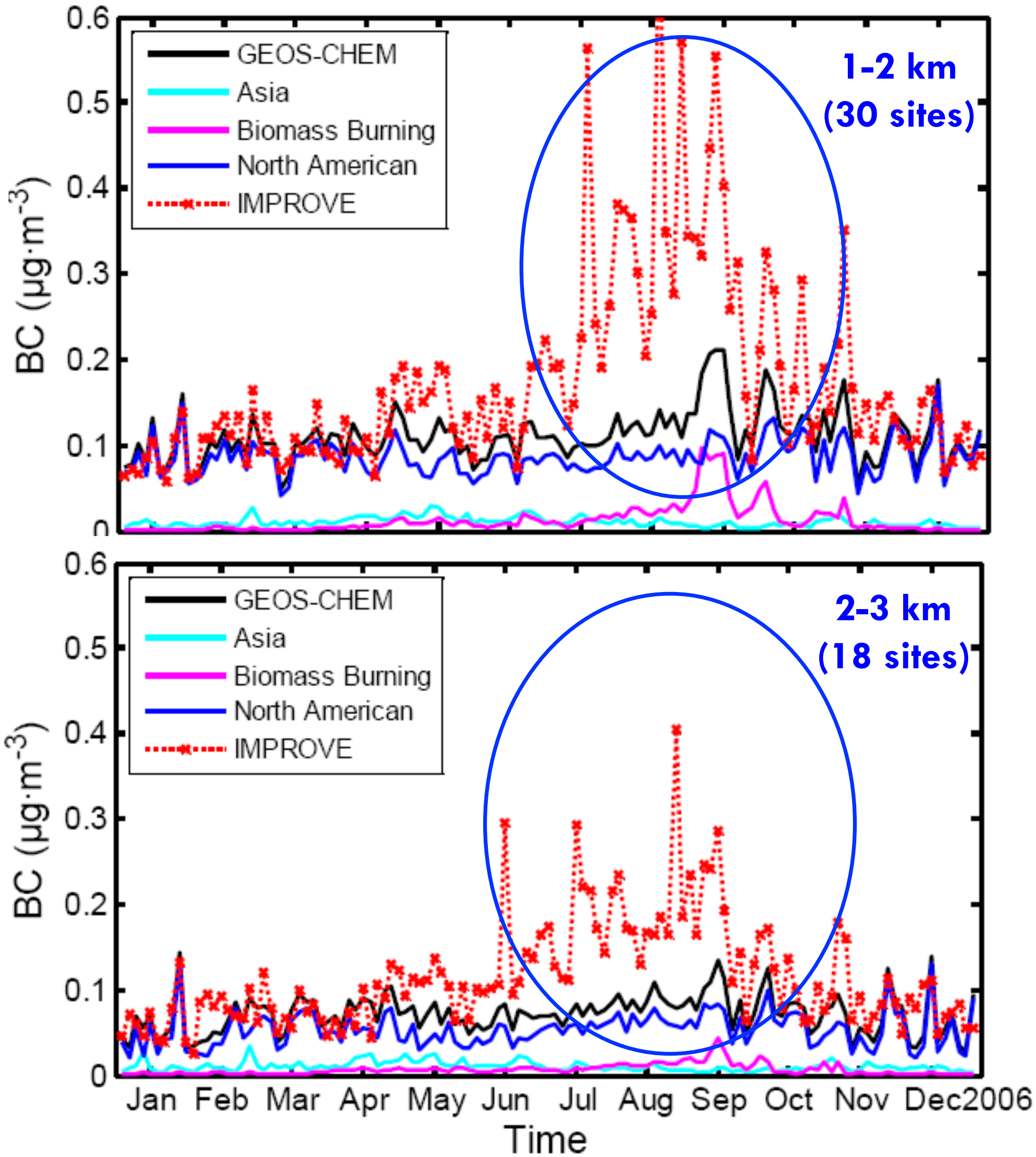


Surface Temperature Response to BC



Emerging paradigm: online calculation using adjoints with aerosol microphysical models WRF-Chem (UI, Saide *et al.*, submitted; GIT, Karydis *et al.*, ACPD 2012)

Surface BC at mountain sites biased low by > 2x during the summer and fall fire season



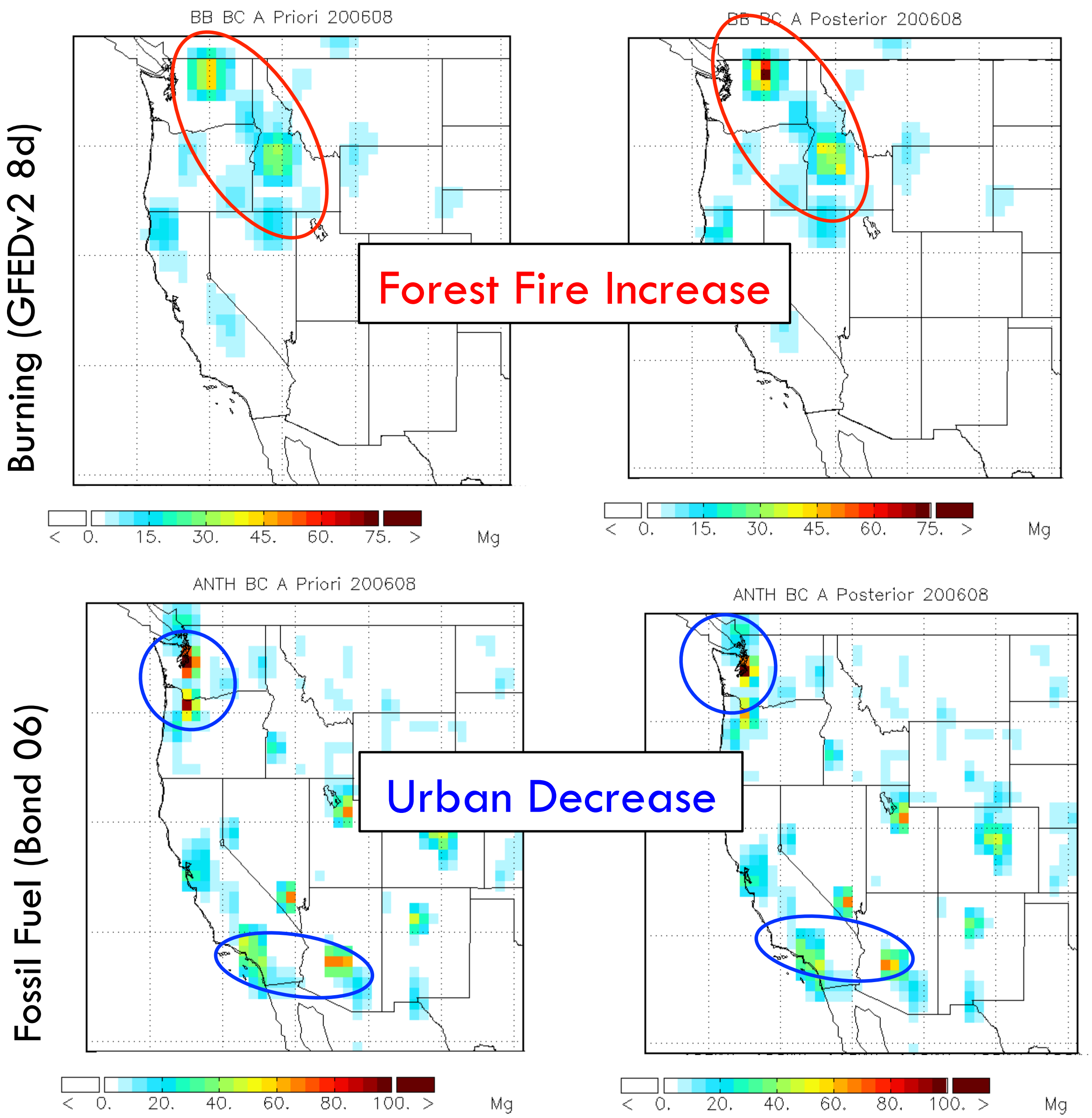
2006 Fire Season

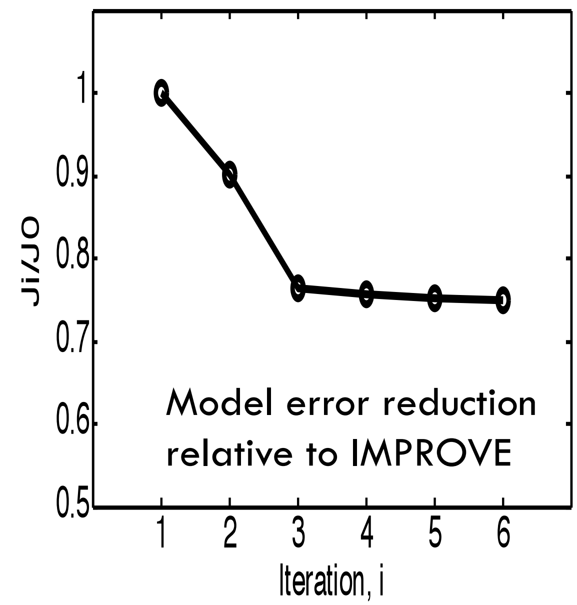
Discrepancies evident in absolute surface BC levels and in timing & enhancements from fire emissions.

Uncertainties in fire BC emissions and the (lack of) detection of (small, agricultural) burning are likely contributors to these discrepancies.

Mao et al., 2011

Initial vs. constrained emissions in GEOS-Chem (8/2006)





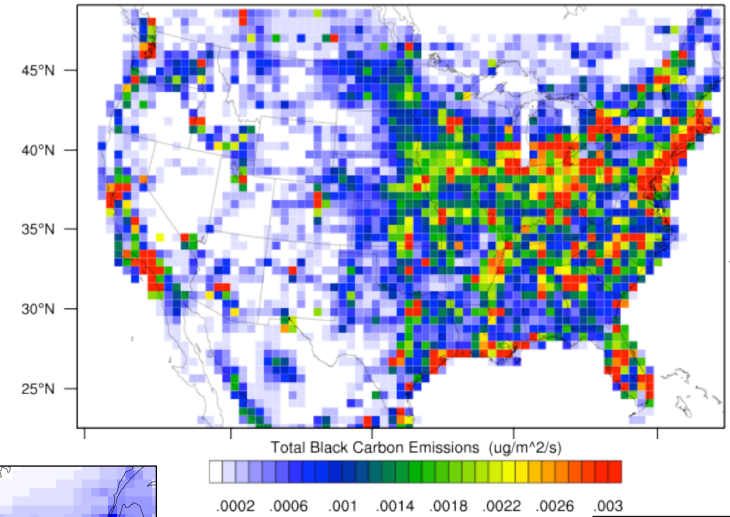
GEOS-Chem NA adjoint *a priori* uncertainty:
FF 20%, BB 100%

Timing & location of burning sources?

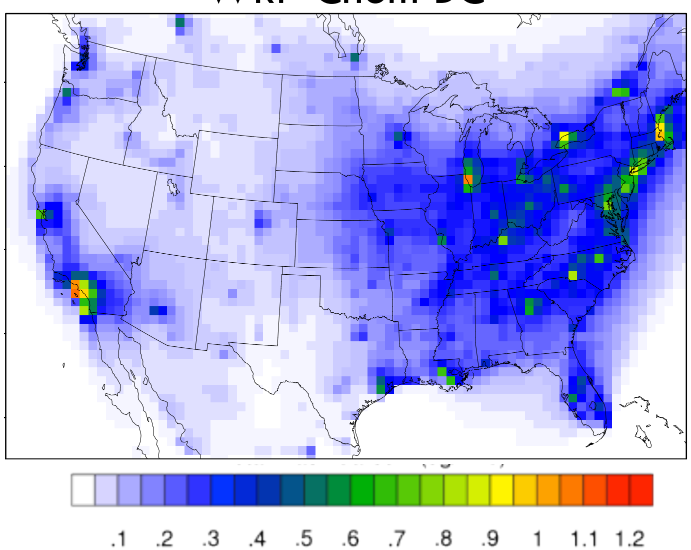
Yuhao Mao, UCLA
preliminary results

Towards multi-model, multi-scale observational constraints with online dynamic feedbacks and inverse sensitivities

NEI 2005 emissions

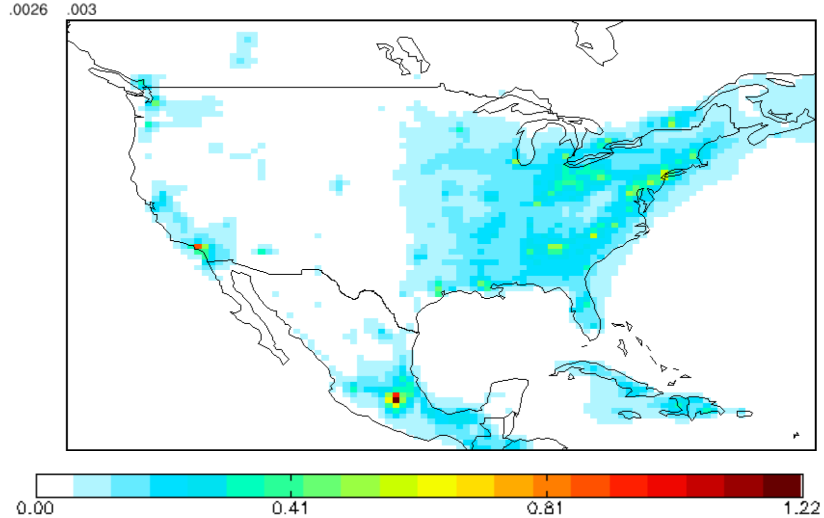


WRF-Chem BC



Online dynamic feedbacks
Inverse capability in progress

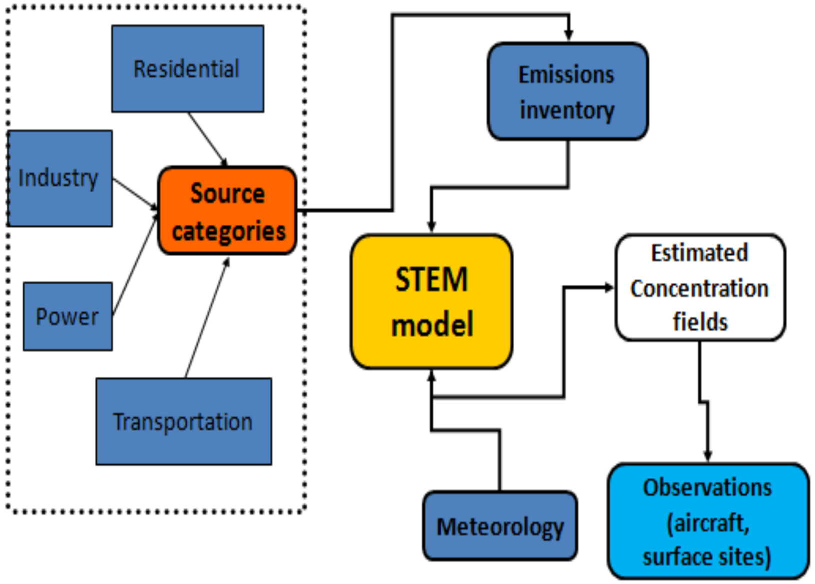
GEOS-Chem BC



Offline global CTM
Inverse capability today

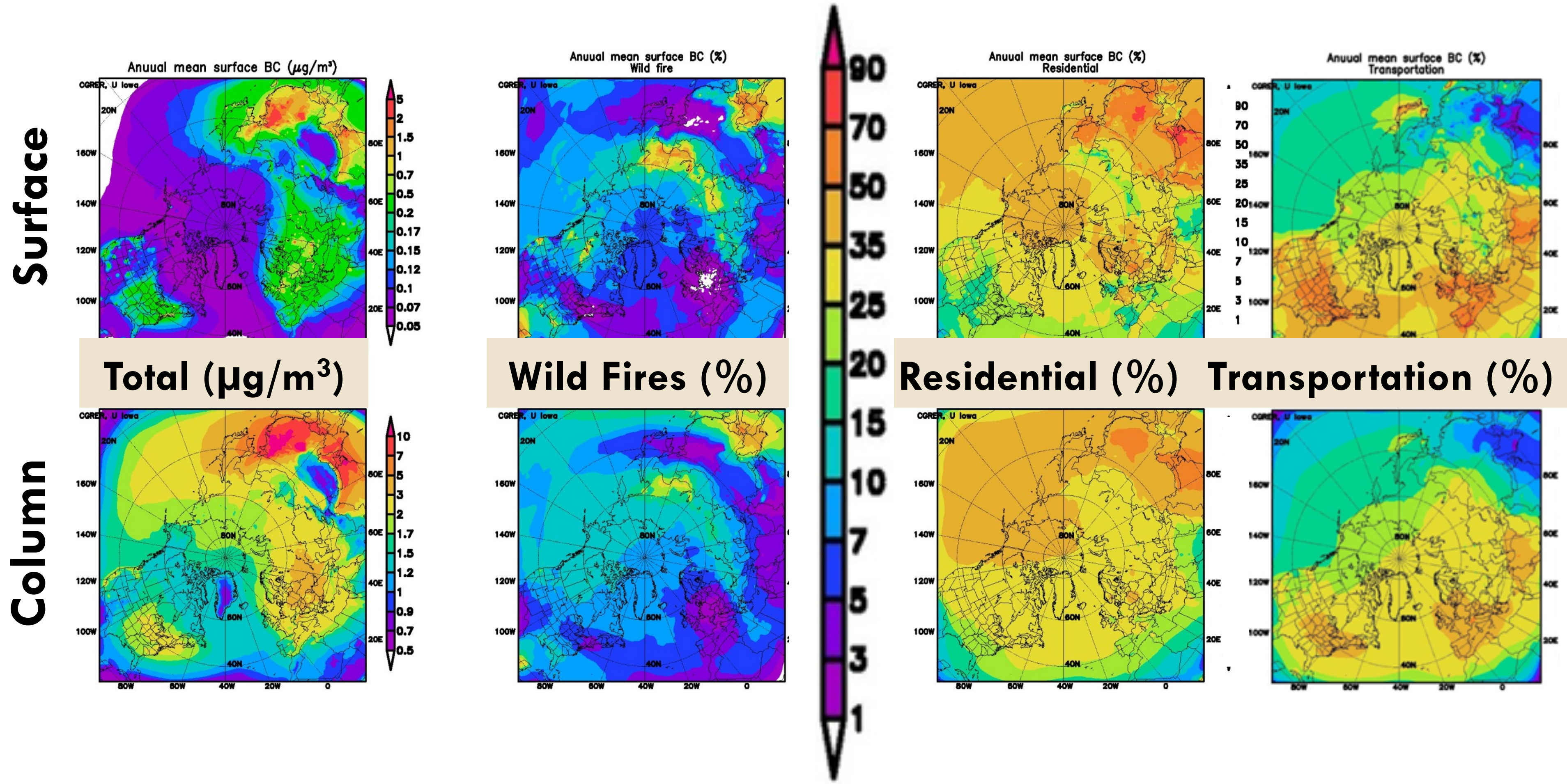
BC Transport to the Arctic

- **Emission sector impacts on Arctic BC during ARCTAS**
  - surface + column
  - Sectors: residential, power, industry, transportation, wild fires
  - Full Year: April 2008 – March 2009



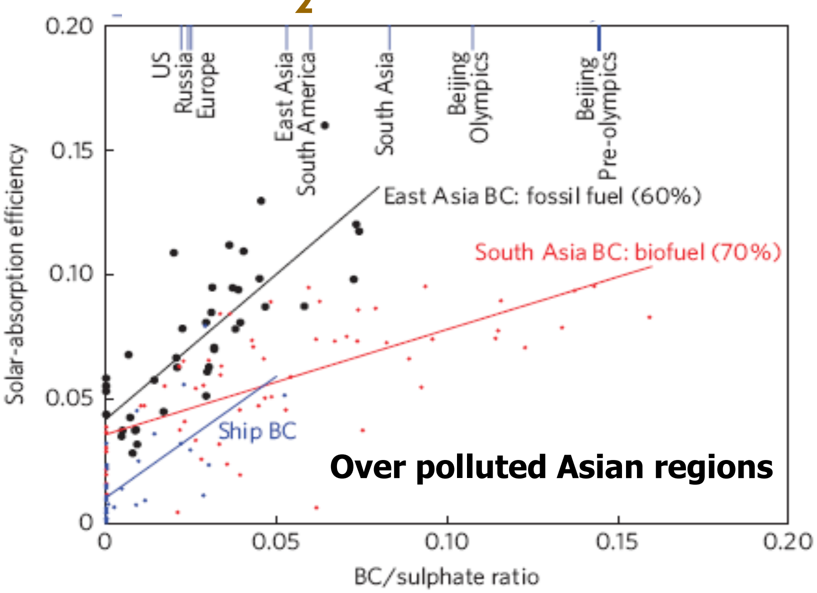
- **Long-range transport Source:Receptor relationships @ intercontinental and hemispheric scales**
  - Emission perturbations over North America (NA), Europe (EU), and East Asia (EA)

Residential sector the largest contributor to annual mean surface & column BC

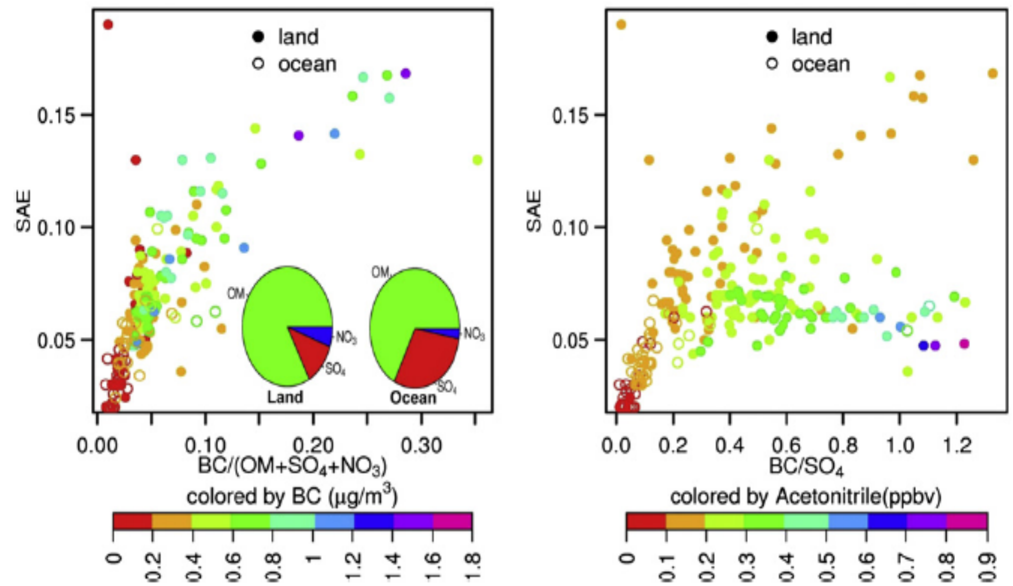


Absorption & scattering metrics further identify sector contributions to warming

$BC:SO_2$ emissions ratio



DC-8 Arctas - CA

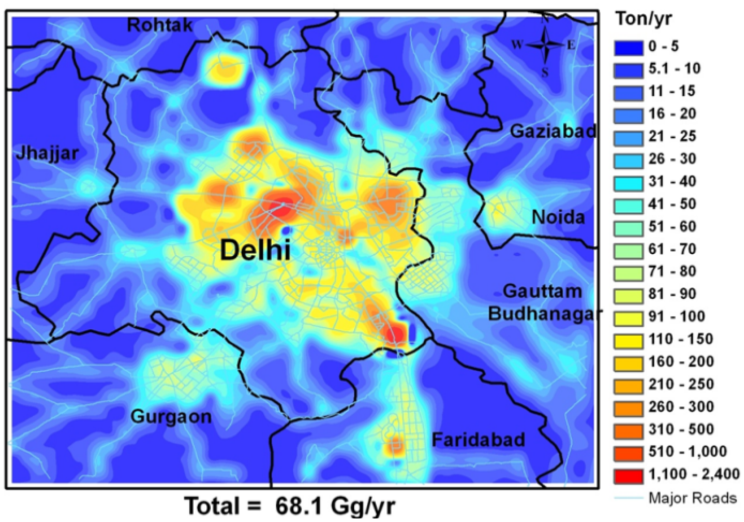


BC/OM, BC/(OM + SO4) and BC/(OM + SO4 + NO3) correlated well with SAE; BC/SO4 only correlated well with SAE for plumes with low fire contributions.

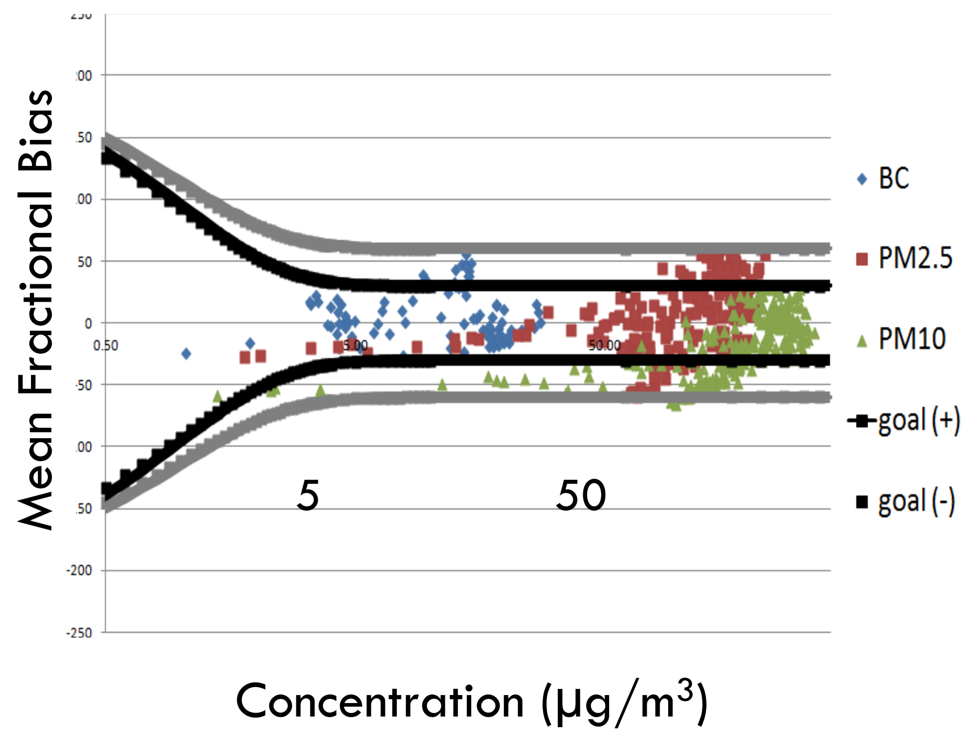
Ramana et al., Nature Geo., 2010 *Huang et al., Atmos. Env., 2012*

Delhi: urban-scale black carbon emissions, observations, modeling

Speciated emissions @1.67 km



Skillful urban scale WRF-Chem simulation



+ 11 new urban observation sites

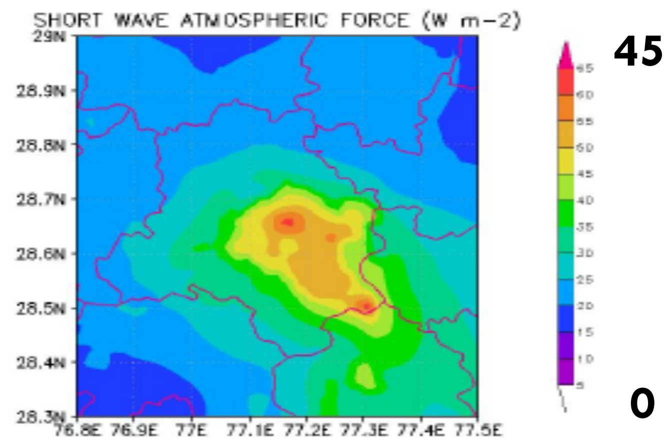
SAFAR Delhi Commonwealth Games – Beig *et al.*

Delhi: urban-scale sector contributions to direct & indirect radiative forcing

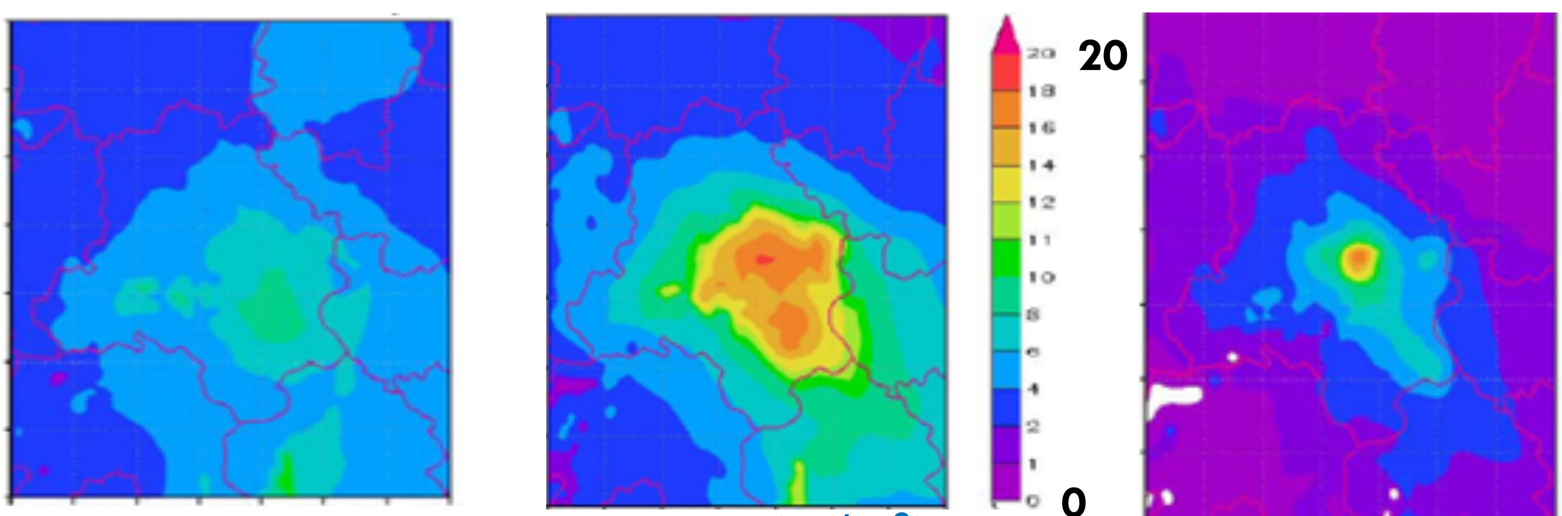
$$\left(\frac{\triangle RF^{NL}}{\triangle E_i}\right)$$

Strong warming from high BC emissions

Strong surface dimming from primary & secondary aerosols, too (> 60 W/m^2)



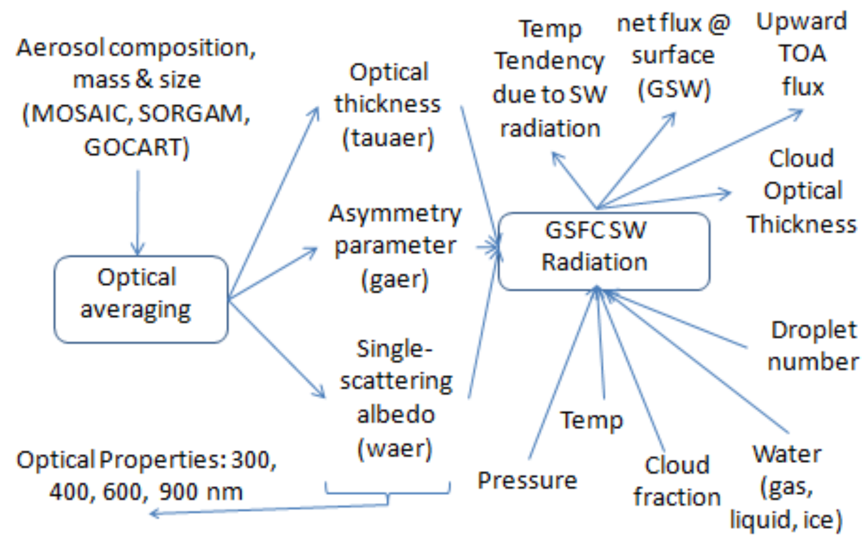
Transportation **Residential** **Industry**



Anthropogenic SW Column Forcing (W/m^2)

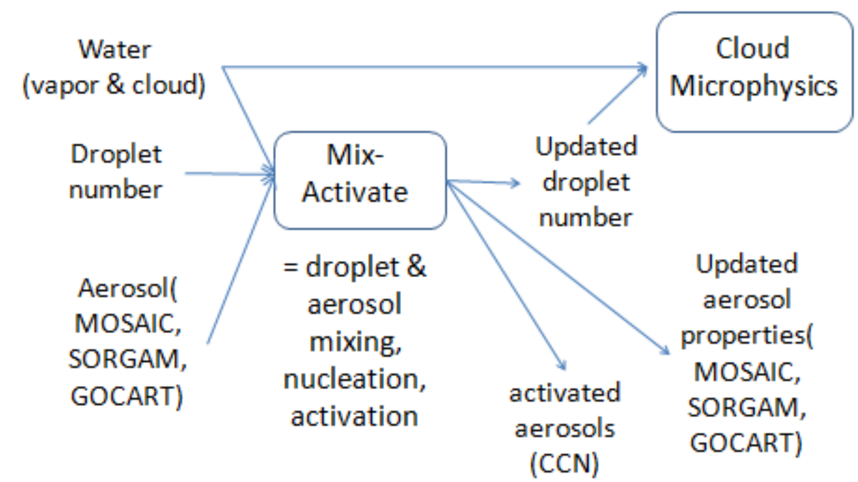
BC Direct & Indirect Forcing Sensitivities: *online, in situ, adjoint*

Aerosol direct effects in WRF-Chem



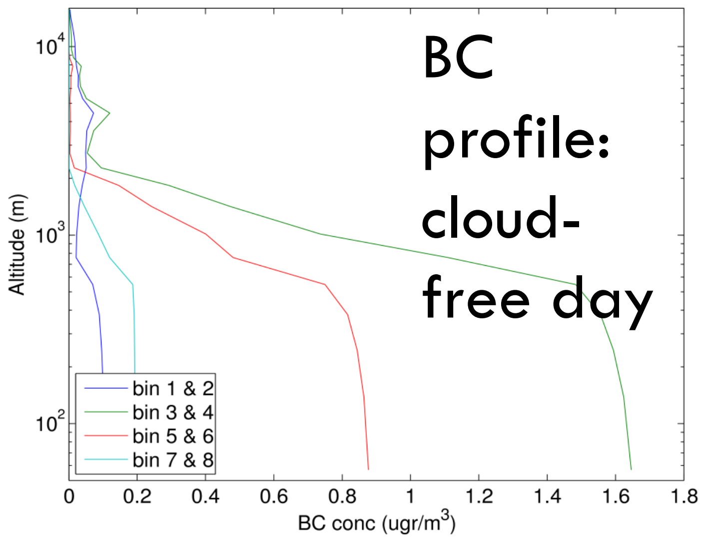
Reference: *Fast et al.* (2006)

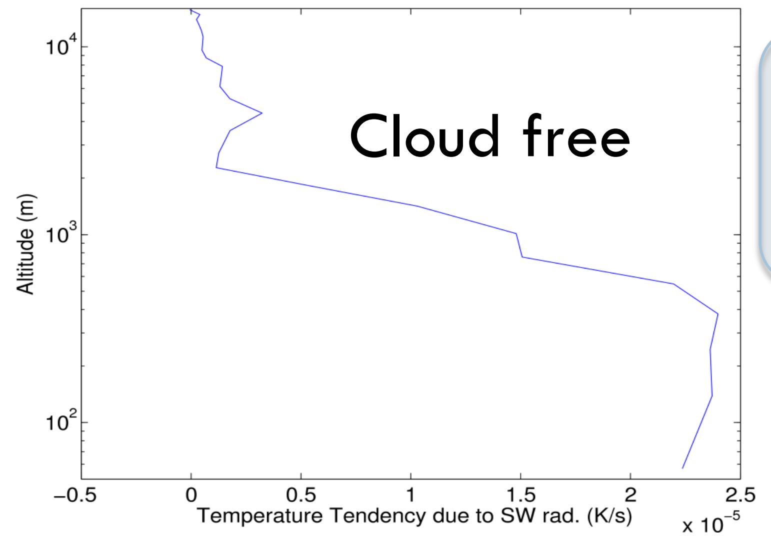
Aerosol indirect effect in WRF-Chem



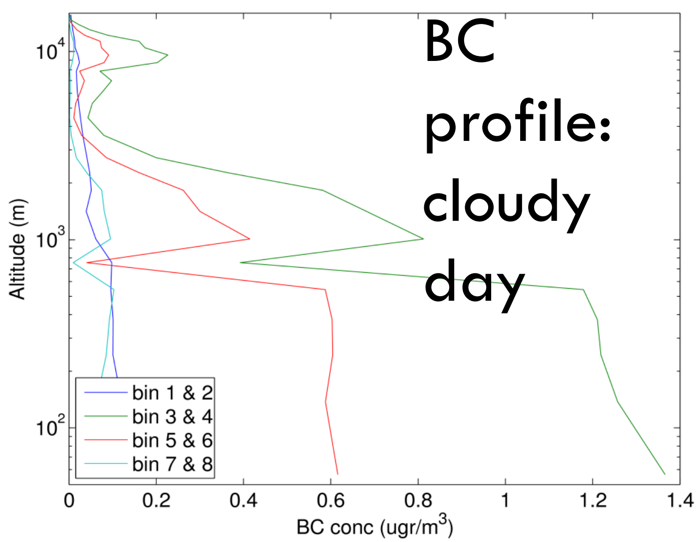
References: *Gustafson et al.* (2007), *Chapman et al.* (2009)

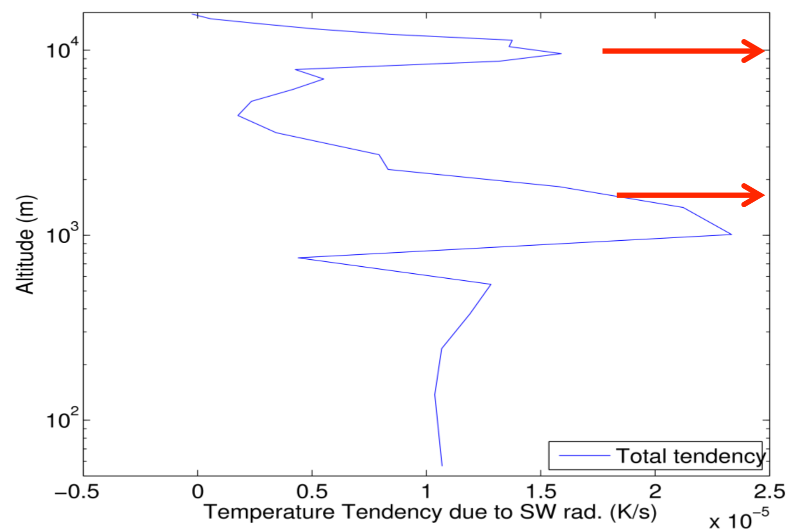
BC Direct & Indirect Forcing Sensitivities in a Column Model





$$\frac{\Delta T_s}{\Delta E_i}$$



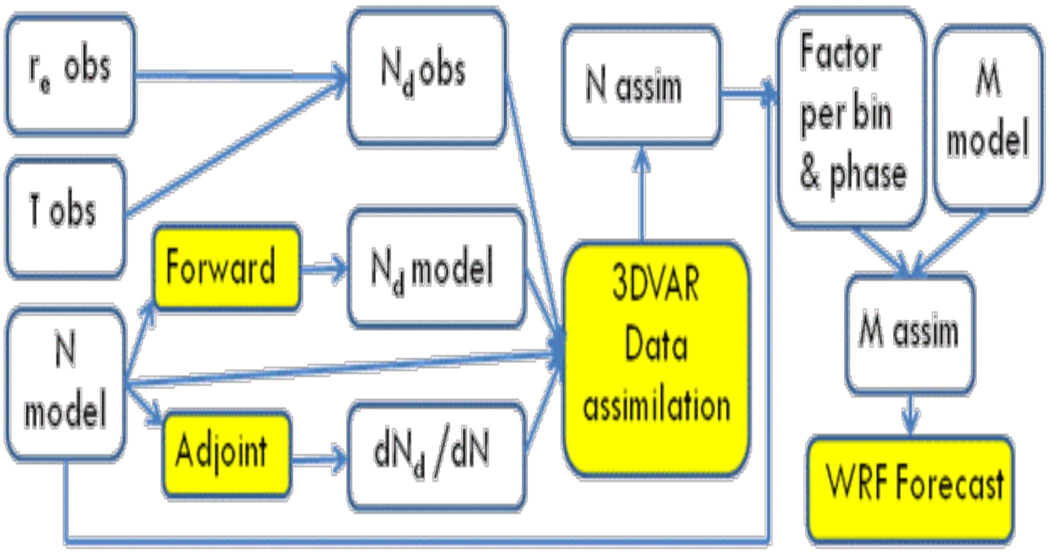


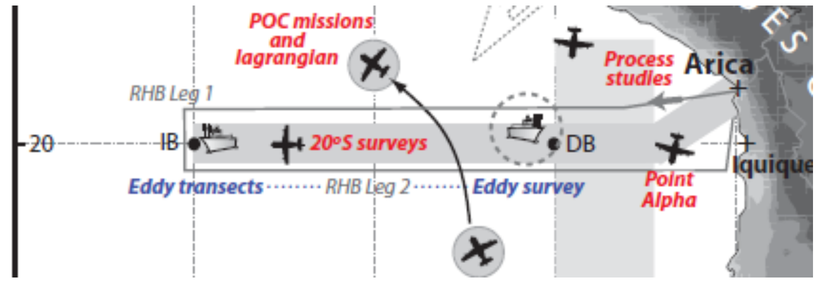
Ice

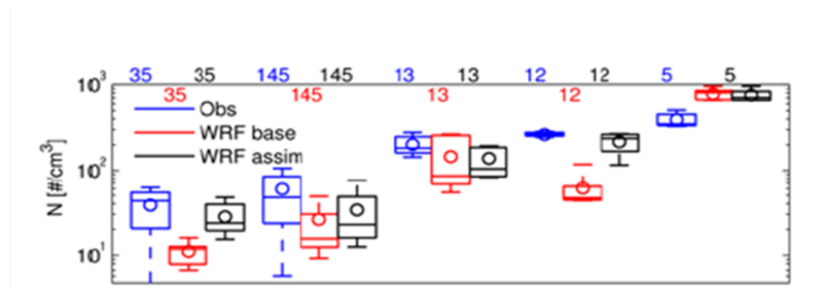
Warm Liquid Cloud

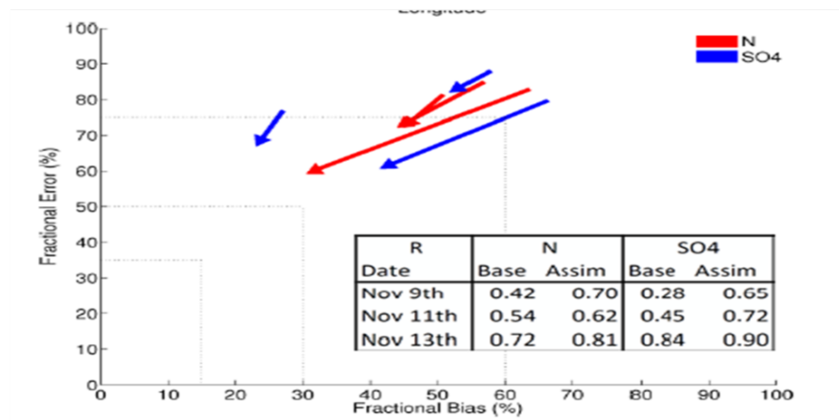
BC Direct and Indirect Forcing Sensitivities in a Column Model

Have demonstrated that cloud retrievals can be used to improve aerosol number, composition and mass distributions









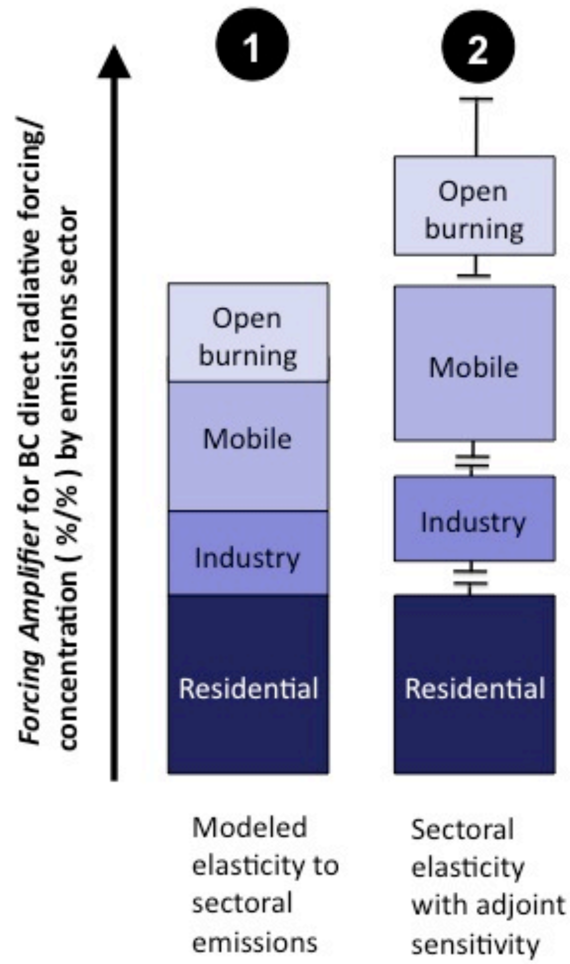
R	N		SO4	
Date	Base	Assim	Base	Assim
Nov 9th	0.42	0.70	0.28	0.65
Nov 11th	0.54	0.62	0.45	0.72
Nov 13th	0.72	0.81	0.84	0.90

Saide et al., in review 2012

Near-Term Objective: Delhi Co-Benefits Metrics

- Proof of concept for non-linear adjoint co-benefits response surfaces
  - direct radiative forcing
  - exposure & crop yields
  - optimizing on combined effect

- Explore sectoral (e.g., BC:S) optimization and non-linearities across scales in WRF-Chem & GEOS-CHEM
  - urban: Delhi (1.67 km)
  - regional: Gangetic Plain (5-15 km)
  - “hi-res” global in both models (0.5º)
  - global (2.5º)



Ongoing & Future Work: Year 2

- Assimilation and assessment of seasonality in sector and geographic source region contribution to North America and the Arctic
- Quantify impacts of proposed BC-specific emission mitigation policy measures (e.g. IIASA 2030 reference scenario emissions)
- Further development of co-benefit metrics & their constraint
- WRF-Chem adjoint *(further)* development, WRF-PLUS integration, evaluation, public release

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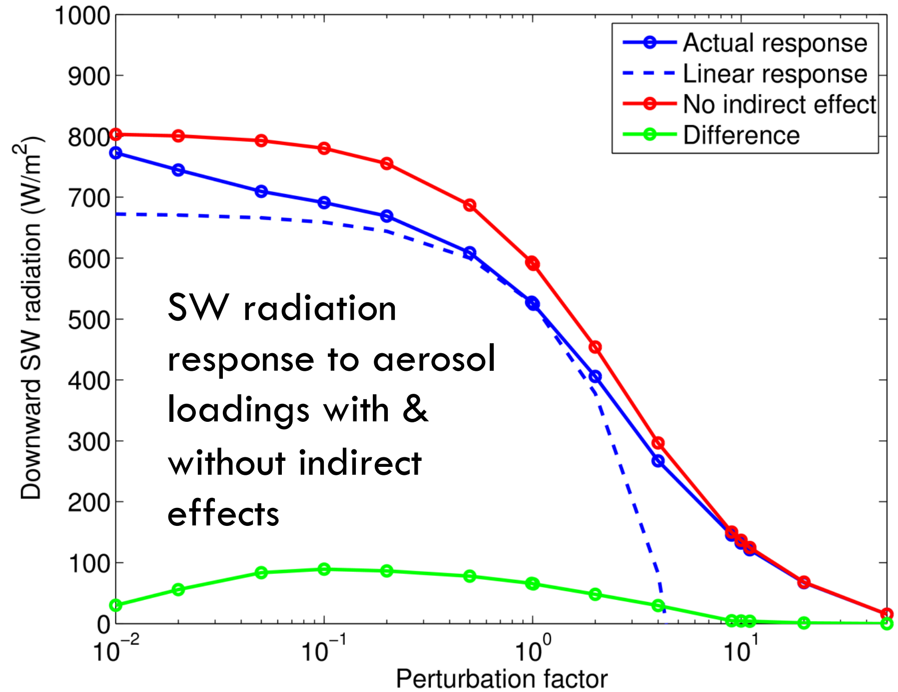
Backup Slides

BC Direct and Indirect Forcing Sensitivities in a Column Model

SW & LW response to perturbing all species concentrations considering indirect effects

- Optimal aerosol load at saturation generates higher droplet number, dimming the surface. Too many or too few aerosol will not change base cloud properties.



Closing comments

1. Policy measures for BC call for a coordinated effort at local, regional and global scales with emphasis on specific emission sectors, source regions and mitigation strategies
2. Many current opportunities for climate + health co-benefits not limited by current uncertainties
3. Increasing win-win mitigation opportunities with further confidence in direct cause & effect (emissions + processes + impacts)