

US EPA ARCHIVE DOCUMENT

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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University of Colorado: Jonathan Guerrette*, Li Zhang*, Forrest Lacey, Daven Henze*

NOAA: Georg Grell*

**supported by EPA STAR*



Innovation in BC modeling & data assimilation

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1. Science
2. Tools
3. Decision Support

Science Objectives

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1. Rank and constrain the contributions of transport, deposition, aerosol properties, and emissions to uncertainty in estimates of BC distributions in urban and remote areas and of BC radiative forcing.
2. Improve model representation of BC distributions at urban to regional scales through assimilation of surface, aircraft and remote sensing measurements.
3. Assess the range of BC uncertainties in climate impacts metrics, and develop novel metrics for air quality and climate impacts that reflect the competing effects of co-pollutants and account for propagation of uncertainties in sources, transport, and radiative processes.

Objectives: Tools & Methods

4

Develop and apply tools that improve model representation of BC distributions at urban to regional scales through assimilation of surface, aircraft and remote sensing measurements.

1. Global to regional: GEOS-Chem adjoint & 4DVAR
2. Urban to global, coupled: WRF-Chem & GSI 3DVAR
3. LES to global, coupled: WRF-Chem adjoint & GSI 4DVAR



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

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



India & East Asia: 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

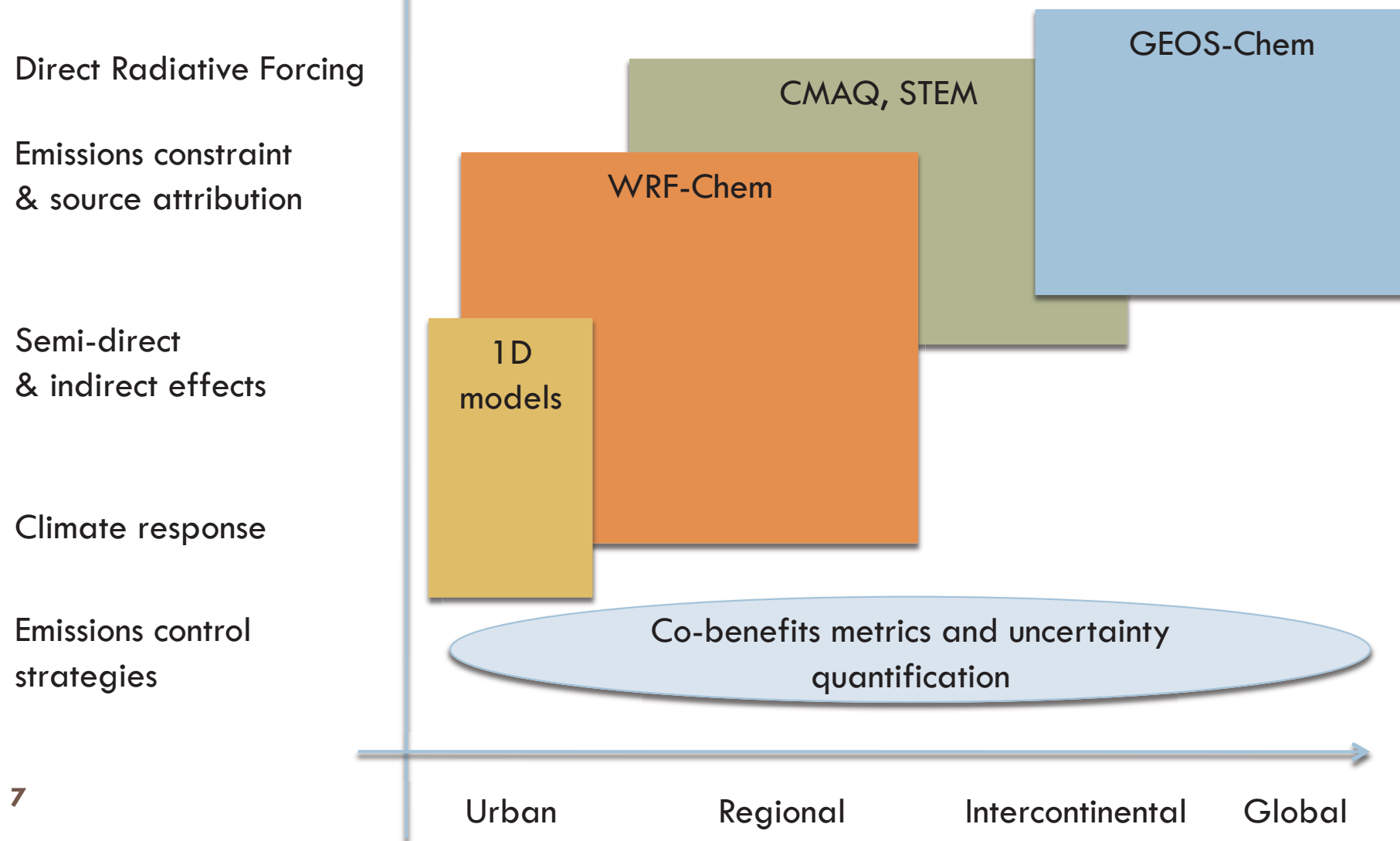


Arctic: long-range BC transport critical to global climate

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

TOOLS

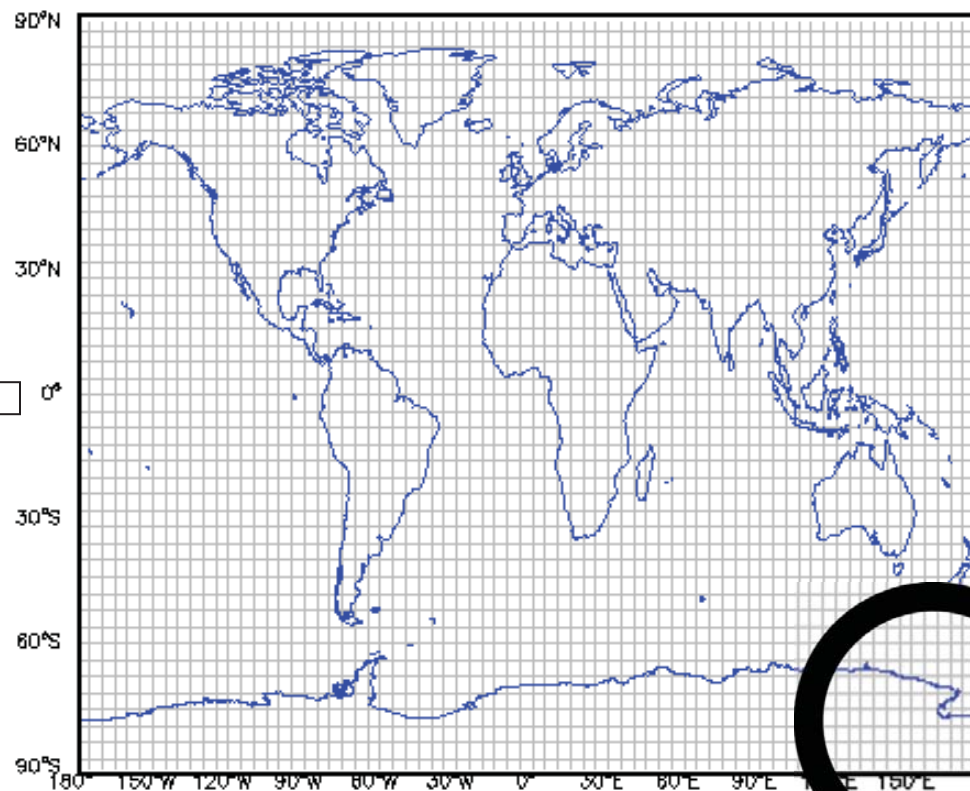
Developing a comprehensive open-source community toolkit for BC across scales



What do adjoint chemistry + climate models do?

8

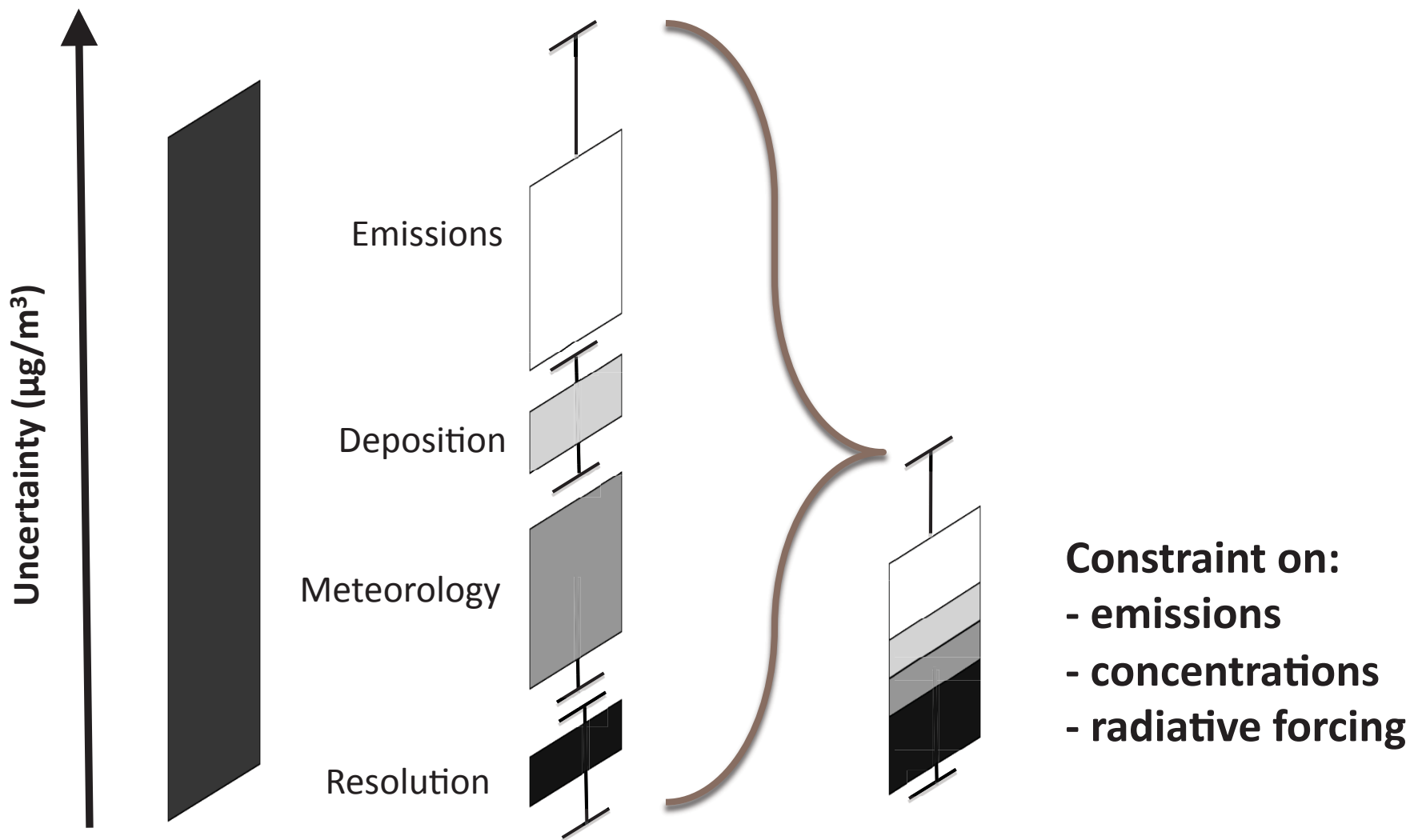
δE_1
 δE_2
 $\vdots$
 δE_{10^5}



δRF

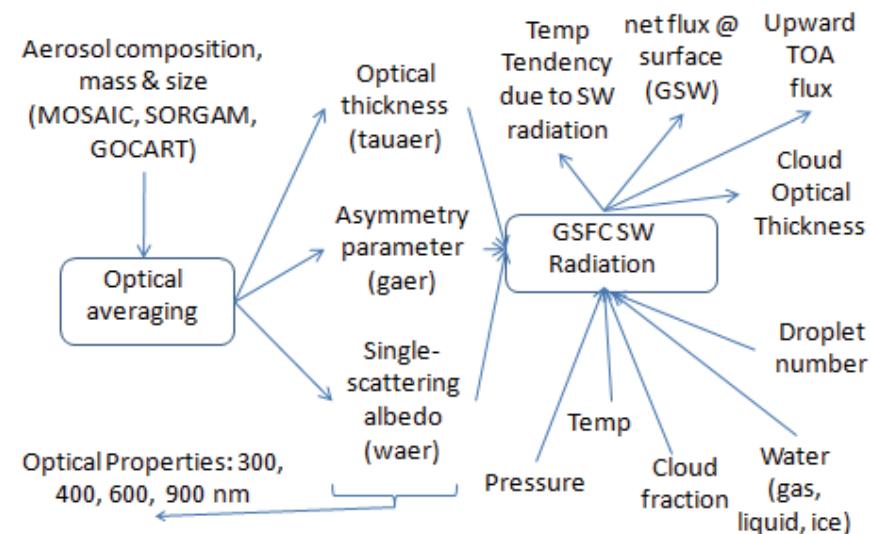
Uncertainty Assessment & Constraint

- 1 Total uncertainty
- 2 Adjoint sensitivities quantify uncertainties
- 3 4DVAR constrained uncertainty



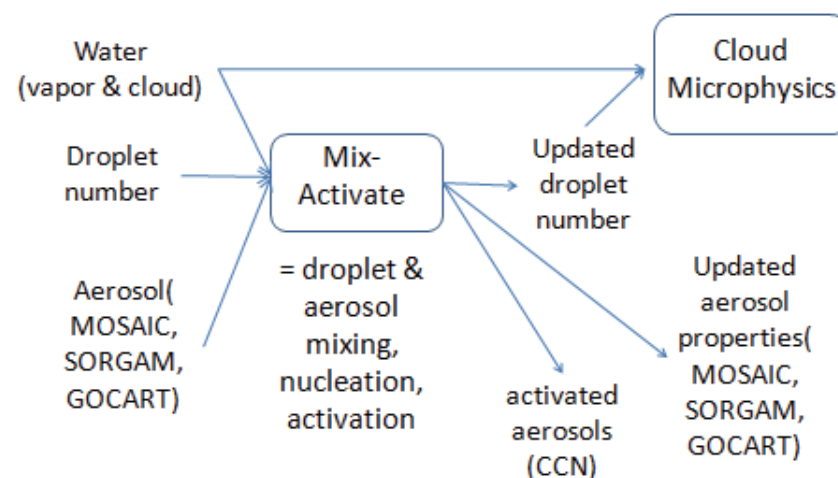
BC Direct, Indirect, Semi-Direct Forcing Sensitivities: *online, in situ, adjoint*

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)

APPLICATIONS



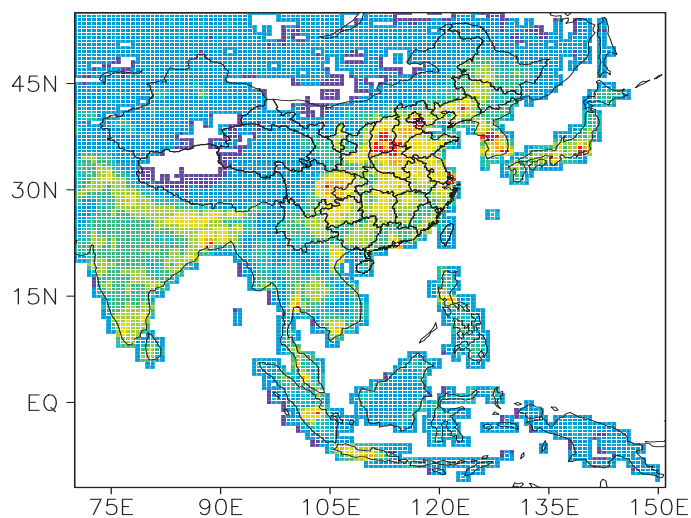
ASSIMILATING AAOD TO IMPROVE BLACK CARBON EMISSIONS & CONCENTRATIONS

L Zhang, DK Henze, GA Grell, GR Carmichael, N Bousserez, Q Zhang, J Cao, (2014). Constraining Black Carbon Aerosol over Southeast Asia using OMI Aerosol Absorption Optical Depth and the adjoint of GEOS-Chem, *Atmos. Chem. Phys. Discuss.*, in press.

Li Zhang

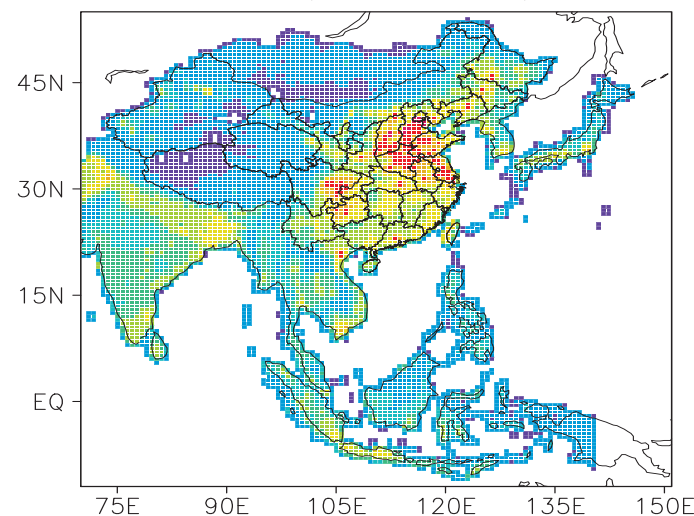
Anthropogenic BC Emissions @ $0.67^\circ \times 0.5^\circ$

Bond, $1.0^\circ \times 1.0^\circ$, 2000



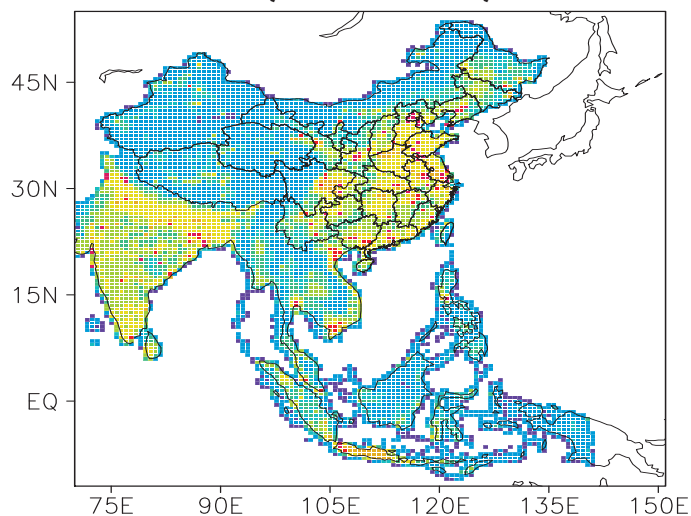
(Bond et al., 2007)

INTEX-B, $0.5^\circ \times 0.5^\circ$, 2006



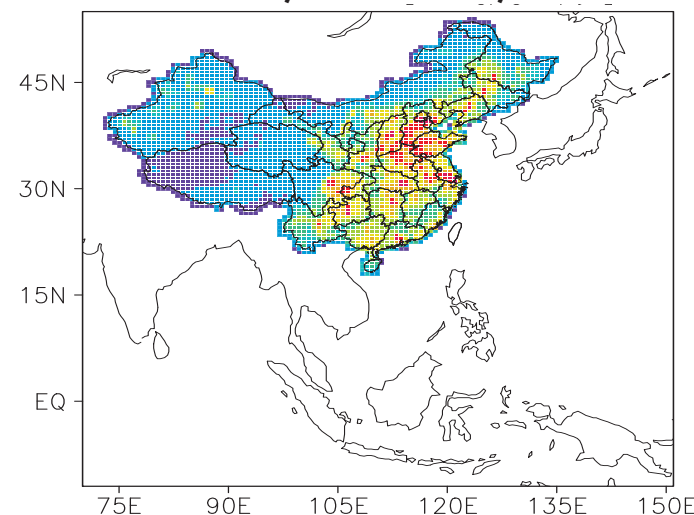
(Zhang et al., 2009)

SEAC⁴RS, $0.1^\circ \times 0.1^\circ$, 2012



(Lu et al., 2011)

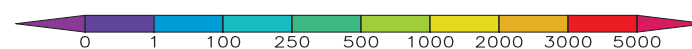
MEIC, $0.5^\circ \times 0.5^\circ$, 2010



(Zhang et al., 2012)



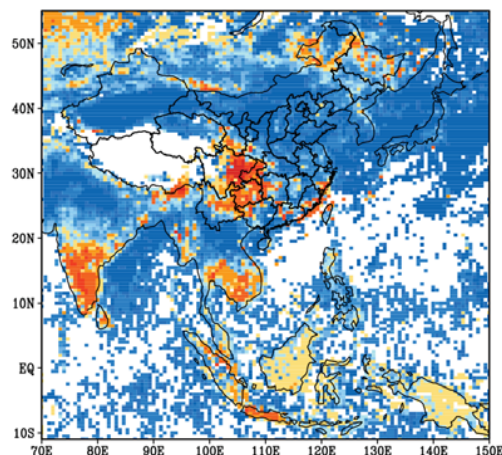
Mg BC/yr



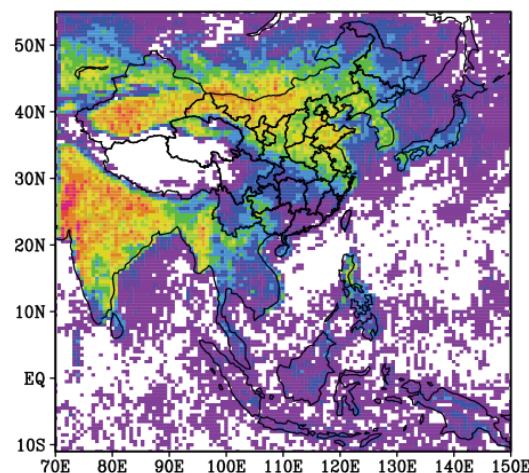
GEOS-Chem simulated AAOD vs. OMI Observed AAOD

April

GEOS-Chem minus OMI

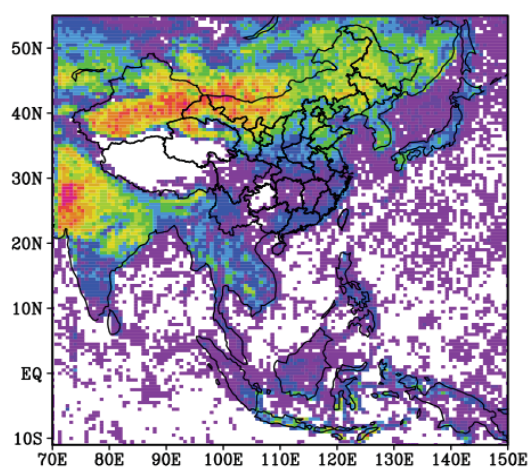
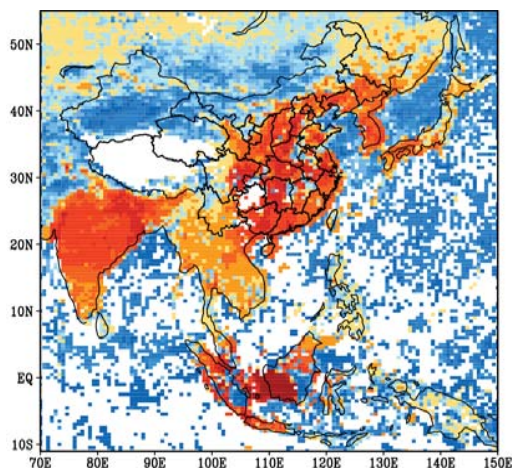


OMI observed data counts



OMI aerosol absorption optical depth (AAOD) is an atmospheric column measurement of absorbing aerosol particles [Torres et al., 2007], which provides much better spatial and temporal coverage to constrain BC.

October

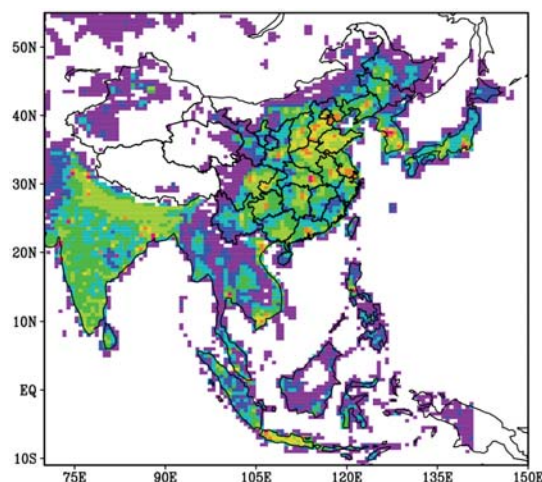


OMI AAOD L2 data were corrected using GEOS-Chem aerosol layer height.

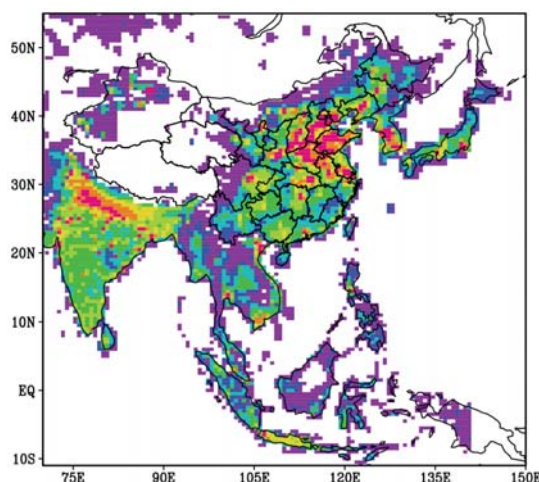
Anthropogenic emissions optimized using GEOS-Chem adjoint + MEIC_SEAC⁴RS

April

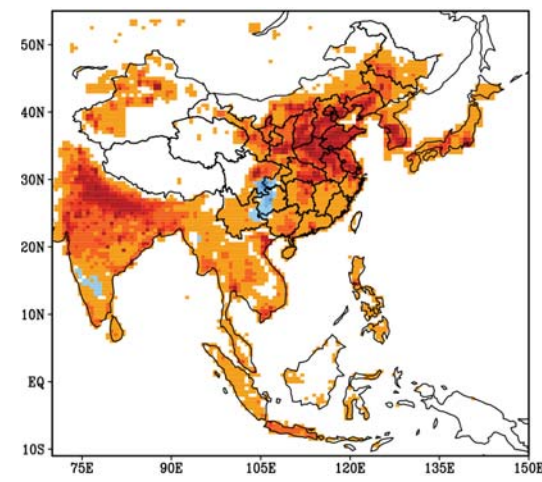
Priori



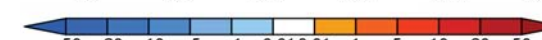
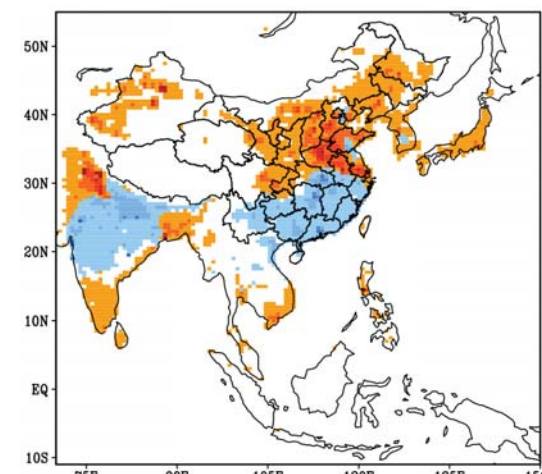
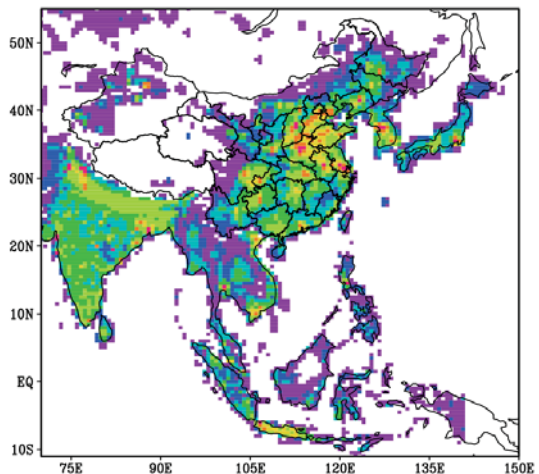
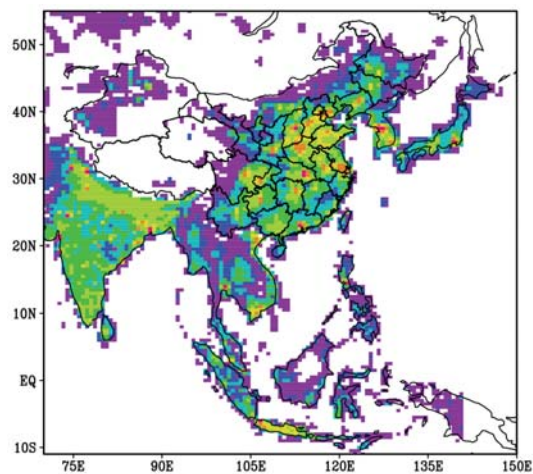
Posteriori



Posteriori - Priori

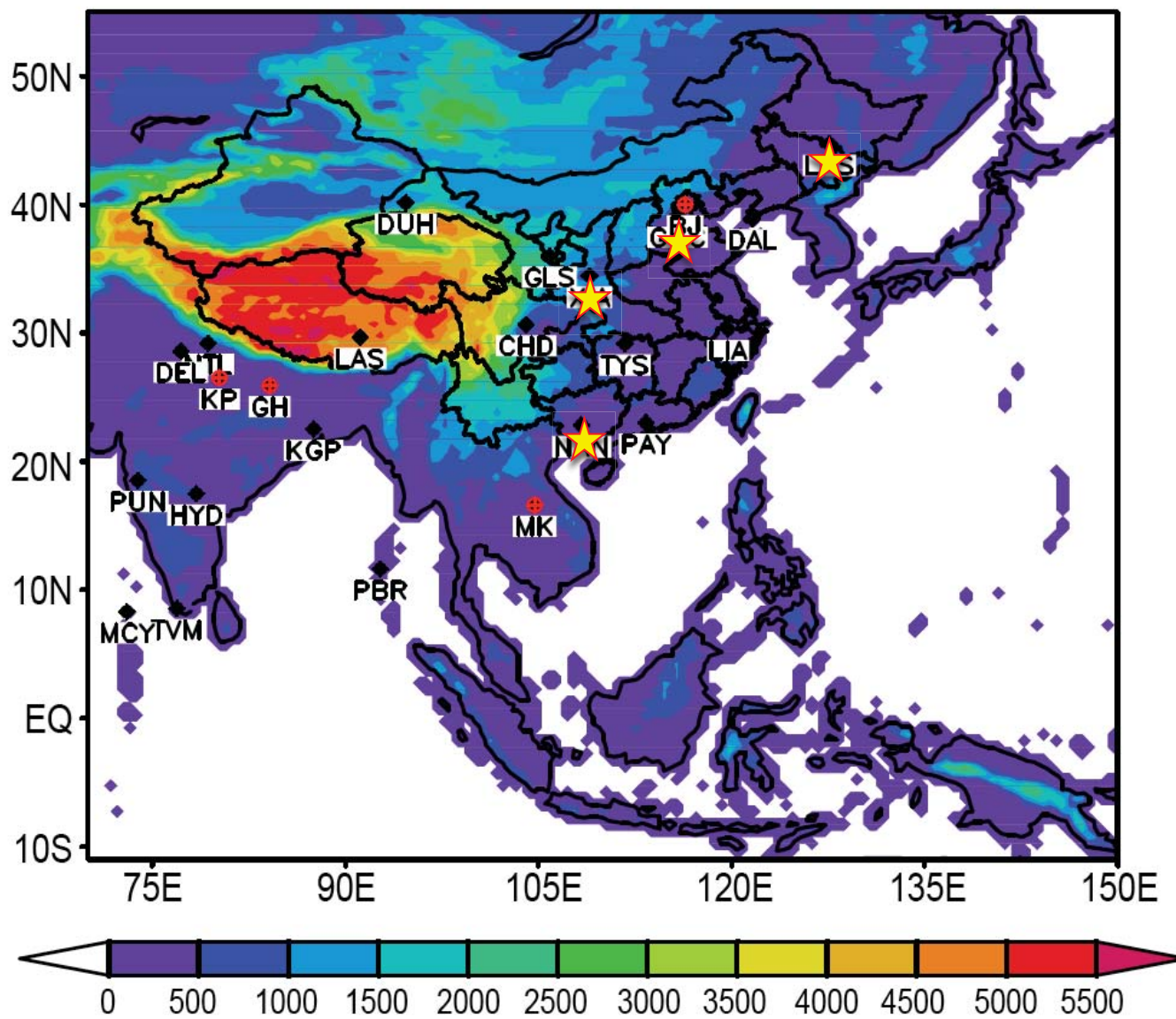


October

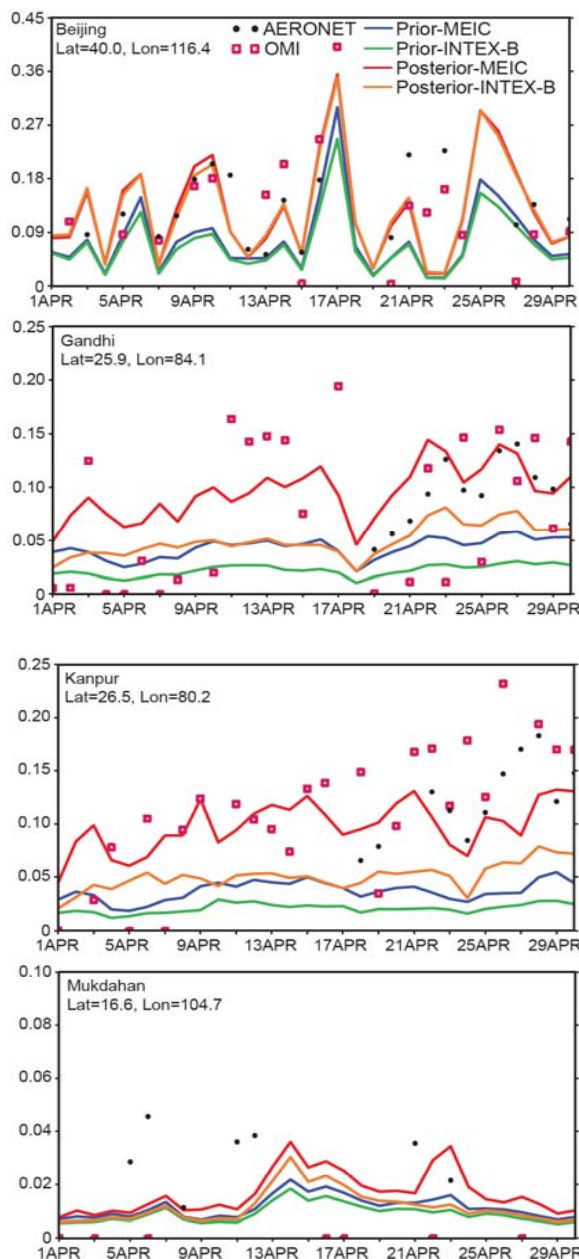


10⁴ Kg

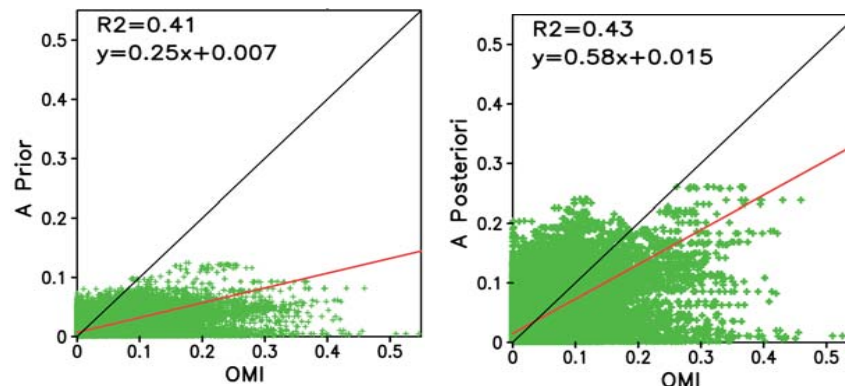
AERONET sites



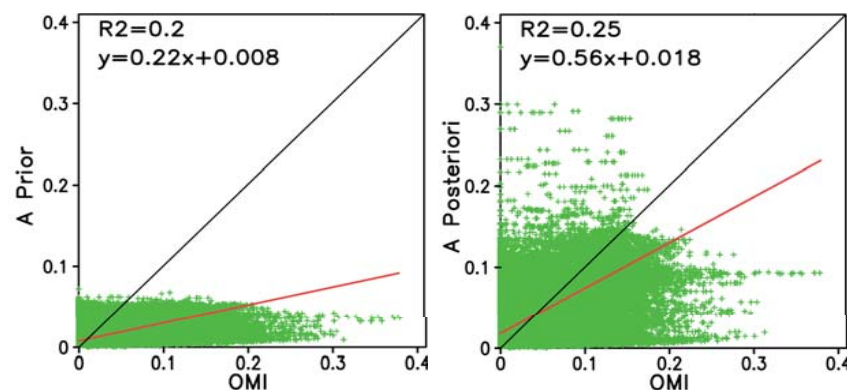
Optimized AAOD evaluation, April 2006



Eastern China (105°-125°E, 20°-45°N)



Indo-Gangetic Plain (70°-90°E, 23°-32°N)

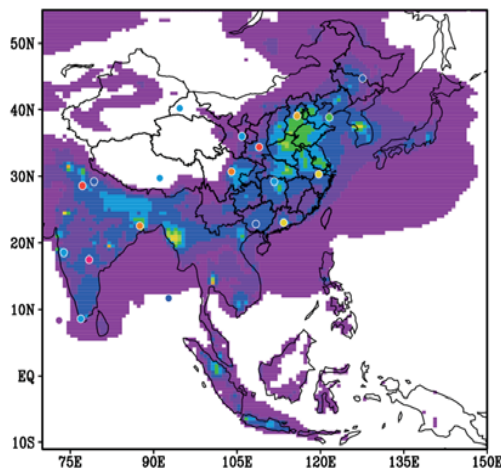


- posterior AAOD consistent with AERONET AAOD observations in April in Beijing and eastern China
- large discrepancies over India and Thailand even after data assimilation
- residual errors associated with limited and sparse OMI AAOD observations, inconsistencies with AERONET products

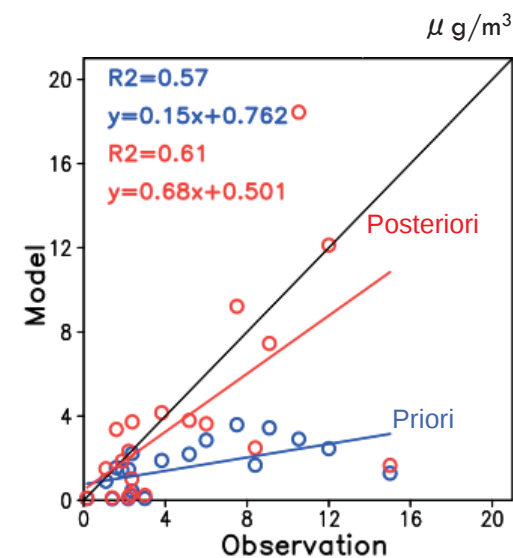
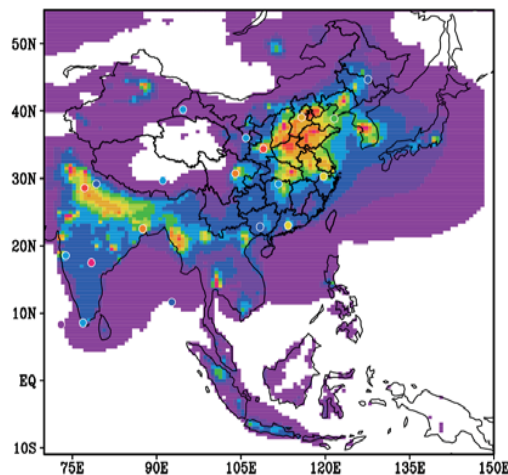
Optimized Surface BC Concentrations

April

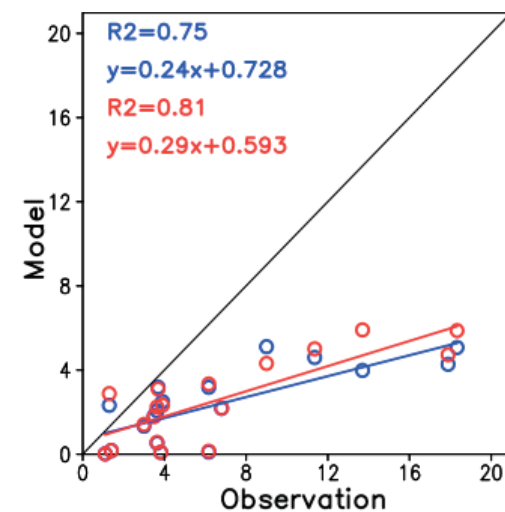
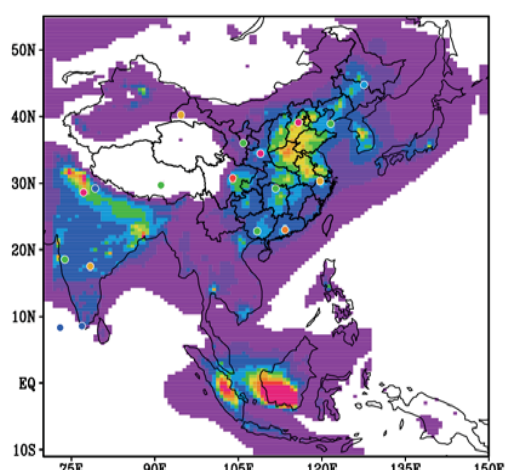
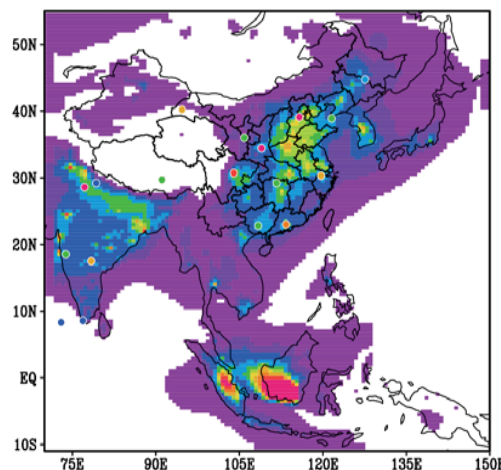
Priori



Posteriori



October



Take Home Points: Constraining BC in GEOS-Chem Adjoint using OMI AAOD

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1. Science: attribution & reduction in uncertainty
 - April: higher anthropogenic emissions after optimization (up to 500%). BB increase significant across south Asia
 - October: +10-50% over eastern China. Higher BB over Indonesia
 - Observational counts near sources determine effectiveness of inversion
2. Tools: ready for operational use
 - top-down, spatially resolved emissions inversion
 - many choices for AOD products & DA methods
3. Policy: better upstream inputs; further improvement by DA requires more satellite and surface obs



INITIAL APPLICATION OF THE WRF ADJOINT FOR BC: FOREST FIRE SMOKE DURING ARCTAS-CARB

JJ Guerrette and DK Henze. Incorporating black carbon aerosol into WRFPLUS adjoint and tangent linear models. *Geosci. Model Dev.*, in preparation.

J.J. Guerette

WRF-Chem Adjoint Development

21

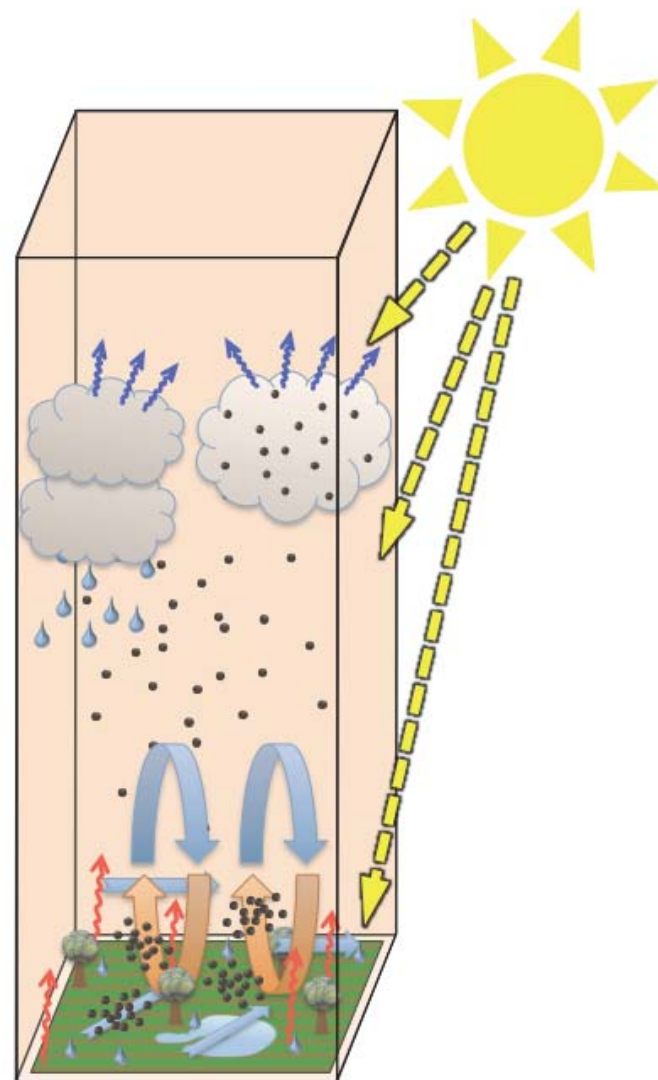
Adjoint: chemical transport

- ✓ Surface-air interactions (LSM,SFCLAY)
- ✓ Turbulent Mixing (PBL)
- ✓ Emissions and Deposition
- ✓ Chemistry (BC aging + sulfate)

Adjoint: climate forcing by aerosols

- Radiation
- Microphysics
- Cumulus Convection

I/O mechanism for long duration
chemical inversions (>3-6hr)

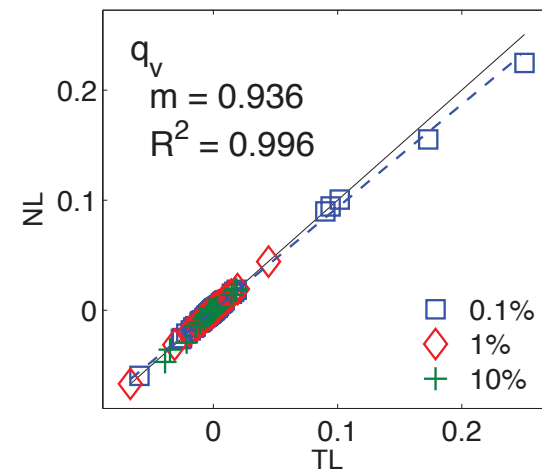
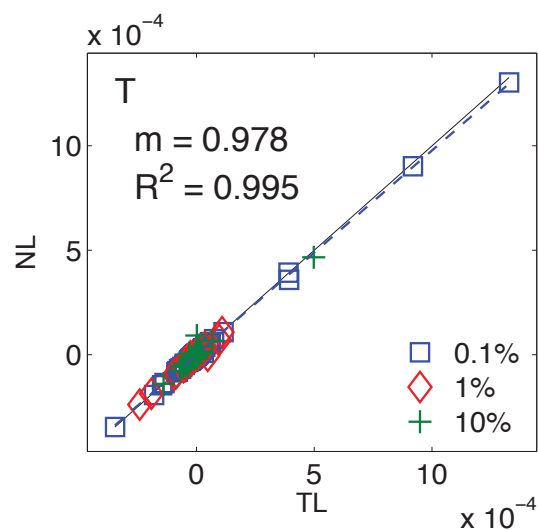
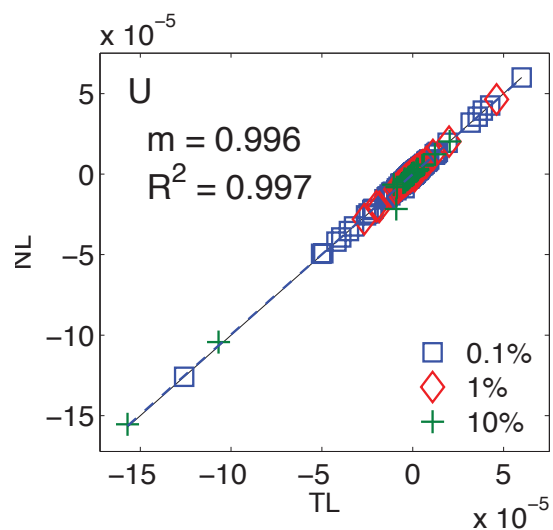
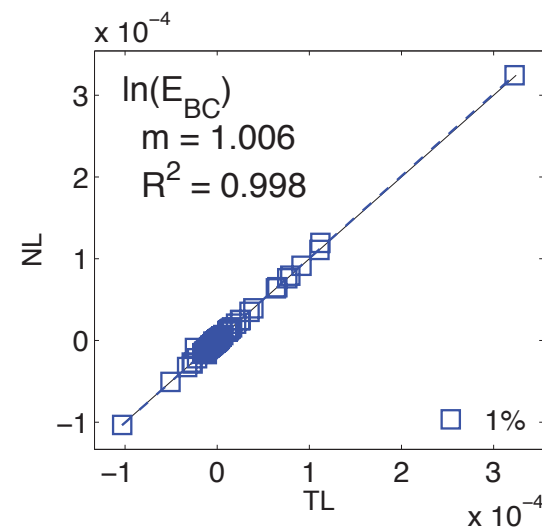
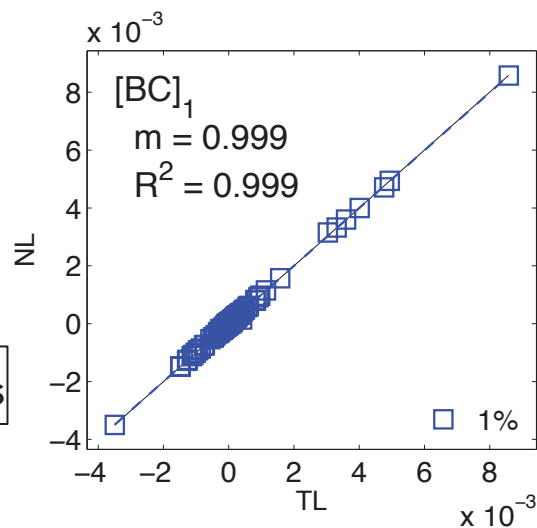


3 hour Derivative Tests

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$$\frac{\partial[\text{BC}]}{\partial X}$$

TL and AD agree to 8+ digits



Sensitivity demonstration: ARCTAS-CARB

Time Period

Jun 20 00Z to Jun 27 09Z, 2008
(Friday to Friday)

Observations

- IMPROVE
 - Jun 20, 23, 26
 - Daily avg. @ ~40 sites (local time)
 - $0.025 \mu\text{g}/\text{m}^3$ mdl
 - 7-50% uncertainty (conc. dependent)
- ARCTAS-CARB (DC-8)
 - Jun 20, 22, 24, 26 (~midday)
 - Single Particle Soot Photometer (SP2)
 - 10 sec sample rate
 - $0.01 \mu\text{g}/\text{m}^3$ mdl
 - 30% uncertainty

Model Configuration

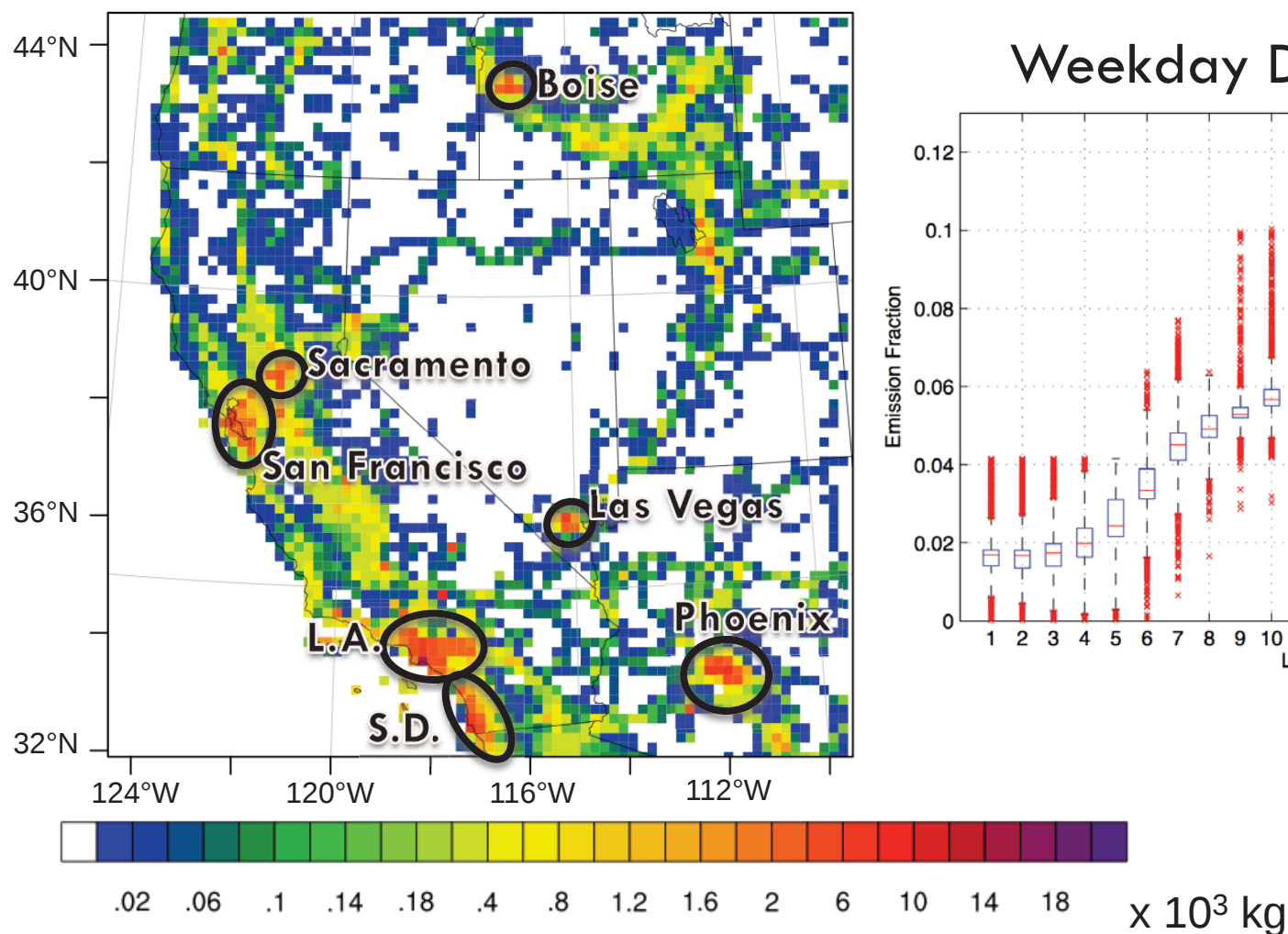
- **WRF-Chem V3.6**
 - 18km – 79 x 79 x 42 levels
 - GOCART Aerosols
- **IC/BC**
 - MET BCs: 32km NARR Reanalysis
 - CHEM spun up from Jun 15
 - $[\text{BC}]_{\text{bound}} = 0.01 \mu\text{g}/\text{m}^3$
- **Emissions**
 - NEI2005 Anthro Emissions (4km)
 - FINN BB Emissions (1km) w/plumerise
- **Physics**
 - ACM2 PBL Mixing (7)
 - Pleim-Xiu SFCLAY & LSM (7)
 - radiation*: RRTM LW (1) & GSFC SW (2)
 - no microphysics, no cumulus convection

*Forward model only for radiation in this application

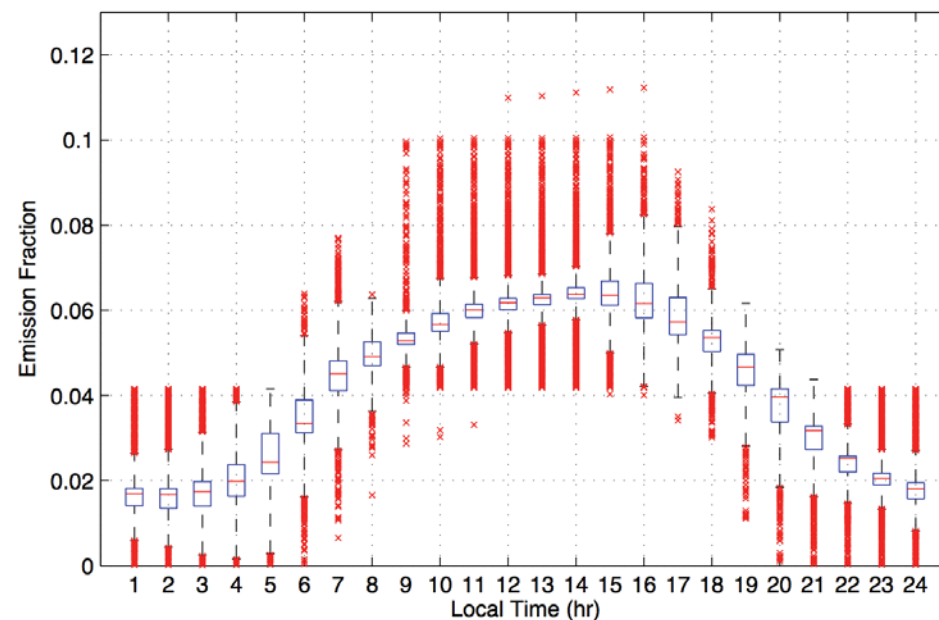
Total Emitted Black Carbon (Jun 20-26, 2008)

24

Anthropogenic - NEI 2005



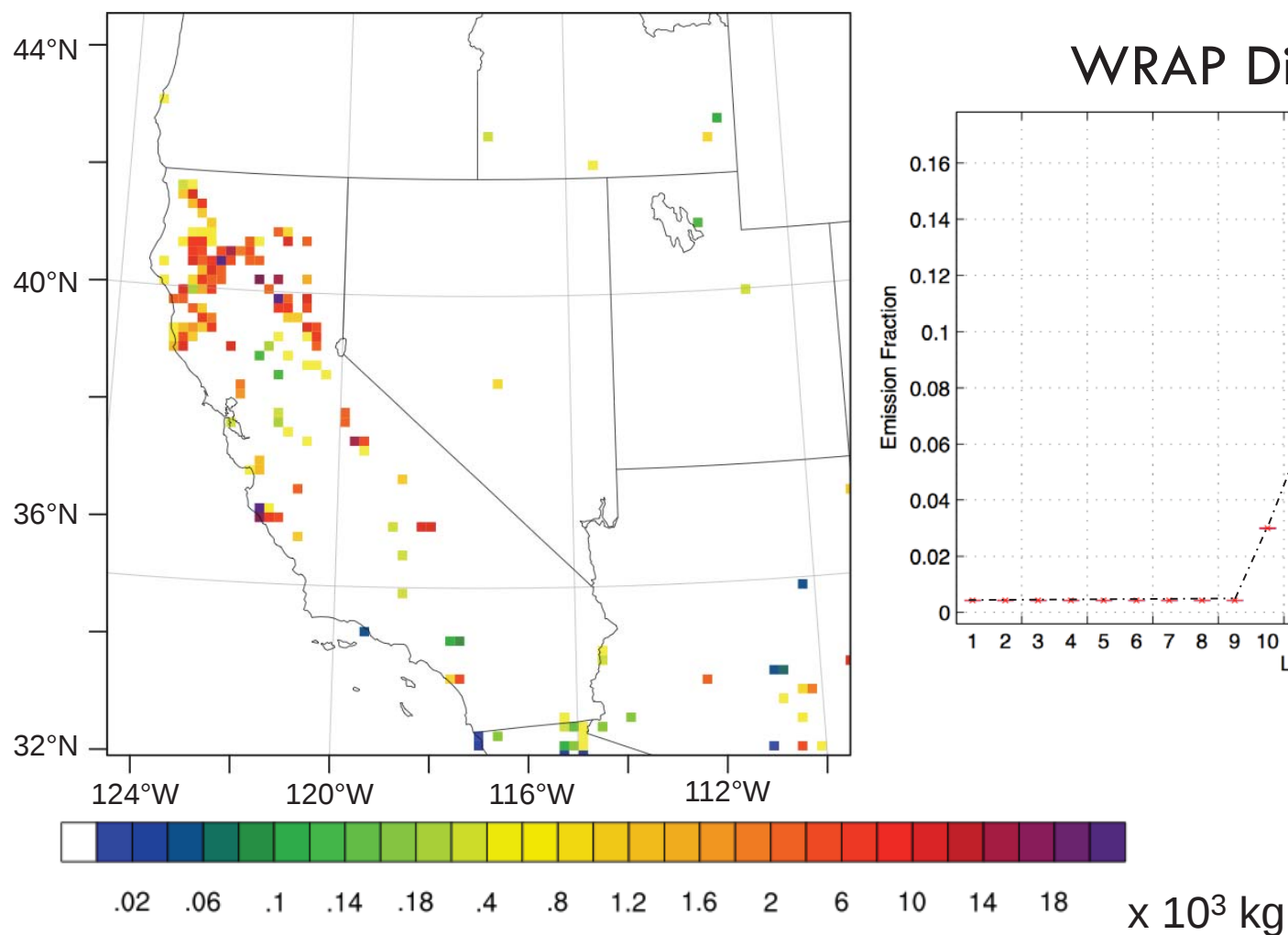
Weekday Diurnal Patterns



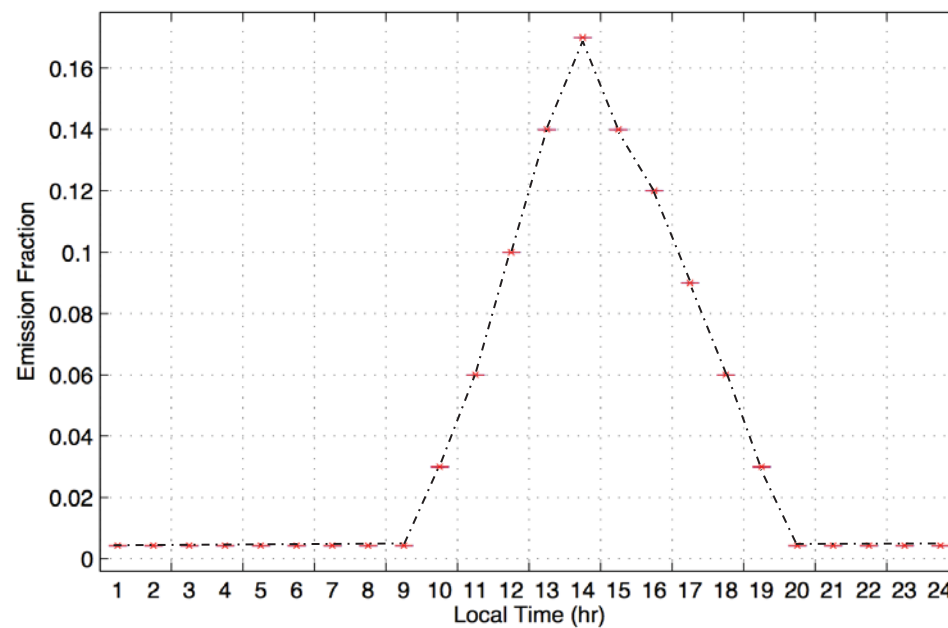
Total Emitted Black Carbon (Jun 20-26, 2008)

25

Burning - FINN



WRAP Diurnal Pattern



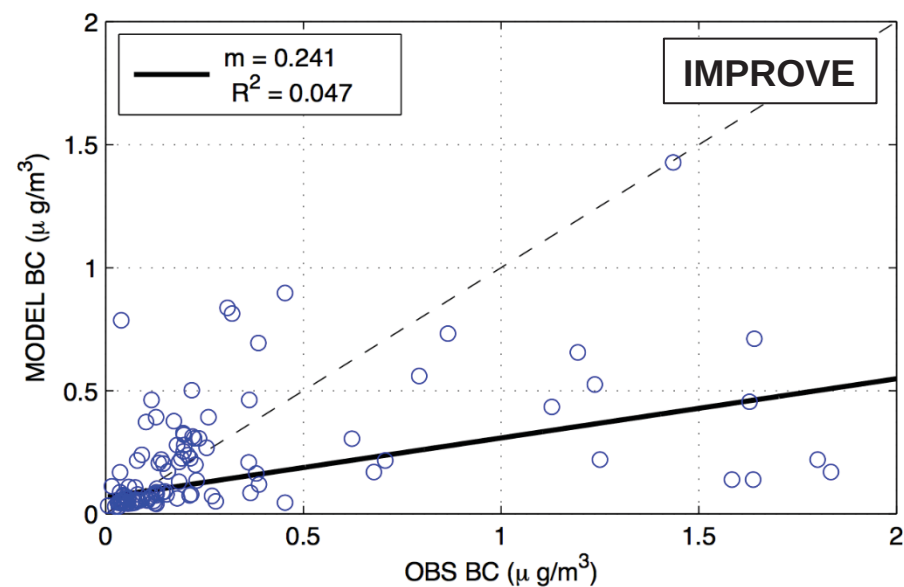
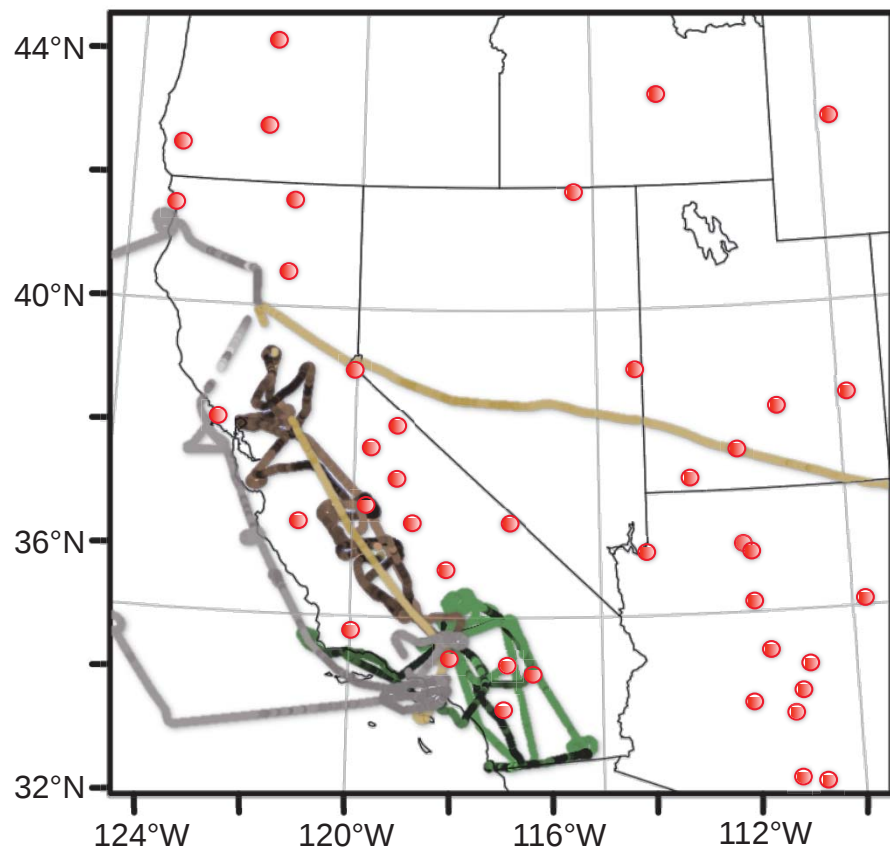
Model to Obs. Comparison

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ARCTAS-CARB, 2008:

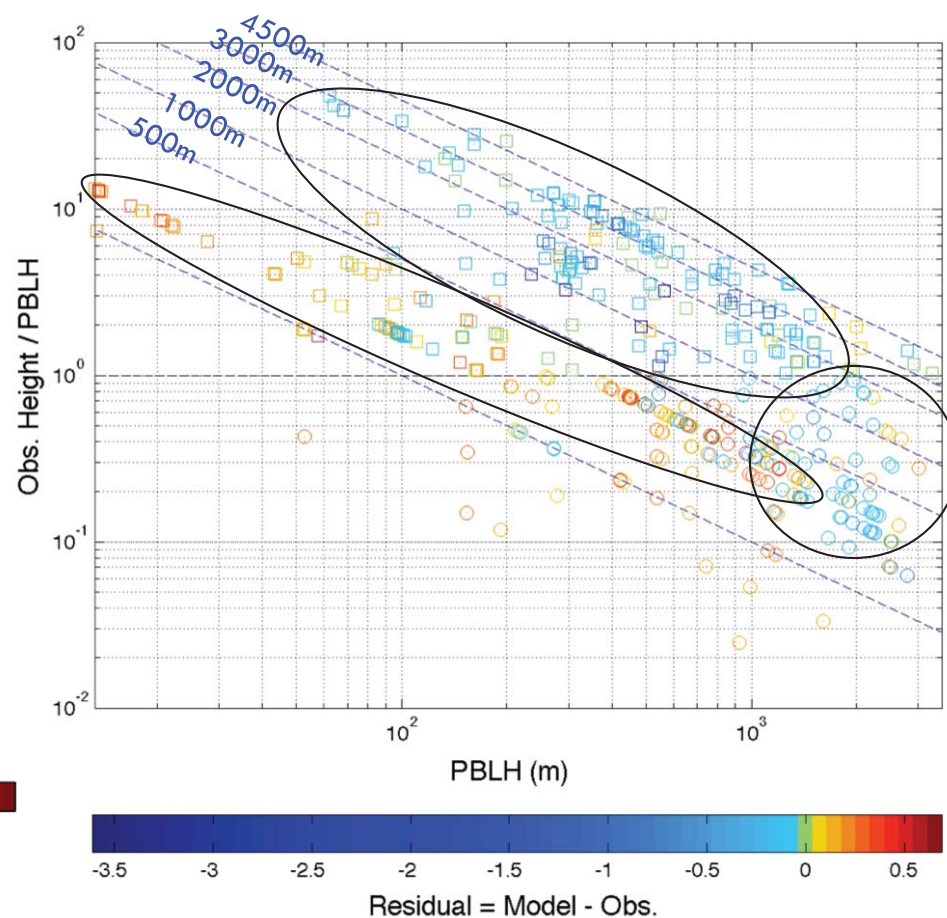
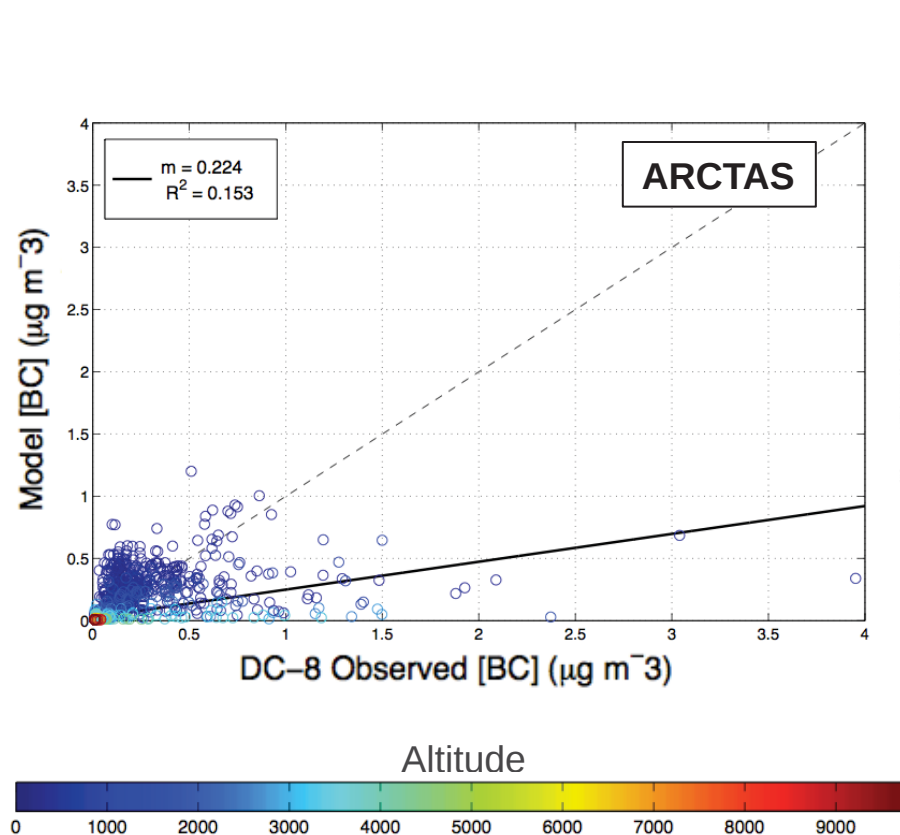


● IMPROVE Sites; June 20, 23, 26



Model to Obs. Comparison

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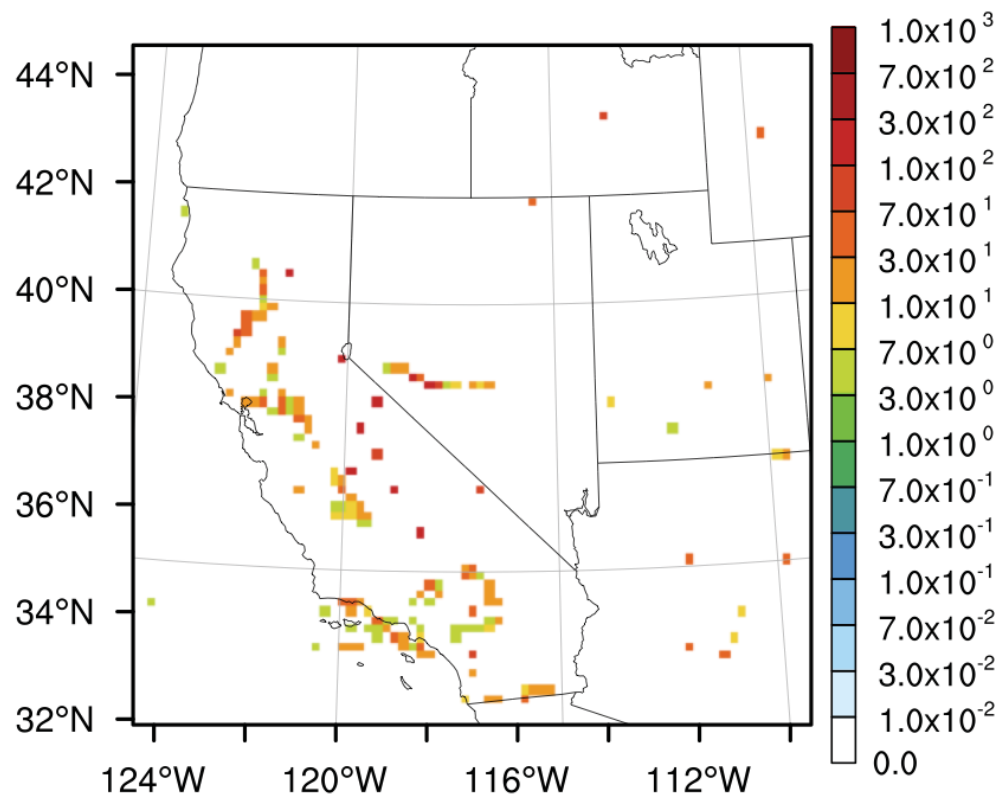


Model/Obs. Misfit structural & parametric uncertainties

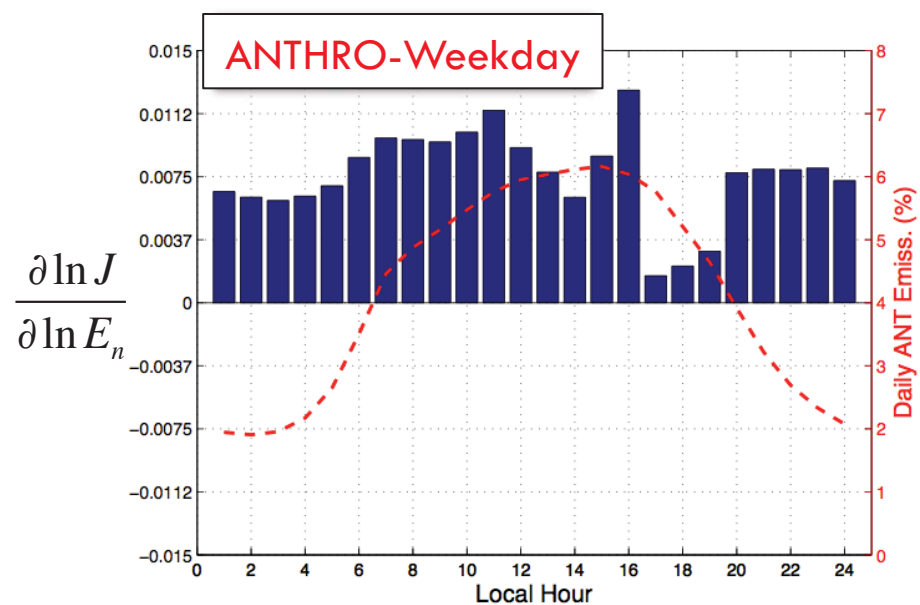
28

$$J = \frac{1}{2} \sum_k \left[H_k \left(M_k (\mathbf{x}) \right) - y_k \right]^T \mathbf{R}^{-1} \left[H_k \left(M_k (\mathbf{x}) \right) - y_k \right]$$

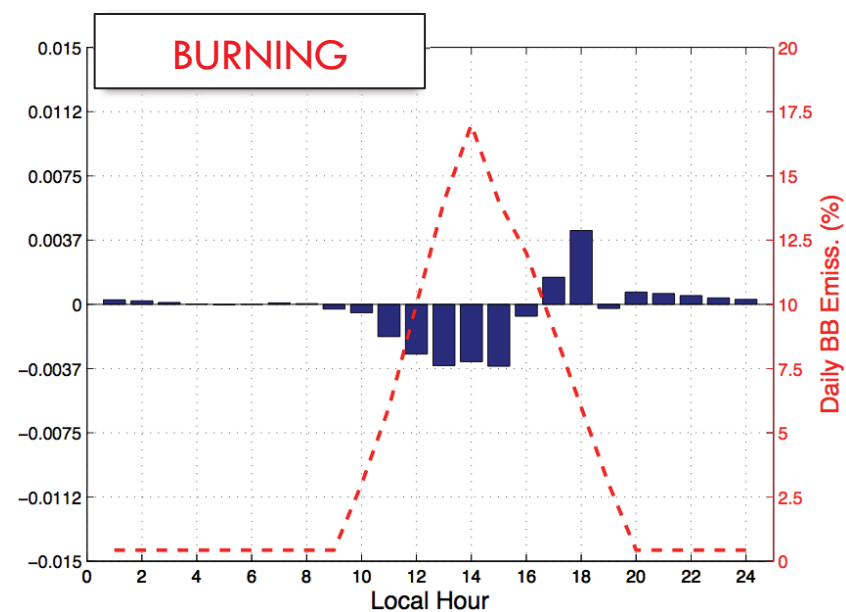
Cost Function



Net Diurnal Sensitivities

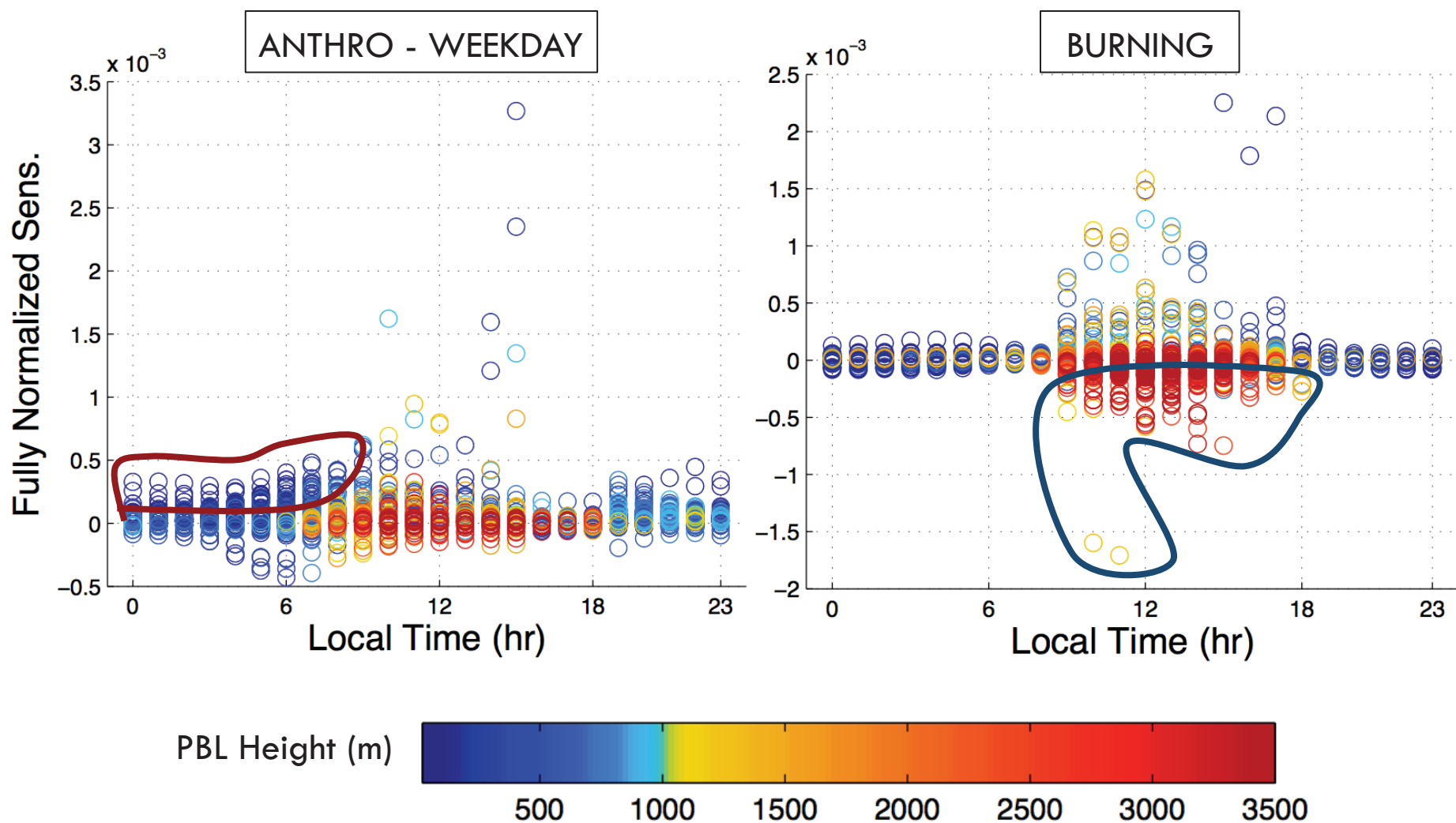


ANTHRO emissions are too high, except during evening rush hour



BURNING peak timing/prominence could be off

PBL Mixing Implications



Take Home Points: WRF Adjoint

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1. Tool: Developed adjoint of NWP + chemistry model
2. Decision Support: Local/regional source attribution
3. Science
 - Enables determination of model process vs. emission contributions to errors
 - Sensitivities of direct & indirect radiative forcing to emissions (ongoing adjoint development)

ASSIMILATION OF NEXT GENERATION GEOSTATIONARY RETRIEVALS & MULTI- PLATFORM INVERSION OF WILDFIRE EMISSIONS

Saide, P.E., Kim, J., Song, C.H., Choi, M., Cheng, Y., Carmichael, G.R., Assimilating next generation geostationary aerosol optical depth retrievals can improve air quality simulations. Submitted.

Saide, P.E., et al. Revealing important nocturnal and day-to-day variations in fire smoke emissions through a novel multiplatform inversion. Submitted.

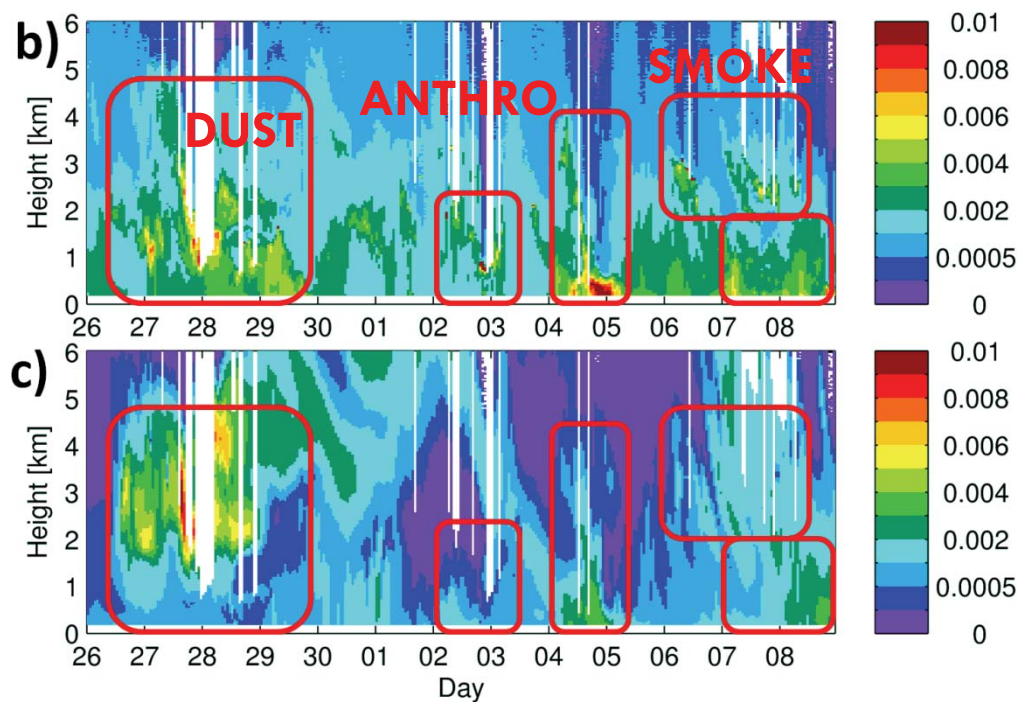
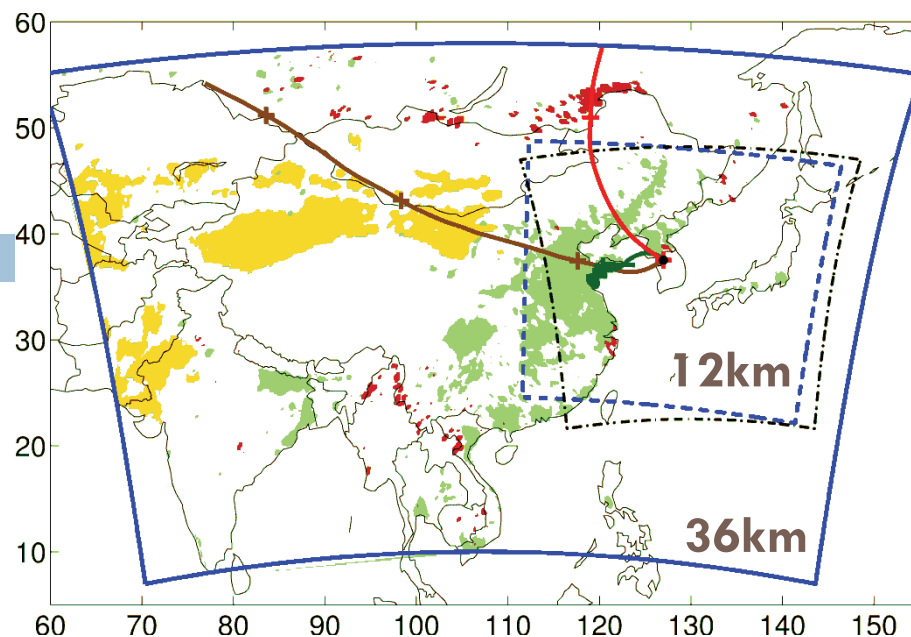


Pablo Saide

East Asia pollution episodes

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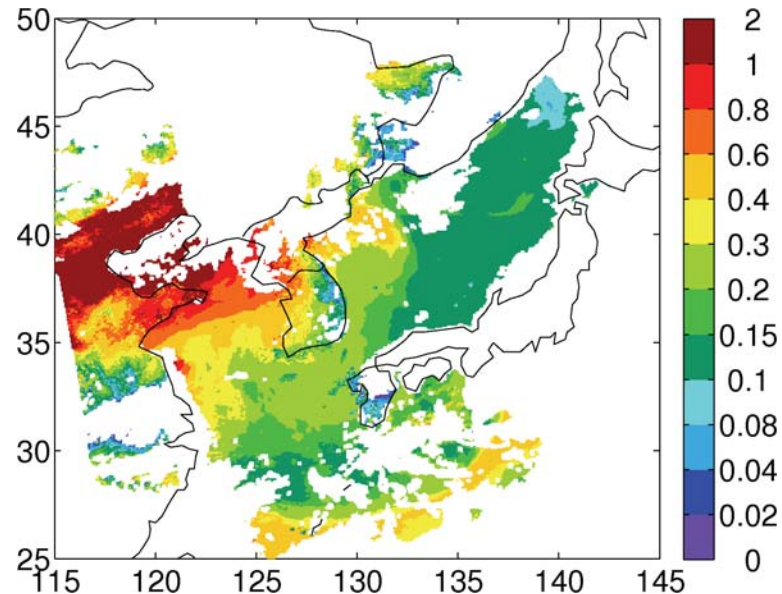
- April 26 – May 9 2012,
3 types of events:
 - ▣ Dust
 - ▣ Anthropogenic
 - ▣ Biomass burning
- WRF-Chem v3.5 CBM-Z, 8bin MOSAIC, anthropogenic emissions (MIX), biomass burning (QFED2), dust (GOCART), MACC boundary conditions
- Regional modeling system resolves episodes but underestimates particle loads



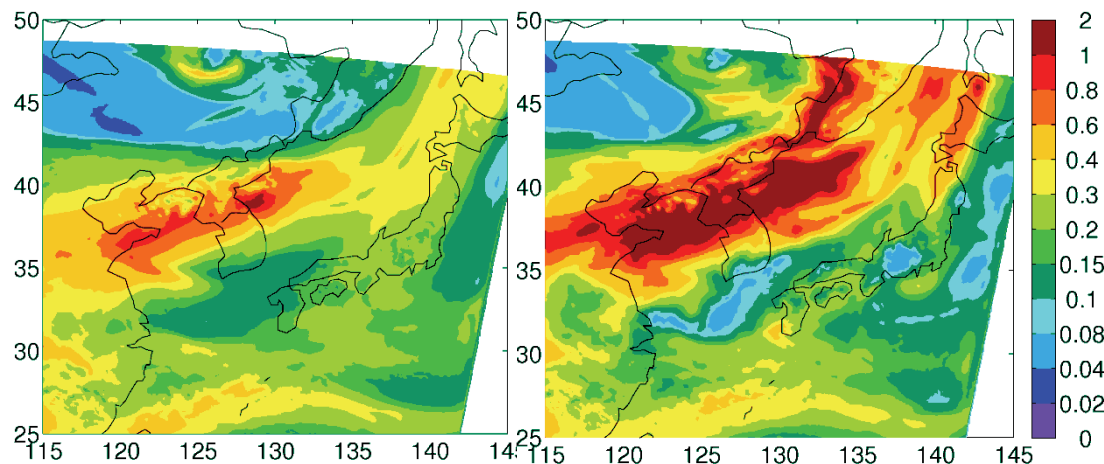
3DVAR experiments

- Objective: Assess performance of adding GOCI AOD to a system already assimilating MODIS AOD
- System: WRF-Chem + GSI for MOSAIC sectional aerosol model (Saide, ACP 2013) supports assimilation of multiple data sources
- GSI AOD assimilation every 3 hours: MODIS, MODIS + GOCI
- GOCI assimilated only over ocean

GOCI AOD



Aug 27-29, 2012



WRF-Chem
NO Assim

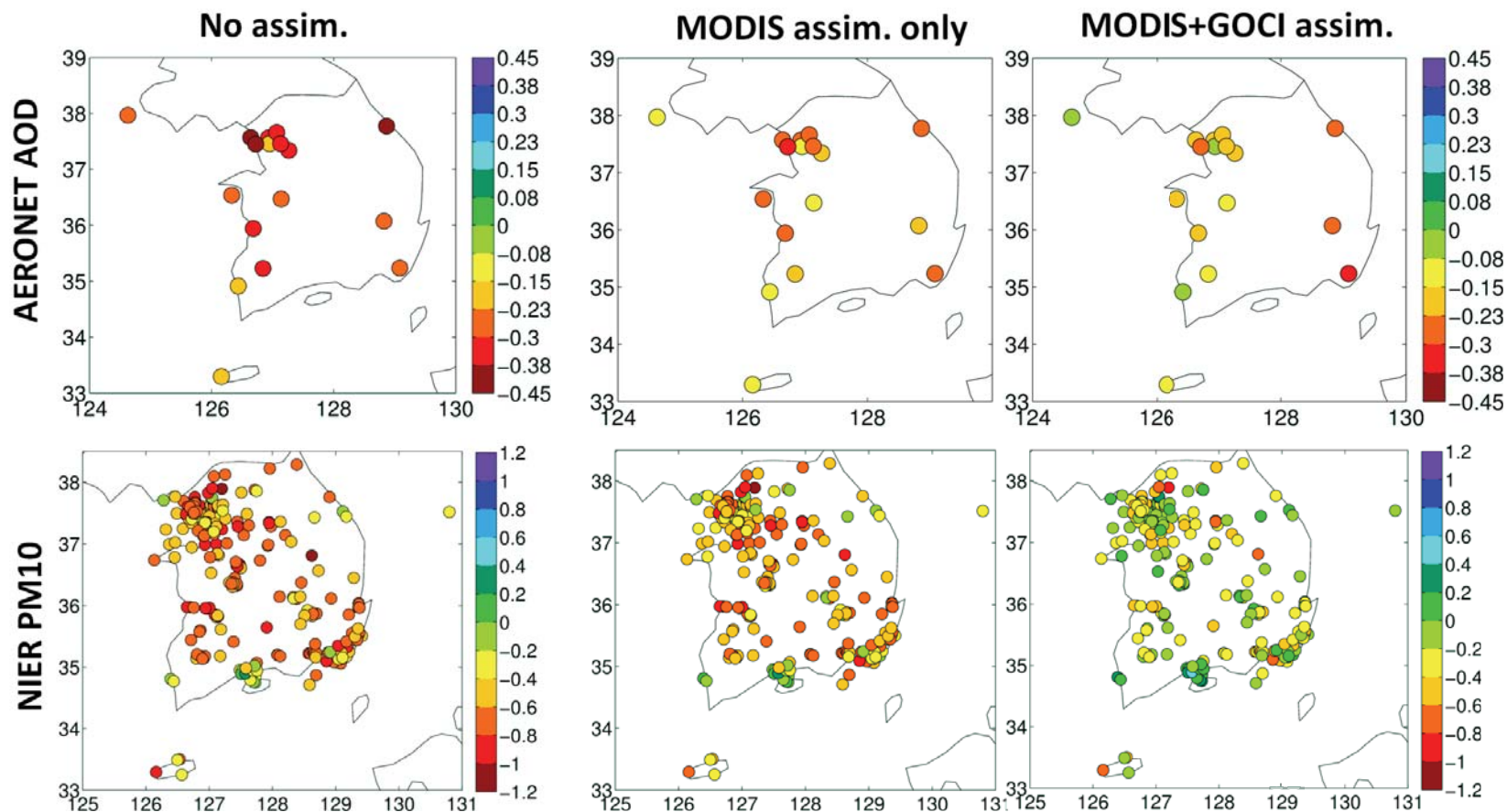
WRF-Chem
MODIS + GOCI Assim

Lee et al., RSE 2010, Park et al., ACP 2014

Improved assimilation from geostationary updates every 3 hours

35

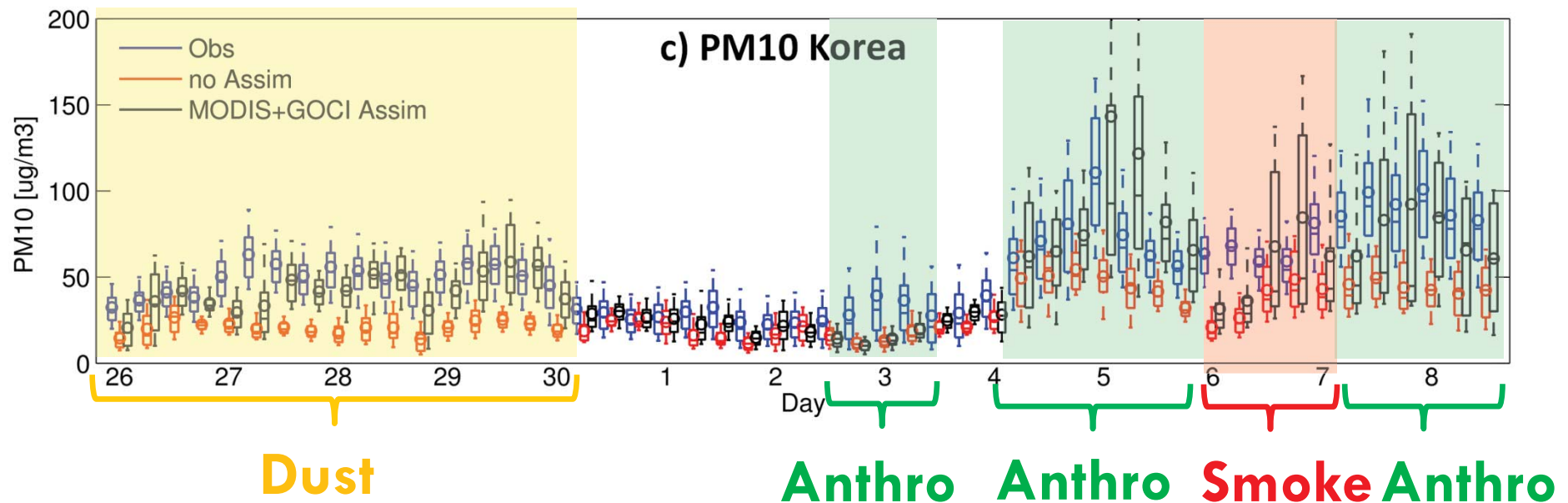
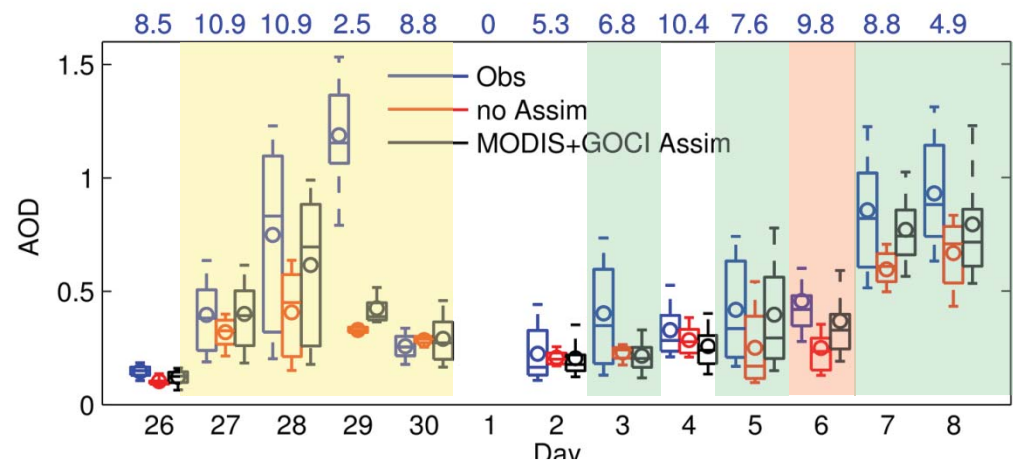
- Evaluation @AERONET DRAGON + PM₁₀ network
- GOCI fills gaps in MODIS (clouds, ocean glint)



Forecasting episode AOD & PM₁₀: from marginal to skillful

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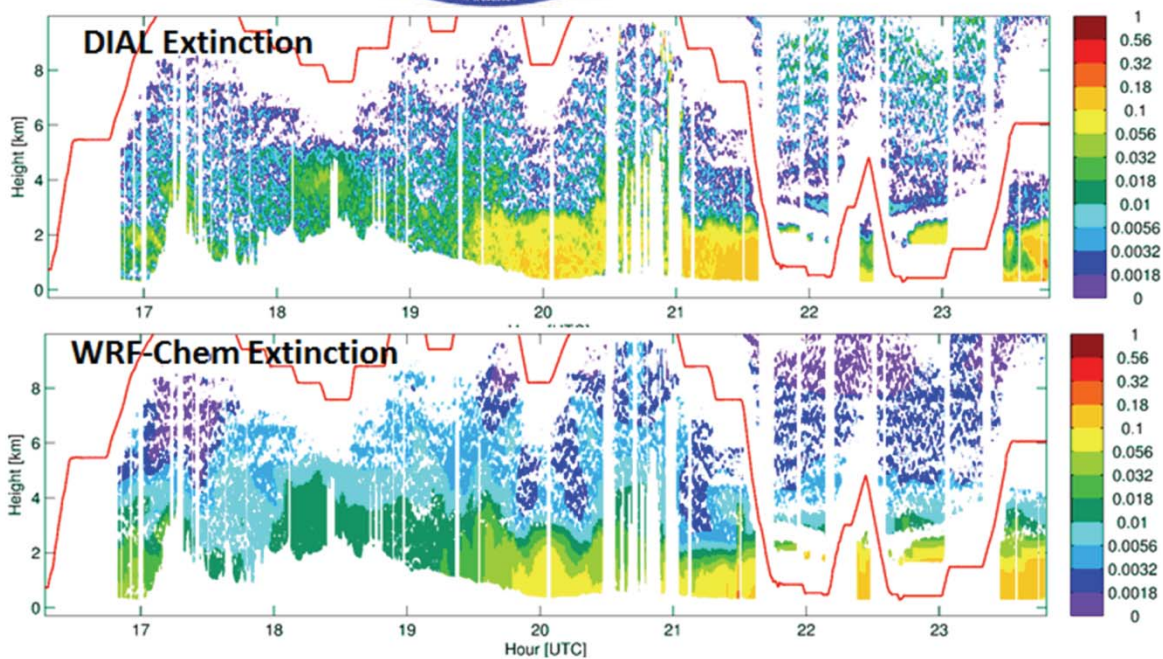
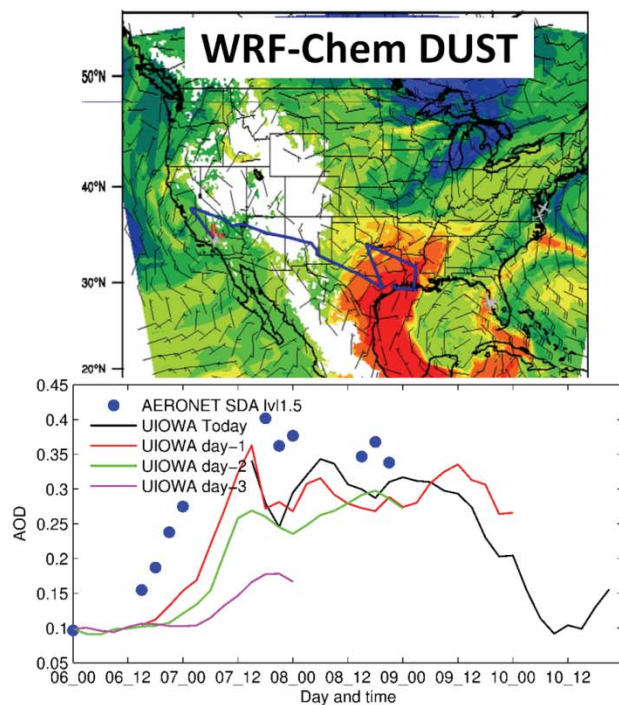
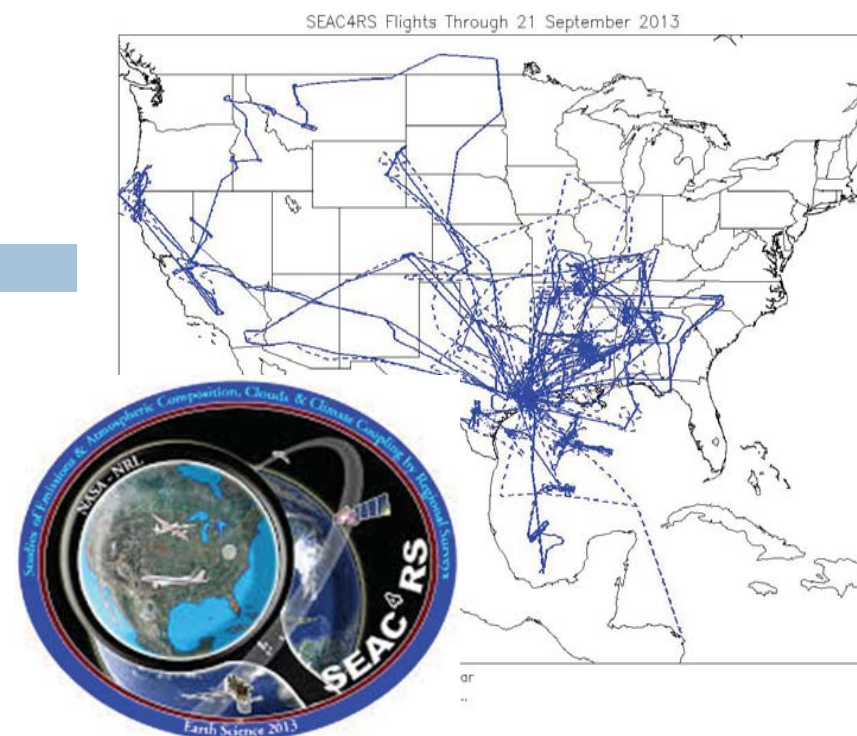
Geostationary DA
improves AQ episode
forecasts: all hours, all
sources



Multiplatform inversion of the 2013 Rim Fire smoke emissions during the SEAC4RS campaign

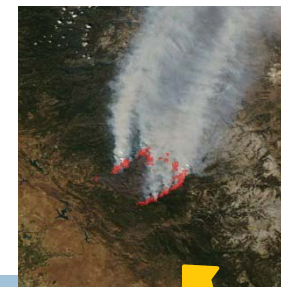
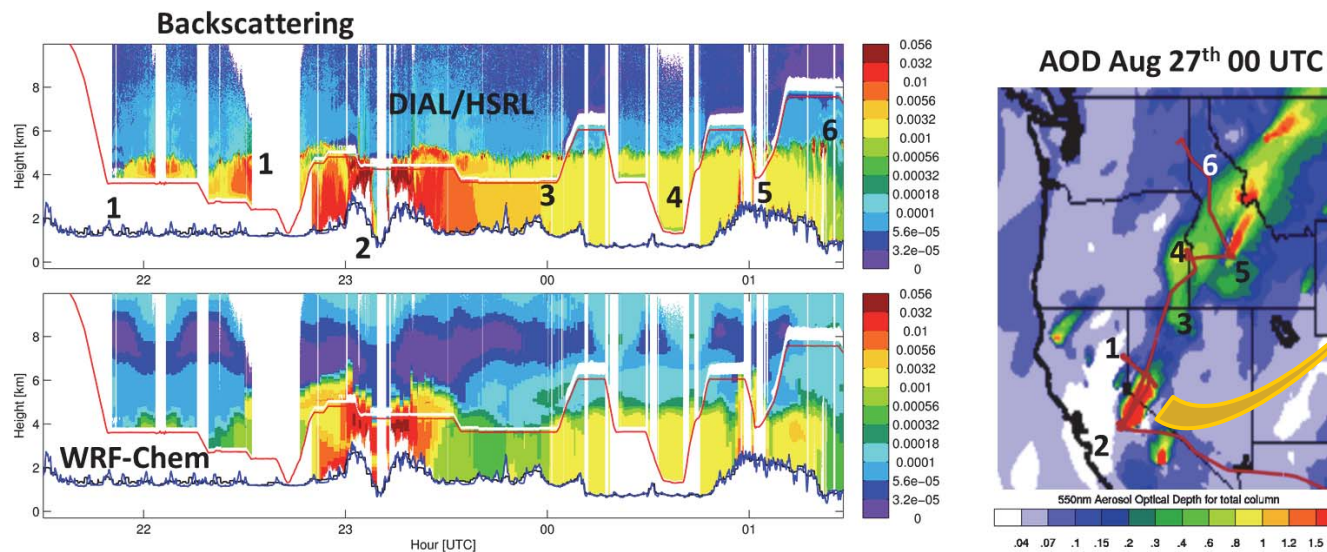
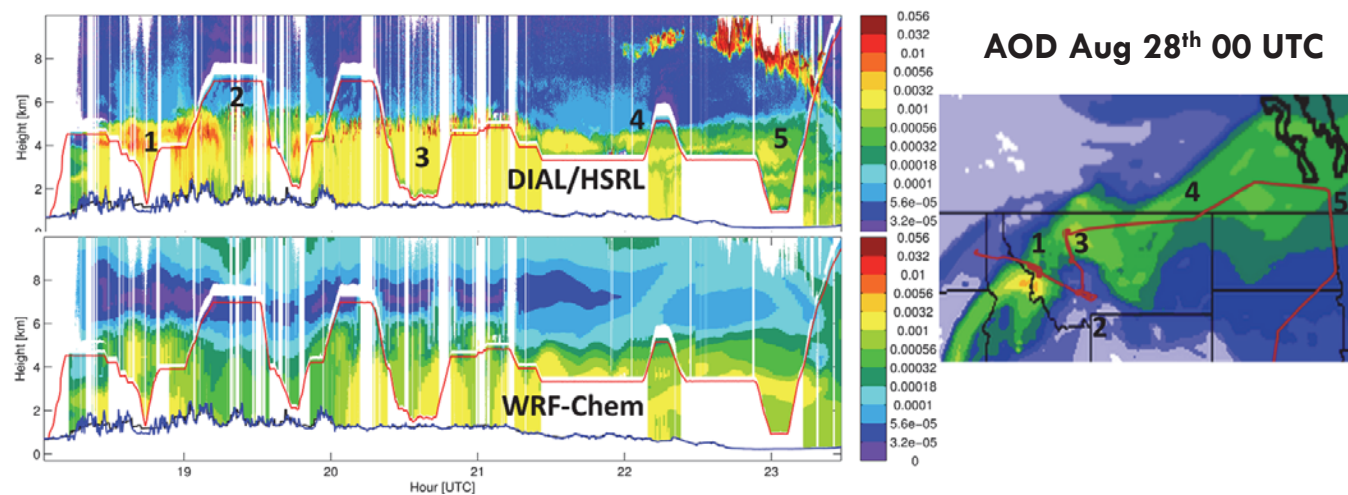
37

- WRF-Chem v3.5, 12km CONUS
- CBM-Z, 4 bin MOSAIC
- NRL AOD assimilated every 3h

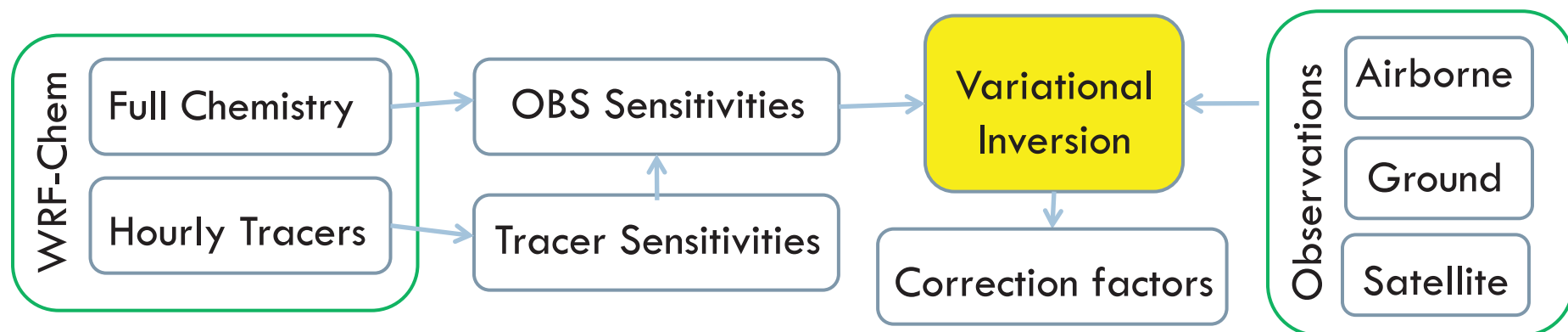


Rim Fire smoke during SEAC4RS

38

**August 26****August 27**

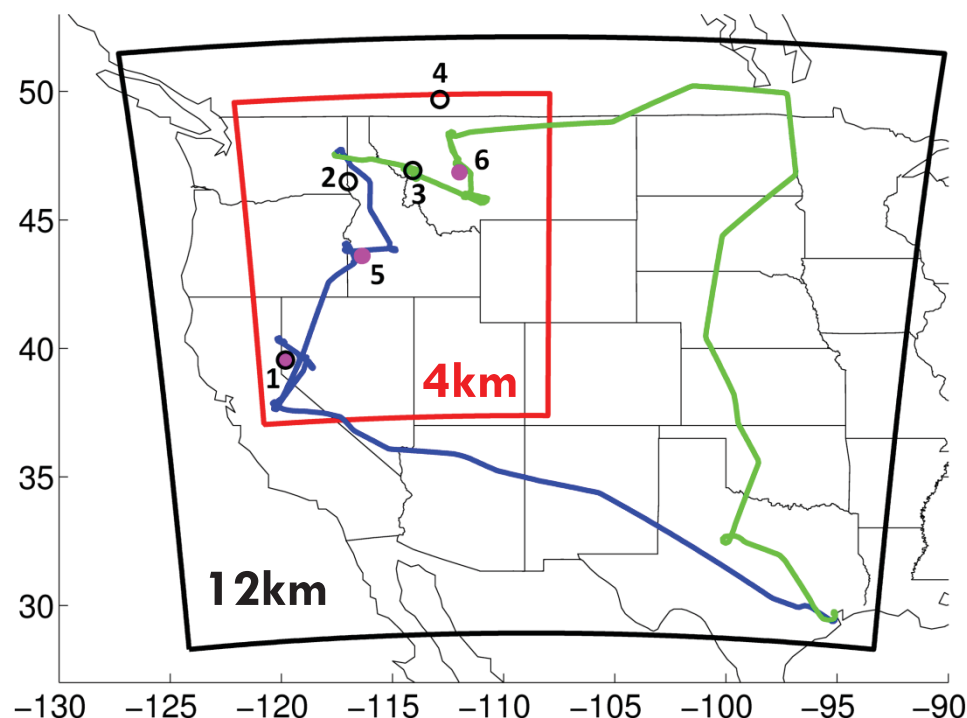
3DVAR emission inversion



- Simultaneously improve model fit to multiple measurements:

- ▣ SEAC4RS in-situ (OA, CO, extinction) and remote sensing (DIAL-HSRL Extinction) from 2 flights
 - ▣ AERONET AOD (1, 2, 3, 4)
 - ▣ Ground-based CO (1, 5, 6)
 - ▣ Satellite AOD

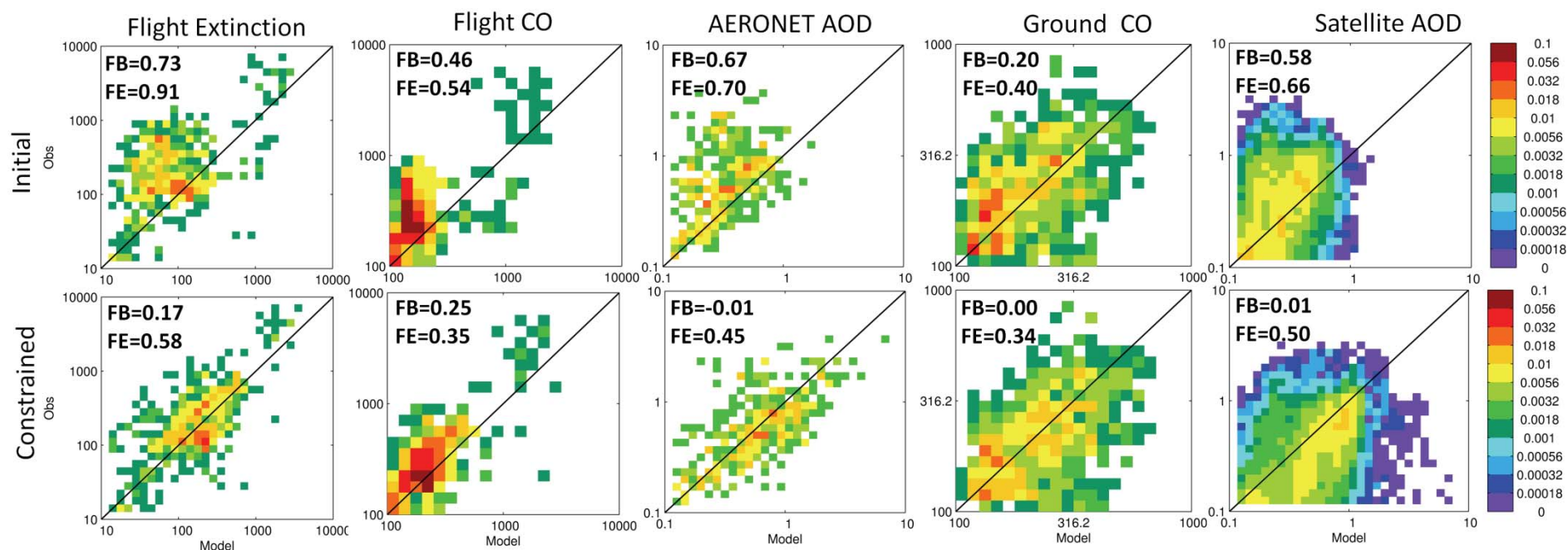
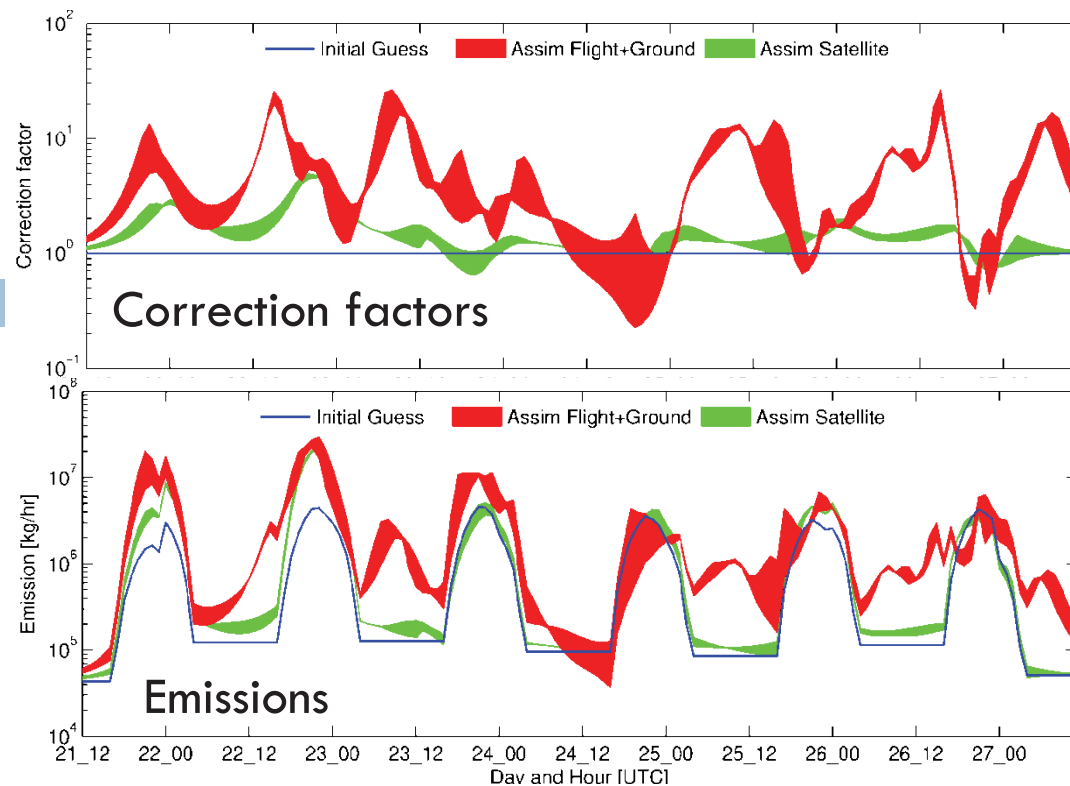
- 2 met boundary conditions (FNL, NARR)



Inversion Process

40

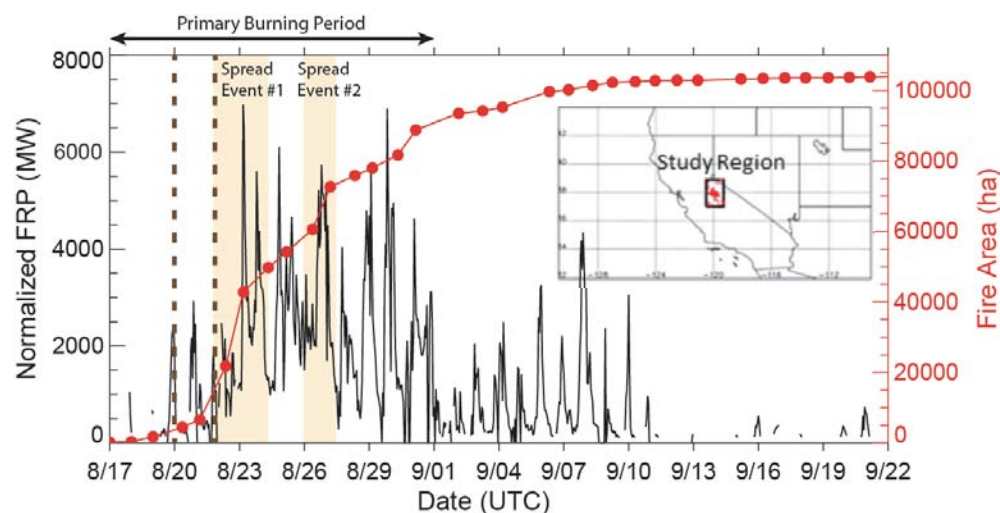
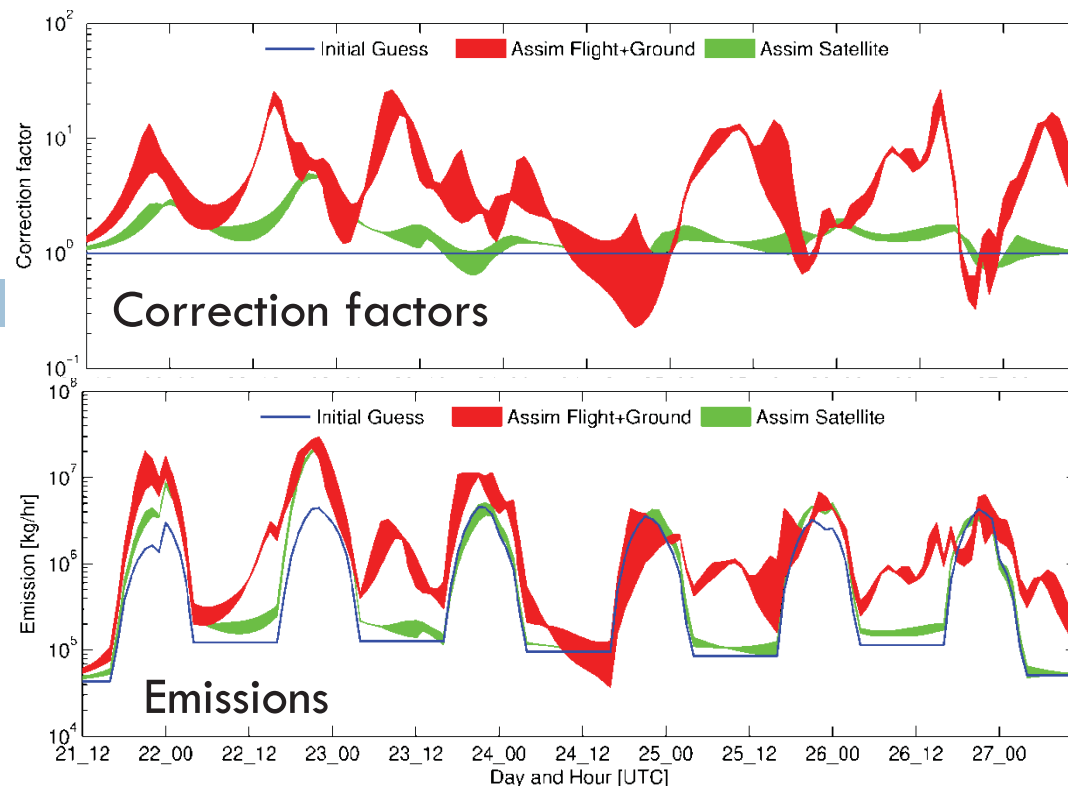
- Constrained emissions factor of 3 higher
- FNL & NARR inversions consistent



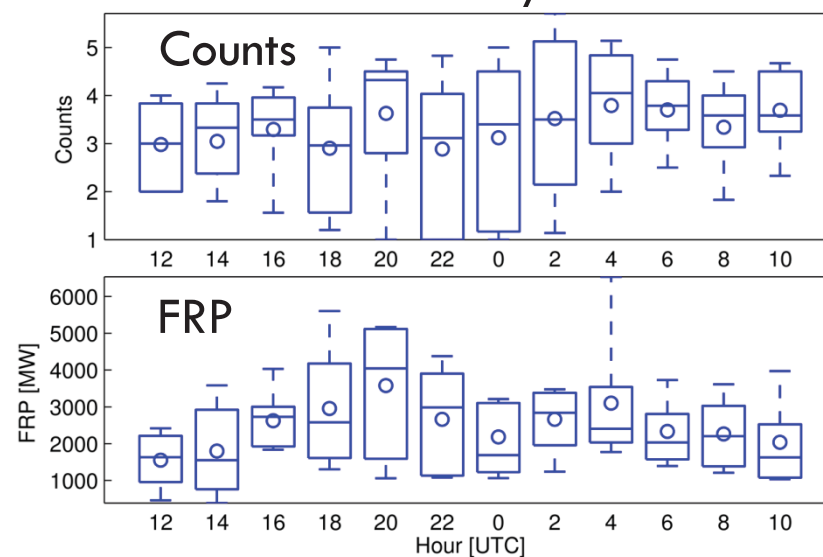
Inversion Results

41

- Flight + Ground
higher correction
factors than satellite
- Nocturnal emissions
up to 26x higher



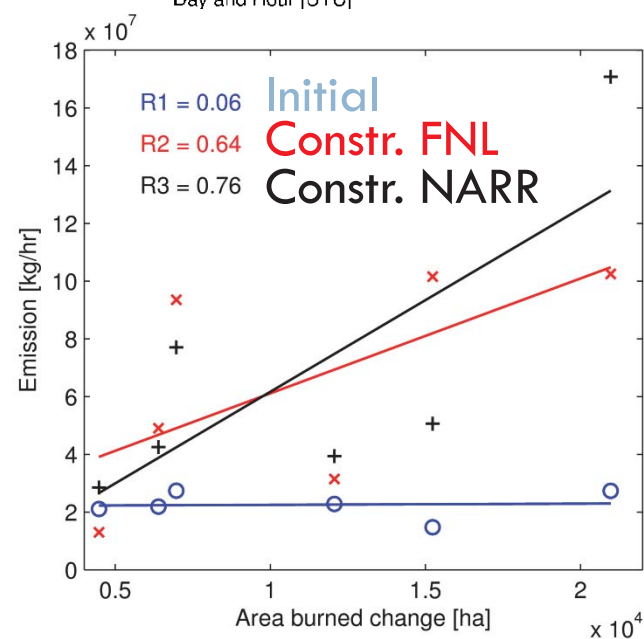
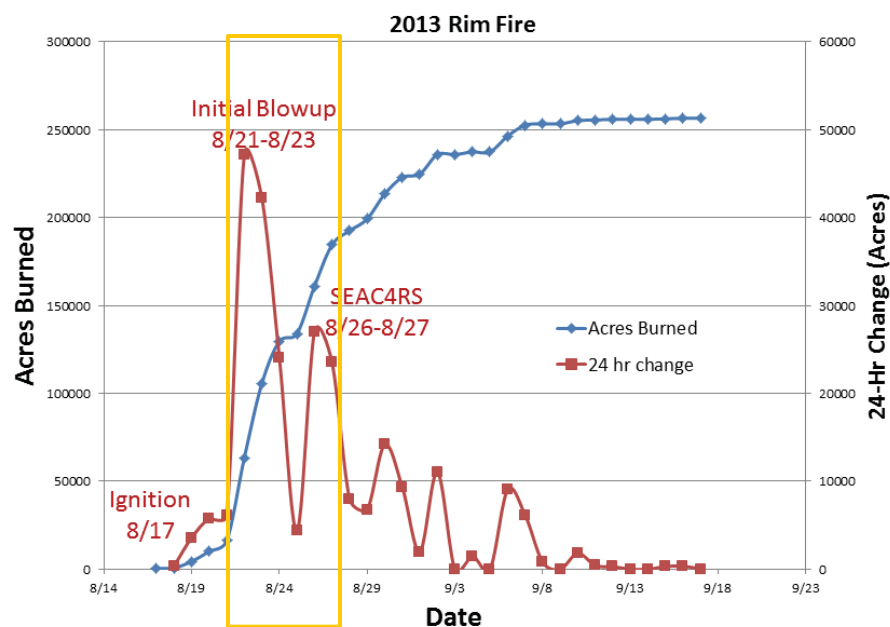
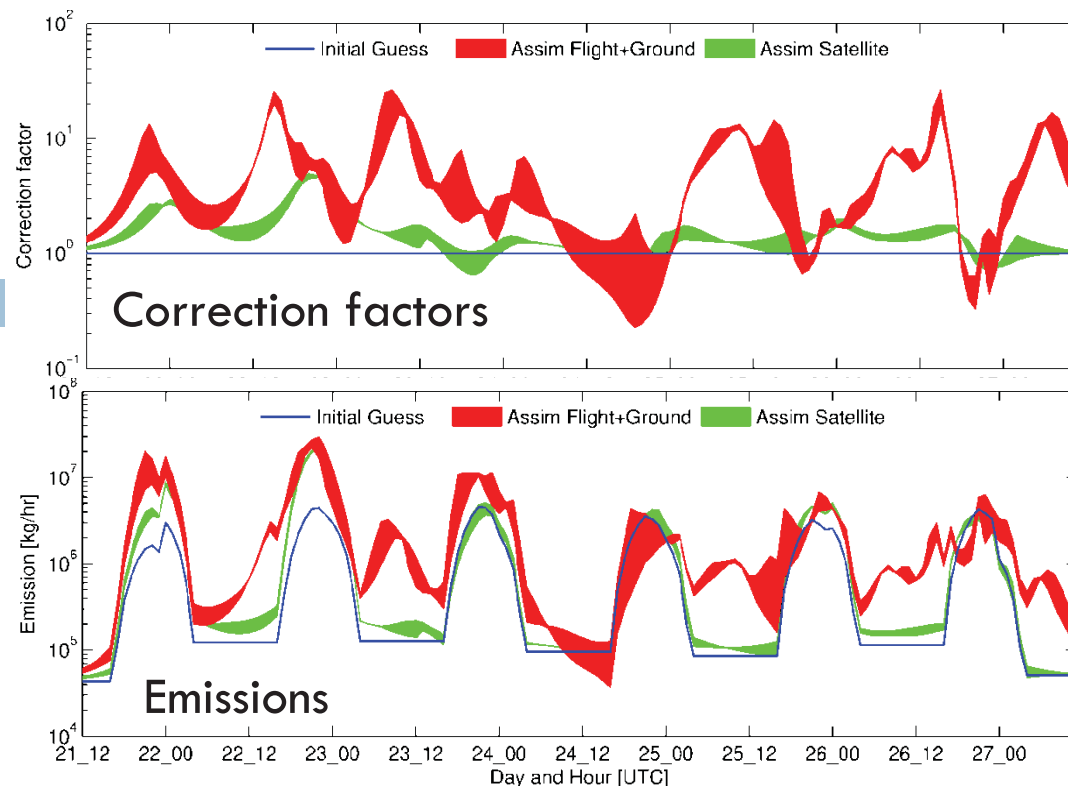
Diurnal Cycle



Inversion Results

42

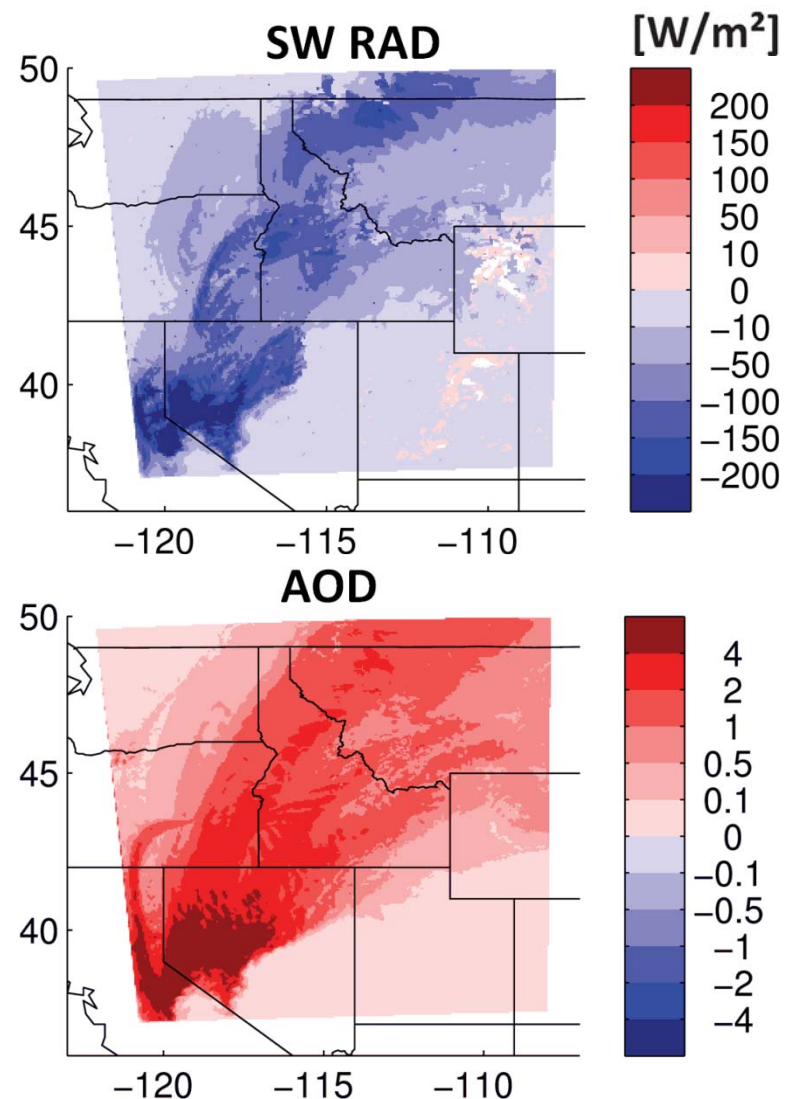
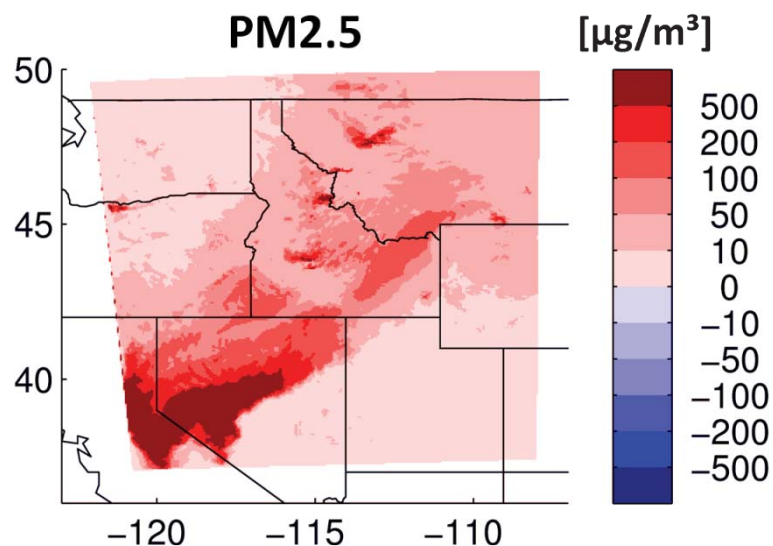
Day to day variability
in constrained emissions
correlates to daily
burned area from
airborne infrared obs



Impacts on smoke $PM_{2.5}$, AOD, radiative forcing

43

- Maximum changes, posterior – prior
- Methods support constraint across observed $PM_{2.5}$ range: 4 orders of magnitude



Take Home Points: GSI Assimilation

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1. Science

- Constraining fire emissions with multiple data sources can better characterize fires and improve air quality predictions
- Assimilating next gen geostationary AOD improves air quality forecasts

2. Tools

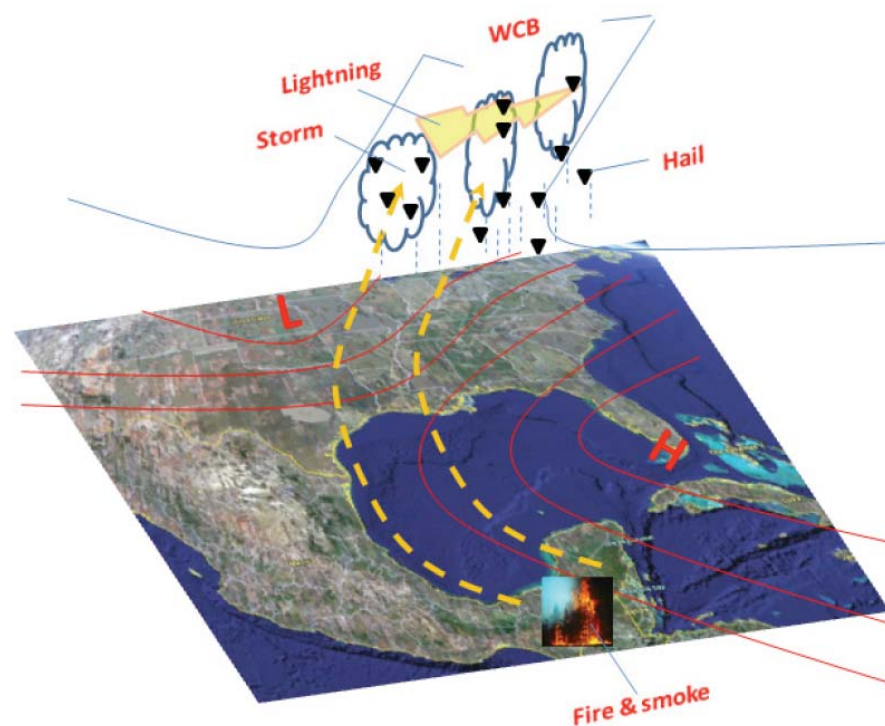
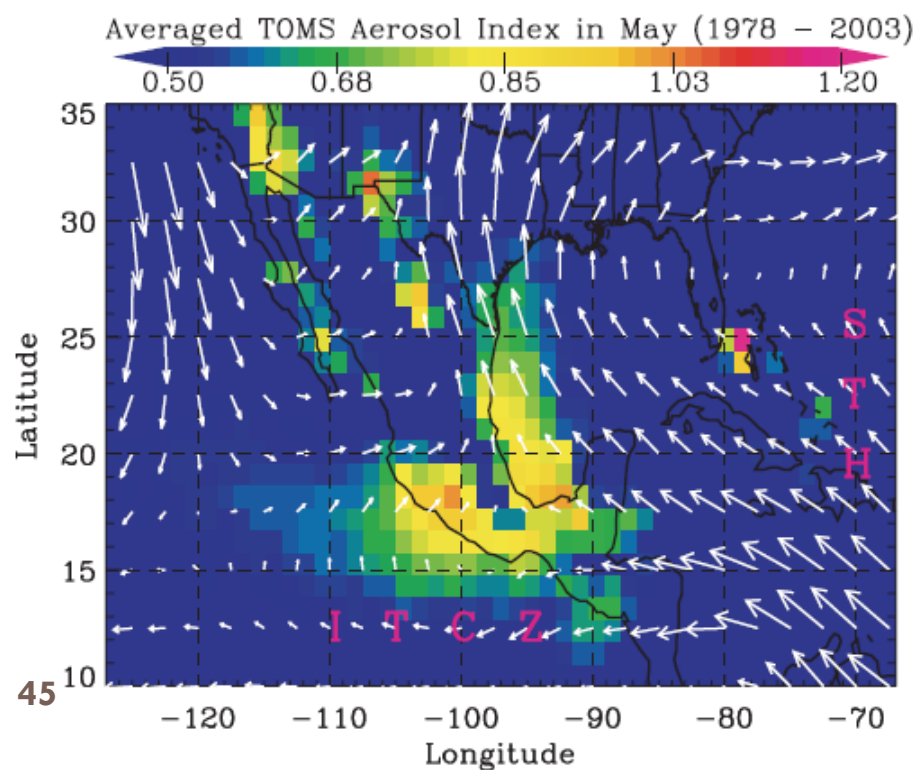
- Practical additions to GSI + any model
- Next: GSI + WRFPLUS adjoint = BC 4DVAR

3. Decision Support

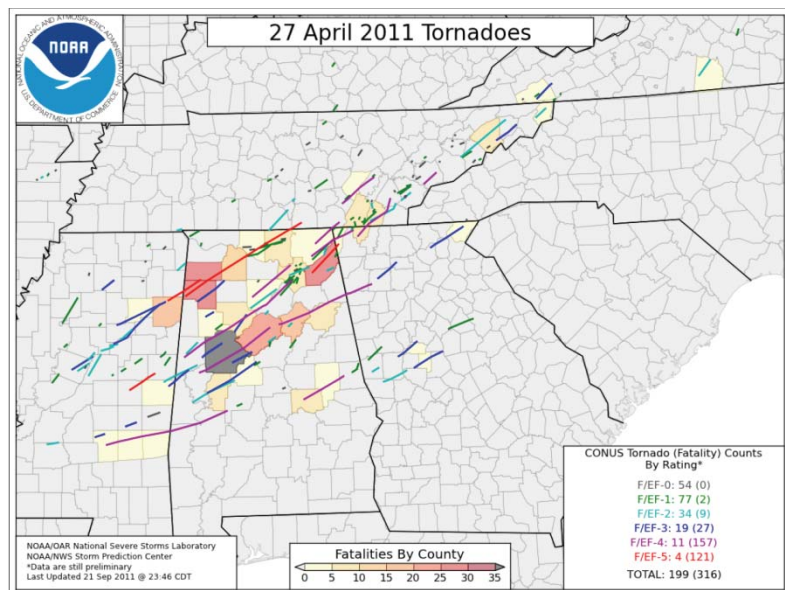
- Fast track to better inputs for monitor siting, forecasting, SIP, policy analysis applications

A conceptual model for the link between Central American biomass burning aerosols and severe weather over the south central United States

Jun Wang^{1,2,3,6}, Susan C van den Heever⁴ and Jeffrey S Reid⁵



Case Study: 27 April 2011 outbreak



Weather - April 2012, Vol. 67, No. 4



METEOROLOGICAL OVERVIEW OF THE DEVASTATING 27 APRIL 2011 TORNADO OUTBREAK

BY KEVIN R. KNUPP, TODD A. MURPHY, TIMOTHY A. COLEMAN, RYAN A. WADE, STEPHANIE A. MULLINS, CHRISTOPHER J. SCHULTZ, ELISE V. SCHULTZ, LAWRENCE CAREY, ADAM SHERRER, EUGENE W. MCCAUL JR., BRIAN CARCIONE, STEPHEN LATIMER, ANDY KULA, KEVIN LAWS, PATRICK T. MARSH, AND KIM KLOCKOW

The tornadoes of spring 2011 in the USA: an historical perspective

Charles A. Doswell III^{1,2},
Gregory W. Carbin³ and
Harold E. Brooks⁴

historical record of tornadoes in the USA. The past offers considerable insight into the deadly tornado events of this past spring, and may also provide a glimpse into the

tornado that strikes in an area with little or no human population may have minimal societal impact even if it is large and violent; these rural events are likely to be under-

CONUS Tornado (Fatality) Counts By Rating*

F/EF-0: 54 (0)
F/EF-1: 77 (2)
F/EF-2: 34 (9)
F/EF-3: 19 (27)
F/EF-4: 11 (157)
F/EF-5: 4 (121)

TOTAL: 199 (316)

Service Assessment

The Historic Tornadoes of April 2011



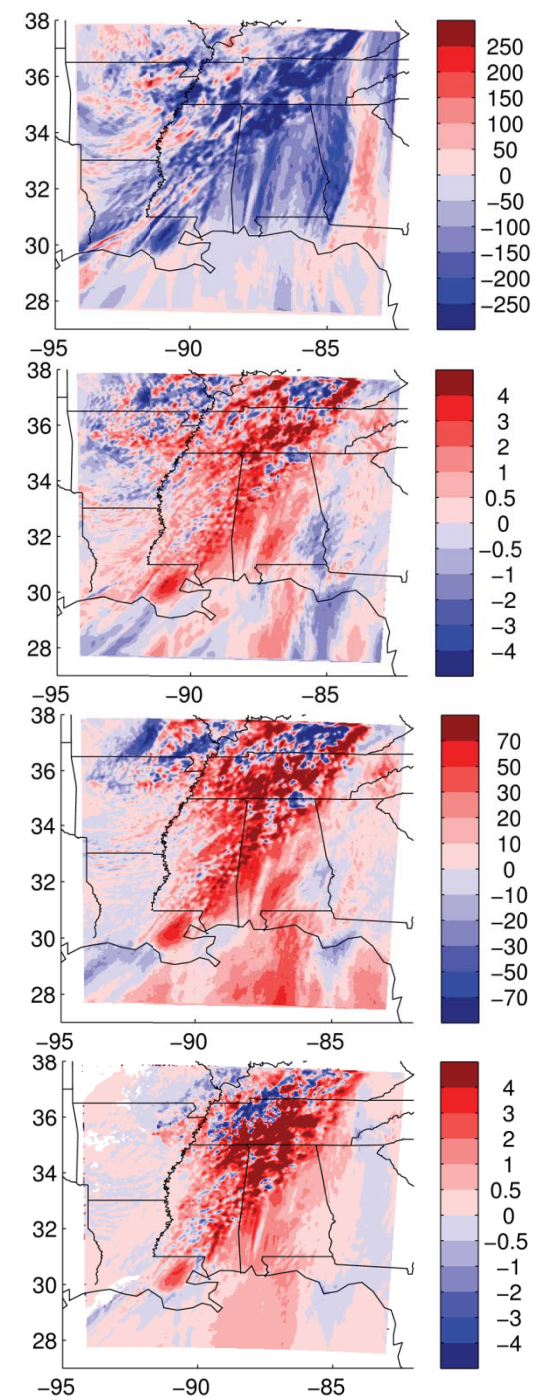
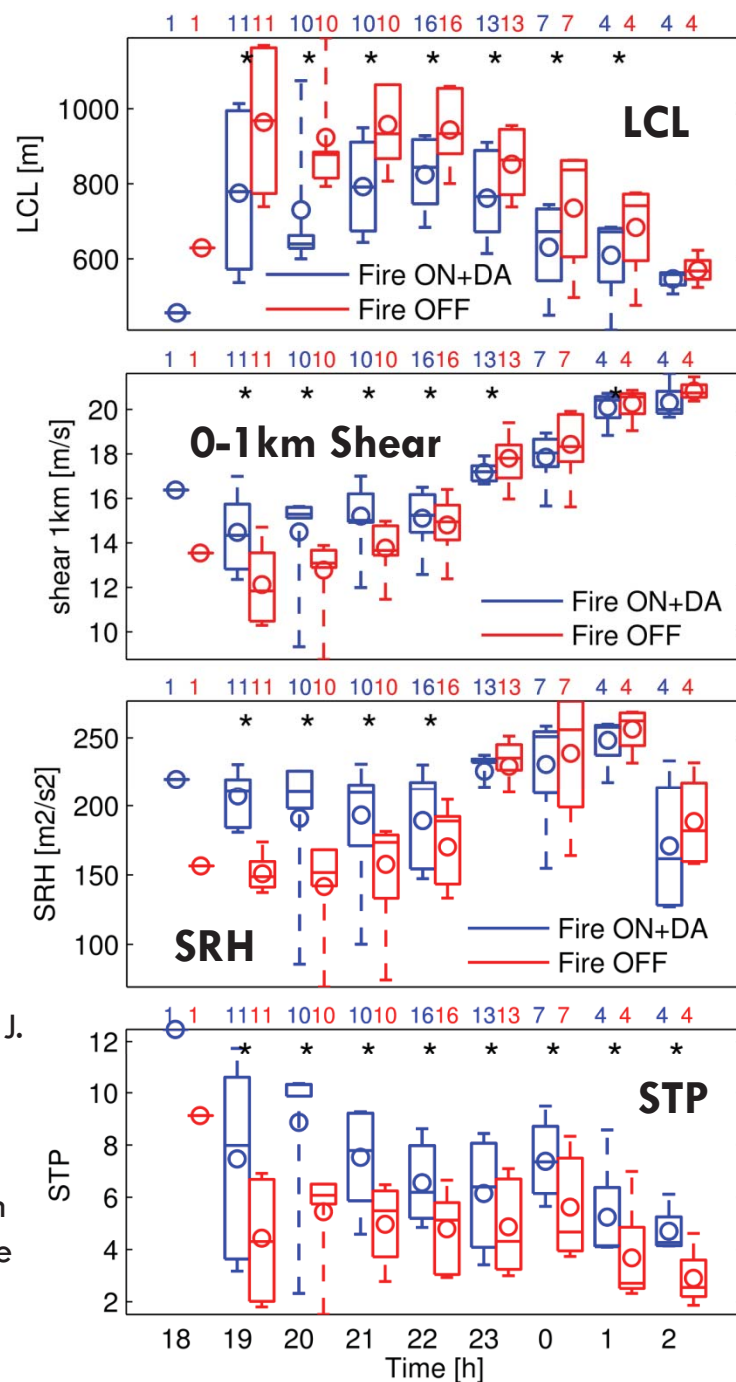
“By many metrics, the tornado outbreak on 27 April 2011 was the most significant outbreak since 1950”

BB smoke, stronger tornadoes

- BC absorption contributes ~40-80% to enhancements in tornado parameters
- Mechanism: strengthening the capping inversion by heating layer above clouds

Saide, P.E., S. N. Spak, R. B. Pierce, J. A. Otkin, T. K. Schaack, A. K., Heidinger, A. M. da Silva, M. Kacenelenbogen, J. Redemann and G. R. Carmichael, Central American biomass burning smoke can increase tornado severity in the US.

Submitted.





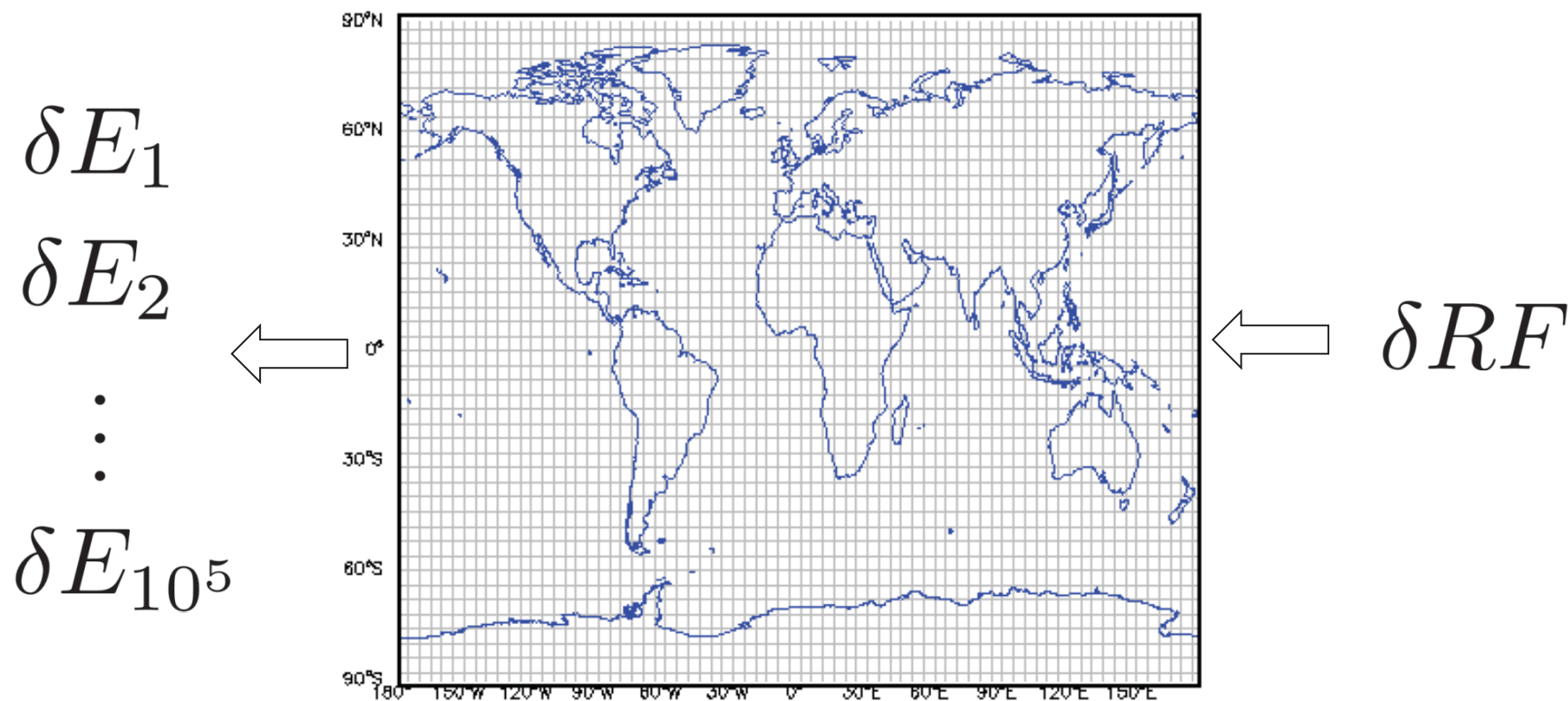
ADJOINT METRICS FOR AIR QUALITY & CLIMATE CO- BENEFITS

SN Spak, DK Henze, F Lacey, EA Minor, GR Carmichael.
Adjoint health and climate co-benefits metrics identify
optimal local and global air pollution control policies. In
preparation.

Scott Spak

Global aerosol direct radiative forcing & population-weighted $PM_{2.5}$ sensitivities from **every sector & region**

49

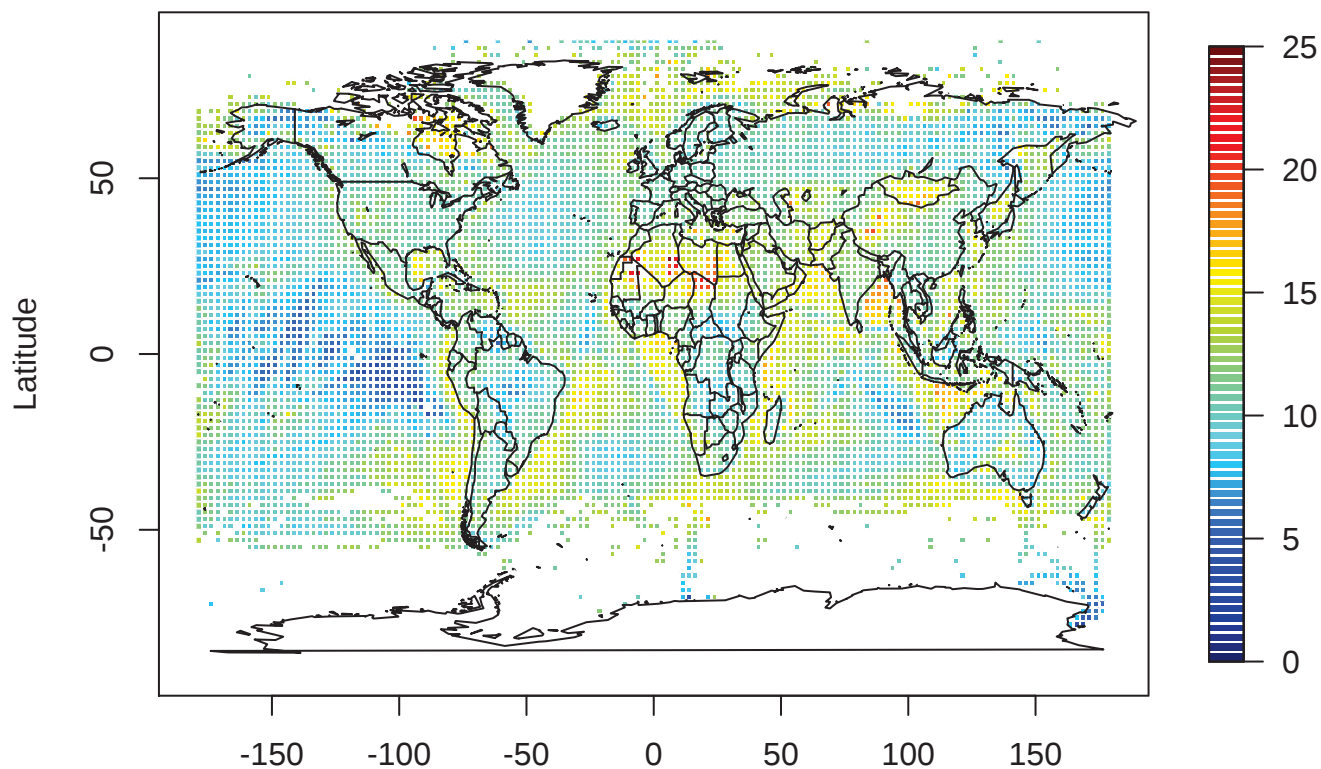


Calculated very efficiently with the
GEOS-Chem adjoint (Henze et al., 2007) + **LIDORT** (Spurr, 2002)

RCP2000 sensitivities: concentrations

50

Population-weighted BC concentrations : emissions
($\mu\text{g}/\text{m}^3/\text{kg}/\text{year}$, log scale)

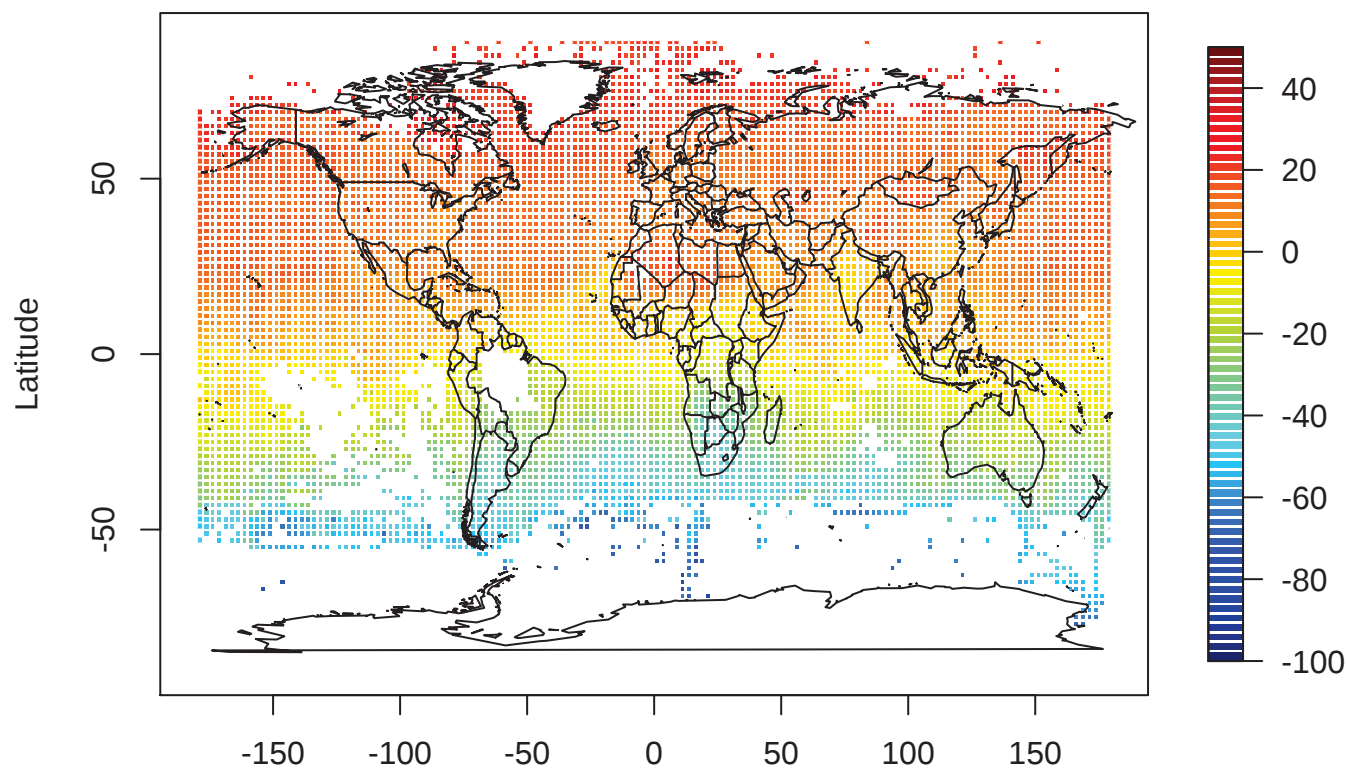


$$Sensitivity_{SLFCA} = \frac{\partial \ln \text{Concentration}[SLFCA]}{\partial \ln \text{Emissions}[SLFCA]}$$

RCP2000 sensitivities: SLFC

51

Arctic BC DRF : emissions
(W/m²/kg/year or %/%, log scale)

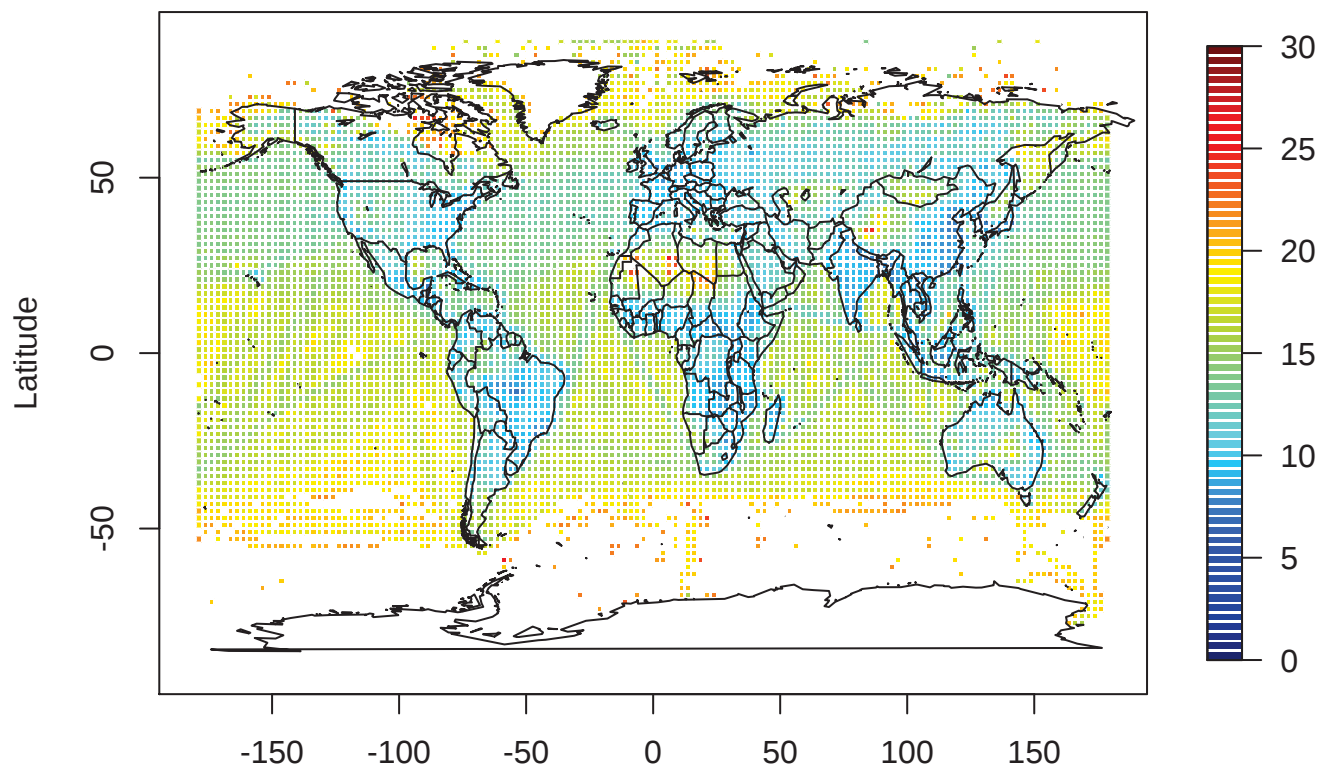


$$Elasticity_{SLFC} = \frac{\Delta SLFC / SLFC}{\Delta Emissions[SLFCA] / Emissions[SLFCA]} = \frac{\partial \ln SLFC}{\partial \ln Emissions[SLFCA]}$$

RCP2000 sensitivities: SLFC

52

Global BC DRF : emissions
(W/m²/kg/year, log scale)

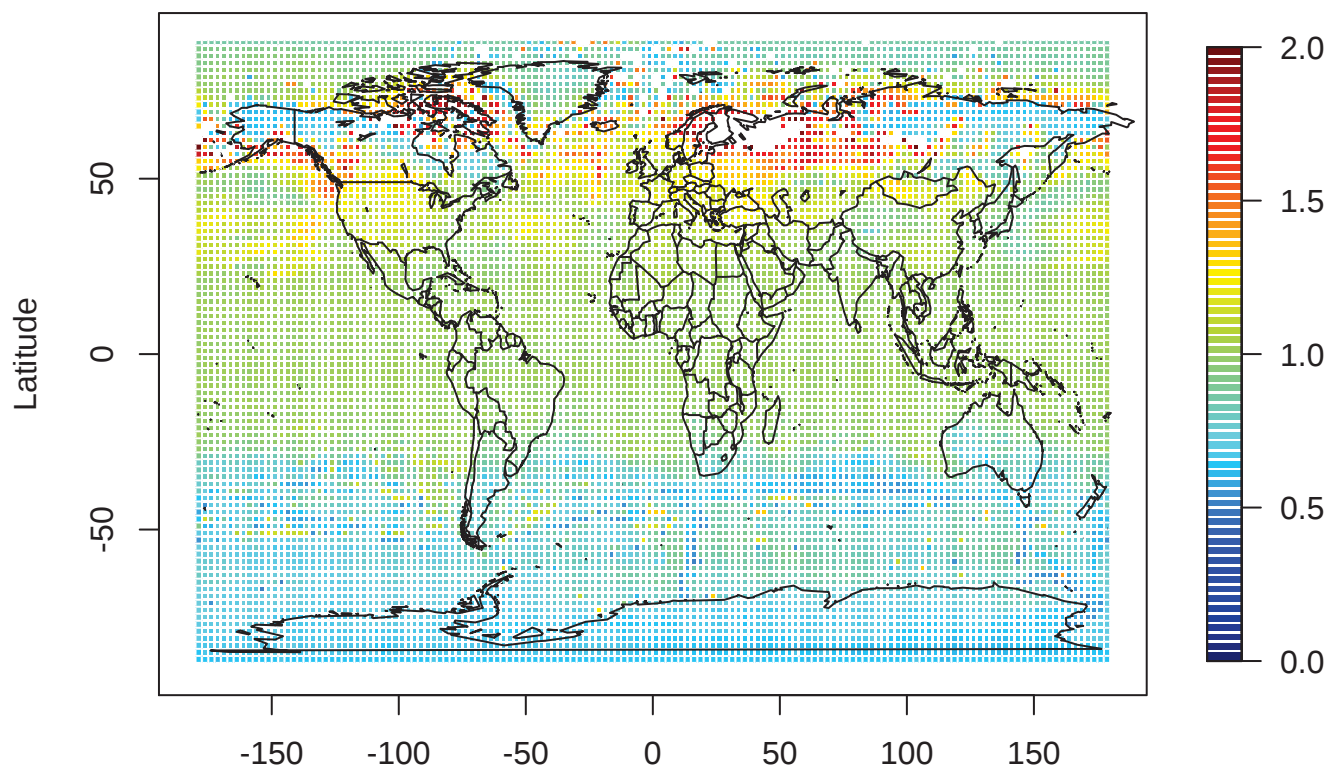


$$Elasticity_{SLFC} = \frac{\Delta SLFC / SLFC}{\Delta Emissions[SLFCA] / Emissions[SLFCA]} = \frac{\partial \ln SLFC}{\partial \ln Emissions[SLFCA]}$$

Reducing uncertainties: adding regional refinement

53

Global BC DRF by Latitude Band / Global Average



Co-benefits metrics

54

Modelers calculate:

$$Elasticity_{SLFC} = \frac{\Delta SLFC / SLFC}{\Delta Emissions[SLFCA] / Emissions[SLFCA]} = \frac{\partial \ln SLFC}{\partial \ln Emissions[SLFCA]}$$

$$Sensitivity_{SLFCA} = \frac{\partial \ln Concentration[SLFCA]}{\partial \ln Emissions[SLFCA]}$$

We're adding:

$$Forcing_Amplifier_{SLFCA} = \frac{\partial \ln SLCF[SLFCA]}{\partial \ln Concentration[SLFCA]} = \frac{Elasticity_{SLFC}}{Elasticity_{SLFCA}}$$

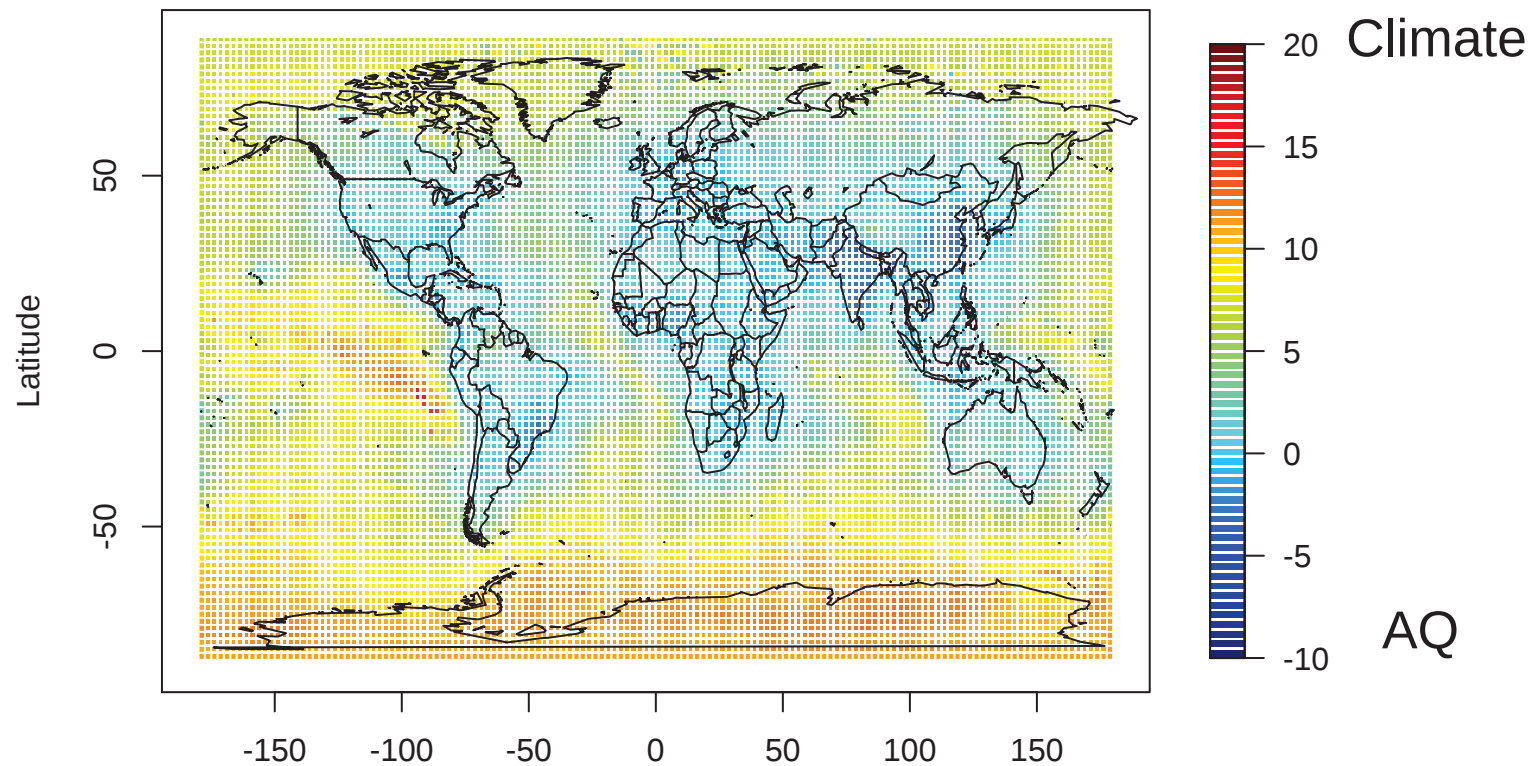
$$Emissions_Reduction_Efficiency_{SLFCA1,SLFCA2} = \frac{Forcing_Amplifier_{SLFCA1}}{Forcing_Amplifier_{SLFCA2}}$$

+ impacts, cost:benefit, uncertainties

Where to focus BC on climate vs AQ?

55

Global BC DRF by latitude band : Population-weighted BC
(W•m/μg, log scale)

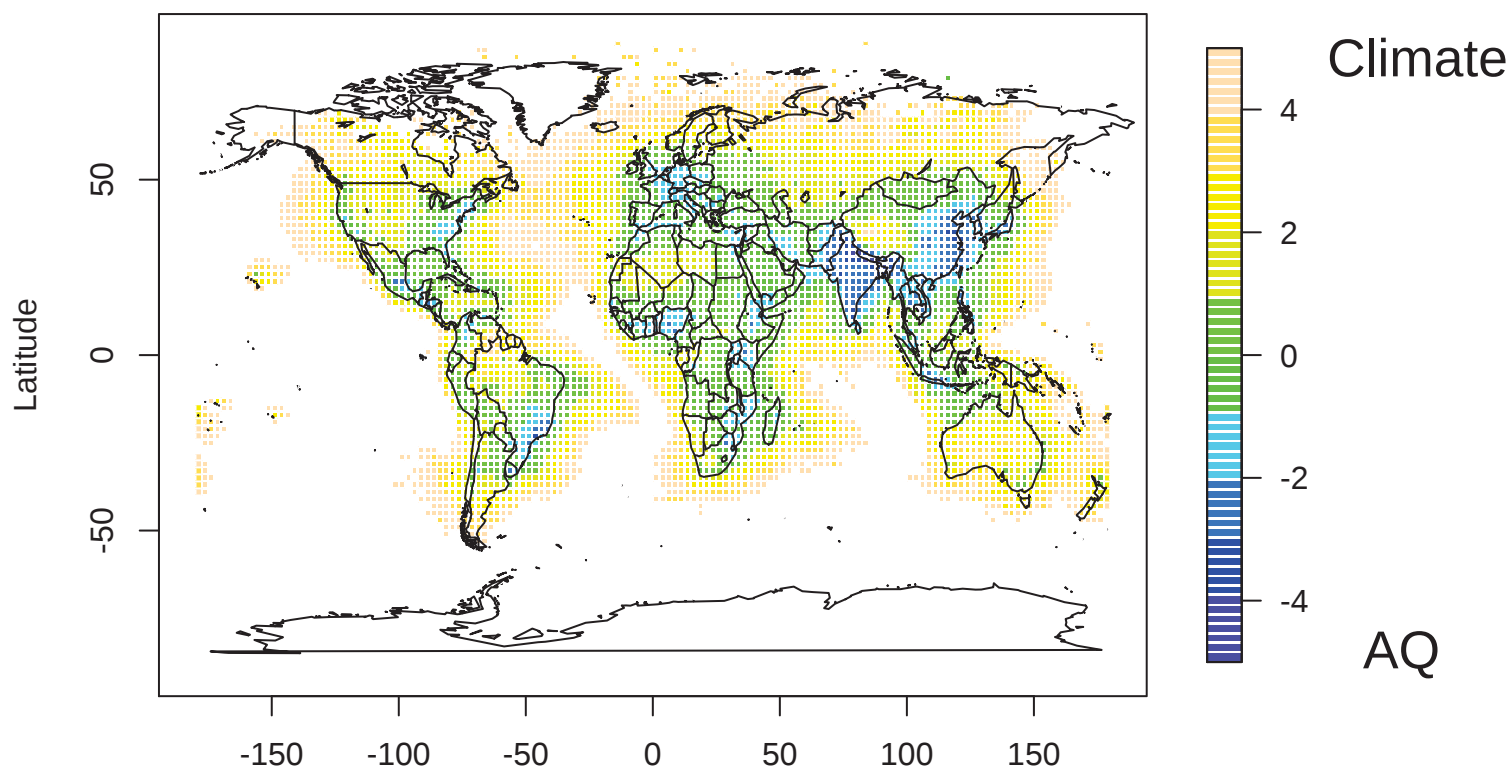


$$Forcing_Amplifier_{SLFCA} = \frac{\partial \ln SLCF[SLFCA]}{\partial \ln Concentration[SLFCA]} = \frac{Elasticity_{SLFC}}{Elasticity_{SLFCA}}$$

Design policies to reflect regional differences?

56

Global BC DRF by latitude band : Population-weighted BC
(W•m/μg, log scale)

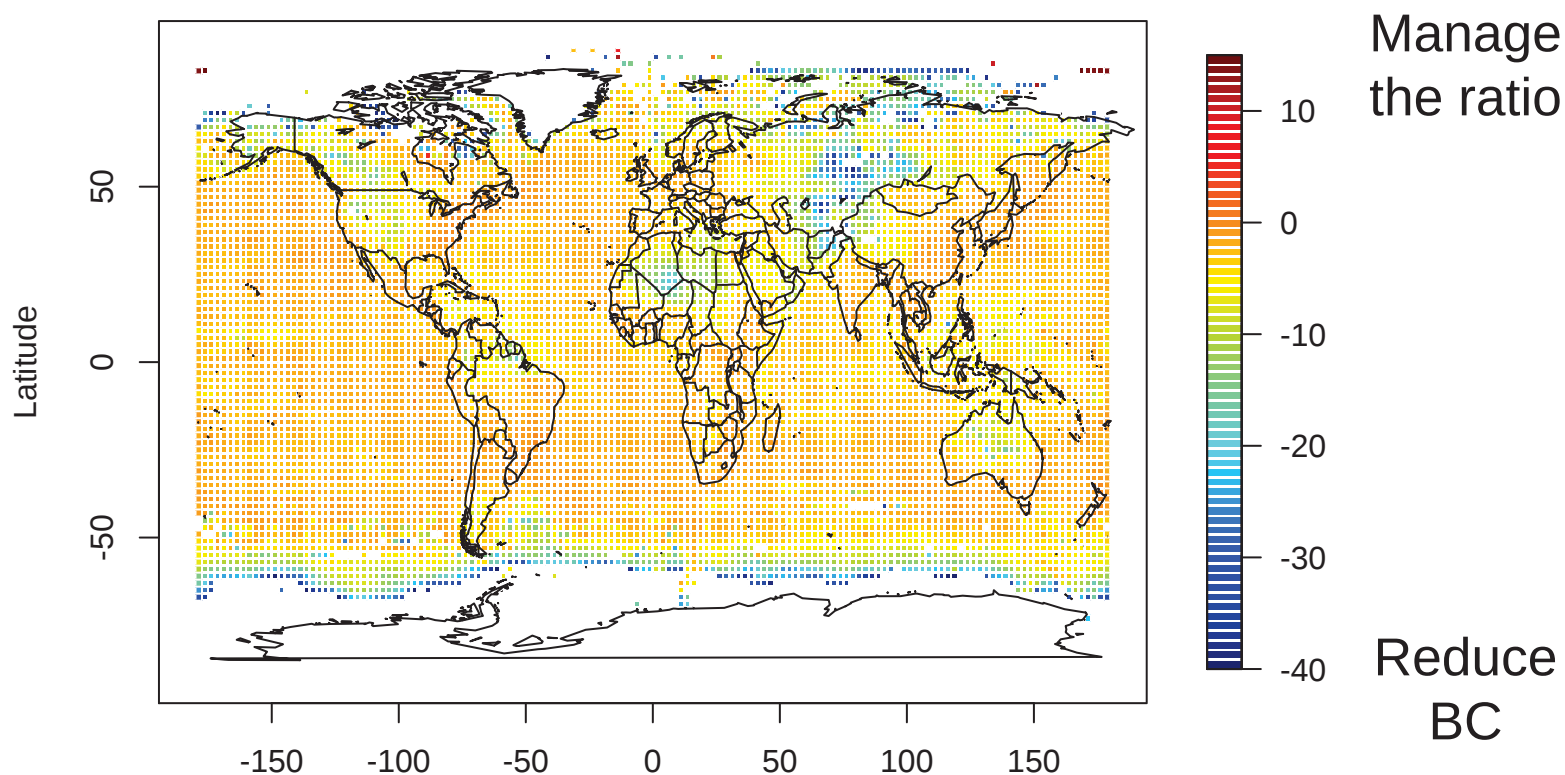


$$Forcing_Amplifier_{SLFCA} = \frac{\partial \ln SLCF[SLFCA]}{\partial \ln Concentration[SLFCA]} = \frac{Elasticity_{SLFC}}{Elasticity_{SLFCA}}$$

Where to focus on BC:SO₂ for climate?

57

Global BC:SO₂ Emissions Reduction Efficiency



The 75 Largest Cities

58

- Population
- Total GDP
- GDP by sector:
 - ▣ Commodities
 - ▣ Construction
 - ▣ Business/Finance
 - ▣ Manufacturing
 - ▣ Local/non-market
 - ▣ Trade/tourism
 - ▣ Transportation
 - ▣ Utilities
- Sources: Brookings Institute
Global MetroMonitor, PWC Global
City GDP rankings 2008-2025

Tokyo	Moscow	Ahmedabad
Shanghai	Rhine-Ruhr	Santiago
Jakarta	Paris	Singapore
Seoul	Tianjin	Chongqing
Delhi	Kinshasa	Kuala Lumpur
Mexico City	Chicago	Baghdad
Karachi	Bangalore	Xi'an
Manila	Madras	Dallas
New York City	Lima	Nanjing
São Paulo	Lahore	Luanda
Mumbai	Bogotá	Riyadh
Beijing	Taipei	Belo Horizonte
Los Angeles	Chengtu	Houston
Osaka	Hyderabad	Toronto
Dhaka	Johannesburg	Miami
Cairo	Nagoya	Bandung
Kolkata	Saigon	Poona
London	Washington	Detroit
Buenos Aires	Shenyang	Atlanta
Bangkok	Philadelphia	Madrid
Istanbul	Hangzhou	Khartoum
Lagos	Boston	Surat
Tehran	San Francisco	Saint Petersburg
Rio de Janeiro	Hong Kong	Shantou
Shenzhen	Wuhan	Rangoon

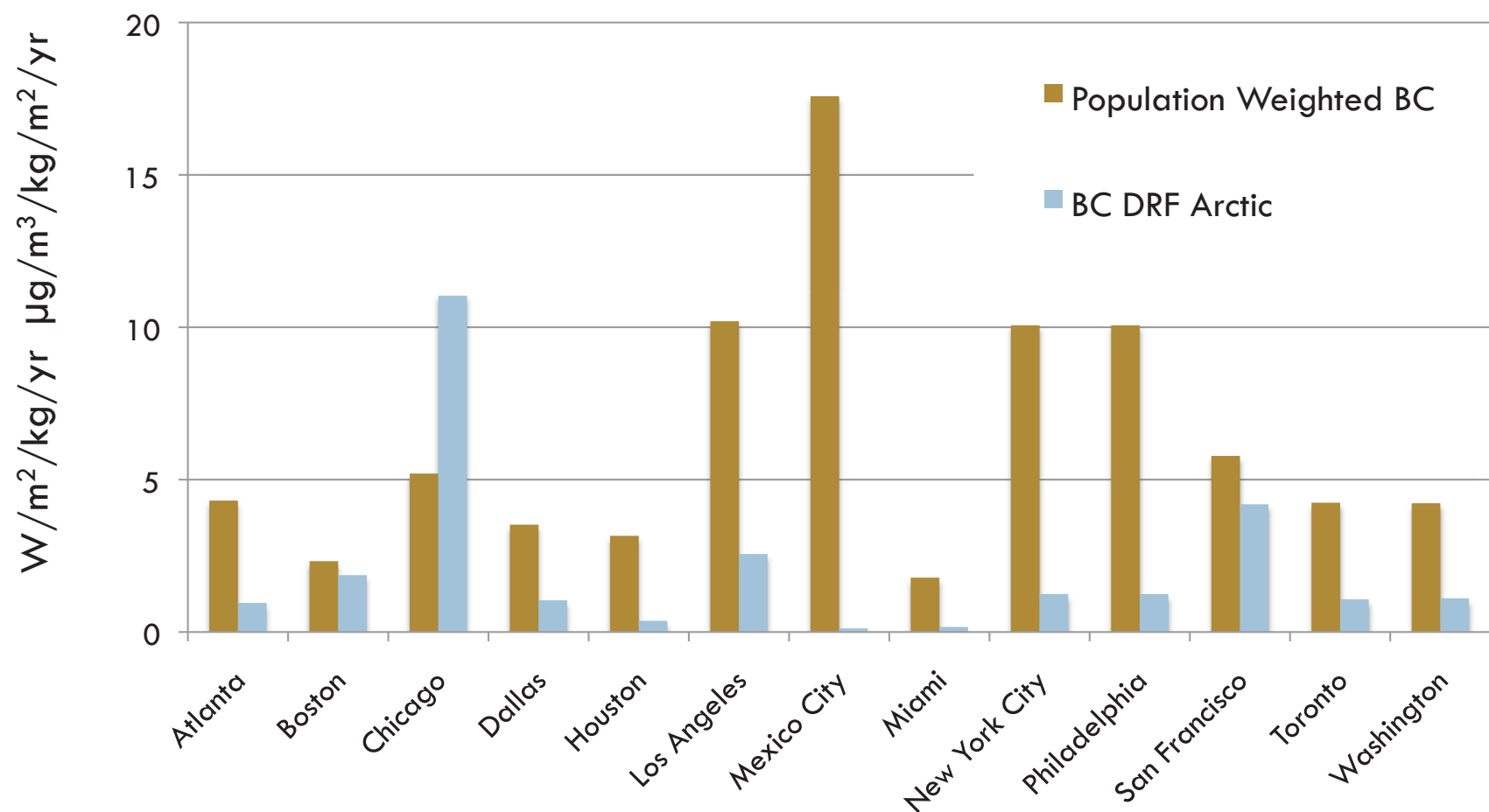
Top 10 Highest BC Sensitivities

59

Global DRF	Per Capita Global DRF	Arctic DRF	Global FA	Emission-Weighted Arctic DRF
Chicago	Chicago	St. Petersburg	St. Petersburg	Moscow
Moscow	St. Petersburg	Moscow	Luanda	Beijing
Dallas	Dallas	Shenyang	Riyadh	Tianjin
Shenyang	Toronto	Chicago	Chicago	St. Petersburg
Toronto	Khartoum	Rhine-Ruhr	Dallas	Shenyang
Chengtu	Xi'an	London	Singapore	Chicago
Los Angeles	Shenyang	Tianjin	Toronto	London
Tianjin	Chongqing	Beijing	Houston	Seoul
Beijing	Moscow	Paris	Lima	Rhine-Ruhr
St. Petersburg	Luanda	San Francisco	Moscow	Paris

North American Cities

60



Publications

61

2012

Huang, M., G. Carmichael, S. Kulkarni, D. Streets, Z. Lu, Q. Zhang, R. B. Pierce, Y. Kondo, J. Jimenez, M. Cubison, B. Anderson, A. Wisthaler (2012). Sectoral and geographical contributions to summertime continental United States (CONUS) black carbon spatial distributions, *Atmos. Environ.* 51, 165-174.

Tsao, C.C., J.E. Campbell, M.A. Mena-Carrasco, S.N. Spak, G.R. Carmichael, Y. Chen. Biofuels that cause land-use change may have much larger non-GHG air quality emissions than fossil fuels, *Environ. Sci. Technol.* 46, 10835–10841.

2013

Saide, P. E., Carmichael, G. R., Liu, Z., Schwartz, C. S., Lin, H. C., da Silva, A. M., Hyer, E.. Aerosol optical depth assimilation for a size-resolved sectional model: impacts of observationally constrained, multi-wavelength and fine mode retrievals on regional scale analyses and forecasts, *Atmos. Chem. Phys.*, 13, 10425-10444.

Zhang, L. J. Kok, D. K. Henze, Q. B. Li, and C. Zhao. Improving simulations of fine dust surface concentrations over the Western United States by optimizing the particle size distribution, *Geophys. Res. Lett.*, 49, 3270-3275.

2014

Mao, Y. H., Q. B. Li, D. K. Henze, Z. Jiang, D. B. A. Jones, M. Kopacz, C. He, L. Qi, M. Gao, W.-M. Hao, K.-N. Liou, Variational estimates of black carbon emissions in the western United States, *Atmos. Chem. Phys. Discuss.*, 14, 21865-21916.

Marrapu, P., Cheng, Y., Beig, G., Sahu, S., Srinivas, R. and Carmichael, G. R. Air quality in Delhi during the Commonwealth Games, *Atmos. Chem. Phys.*, 14, 10619-10630.

Mena-Carrasco, M.A., P.E. Saide, R. Delgado, P. Hernandez, S.N. Spak, L.T. Molina, G.R. Carmichael, X. Jiang. Regional climate feedbacks in Central Chile and their effect on air quality episodes and meteorology. *Urban Climate*, in press, doi: 10.1016/j.uclim.2014.06.006..

Shen, Z., J. Liu, L. W. Horowitz, D. K. Henze, S. Fan, H. Levy II, D. L. Mauzerall, J. Lin, S. Tao. Analysis of transpacific transport of black carbon during HIPPO-3: implications for black carbon aging, *Atmos. Chem. Phys.*, 14, 6315-6327.

Articles submitted & in preparation

62

Submitted

Kulkarni, S., Sobhani, N., Miller-Schulze, J. P., Shafer, M. M., Schauer, J. J., Solomon, P. A., Saide, P. E., Spak, S. N., Cheng, Y. F., Denier van der Gon, H. A. C., Lu, Z., Streets, D. G., Janssens-Maenhout, G., Wiedinmyer, C., Lantz, J., Artamonova, M., Chen, B., Imashev, S., Sverdlik, L., Deminter, J. T., Adhikary, B., D'Allura, A., Wei, C., and Carmichael, G. R.: Source sector and region contributions to BC and PM_{2.5} in Central Asia, *Atmos. Chem. Phys. Discuss.*, 14, 11343-11392, 2014.

Saide, P.E., Peterson, D., da Silva, A., Anderson, B., Ziemba L.D., Diskin, G., Sachse, G., Hair, J., Butler, C., Fenn, M., Jimenez, J.L., Campuzano-Jost, O., Perring, A., Schwarz, J., Markovic, M.Z., Russell, P., Redemann, J., Shinozuka, Y., Streets, D.G., Yan, F., Dibb, J., Yokelson, R., Toon, O.B., Hyer, E., Carmichael, G.R., Revealing important nocturnal and day-to-day variations in fire smoke emissions through a novel multiplatform inversion. Submitted.

Saide, P.E., Kim, J., Song, C.H., Choi, M., Cheng, Y., Carmichael, G.R., Assimilating next generation geostationary aerosol optical depth retrievals can improve air quality simulations. Submitted.

Saide, P.E., S. N. Spak, R. B. Pierce, J. A. Otkin, T. K. Schaack, A. K., Heidinger, A. M. da Silva, M. Kacenelenbogen, J. Redemann and G. R. Carmichael, Central American biomass burning smoke can increase tornado severity in the US. Submitted.

Zhang, L., D. K. Henze, G. A. Grell, G. R. Carmichael, N. Bousserez, Q. Zhang, J. Cao, (2014). Constraining Black Carbon Aerosol over Southeast Asia using OMI Aerosol Absorption Optical Depth and the adjoint of GEOS-Chem, *Atmos. Chem. Phys. Discuss.*, in press.

In preparation

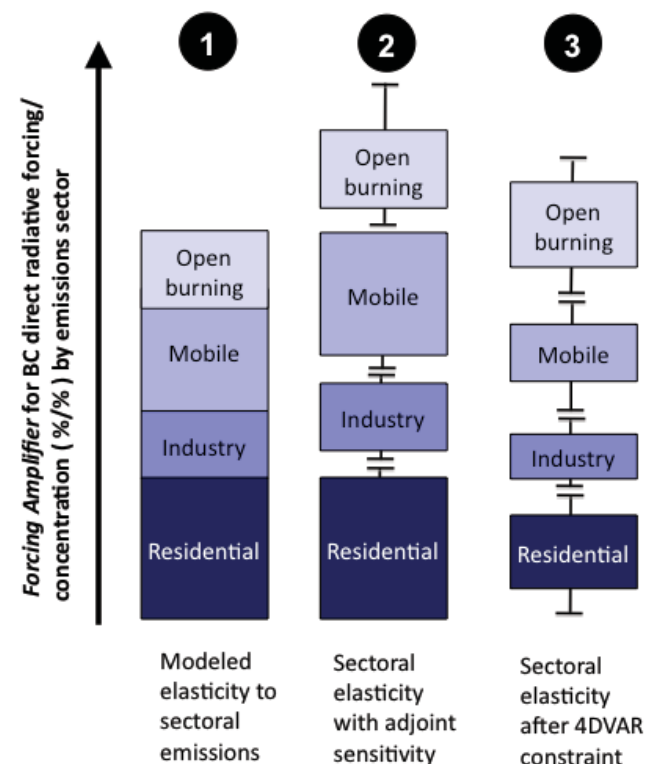
Guerrette, J.J. and D.K. Henze. Incorporating black carbon aerosol into WRFPLUS adjoint and tangent linear models. *Geosci. Model Dev.*, to be submitted (December, 2014).

Spak, S.N., D.K. Henze, F. Lacey, E.A. Minor, G.R. Carmichael. Adjoint health and climate co-benefits metrics identify optimal local and global air pollution control policies.

Ongoing: Year 4

63

- WRF-Chem adjoint development
 - public release with climate coupling
 - publication
- Co-benefits Applications
 - Global futures: quantify impacts of proposed BC-specific emission mitigation policy measures
 - Impacts of emissions inversion: Asia
 - Process uncertainties: CA



Conclusions

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1. Science

- Emissions the greatest parametric uncertainty, and the most readily reduced through assimilation

2. Tools

- We have advanced BC adjoint and DA capabilities for AQ + climate, extended them to multi-scale coupled modeling in WRF-Chem, and incorporated them in public model releases and operational DA platforms
- synergy between non-linear sensitivity tools & emerging observing systems for understanding and reducing uncertainties in BC

3. Policy analysis & decision-making support

- Adjoint metrics identify where and how to most quickly improve climate & AQ



Thank you!

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