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*

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Innovation in BC modeling & data assimilation

1. Science
2. Tools
3. Decision Support

Science Objectives

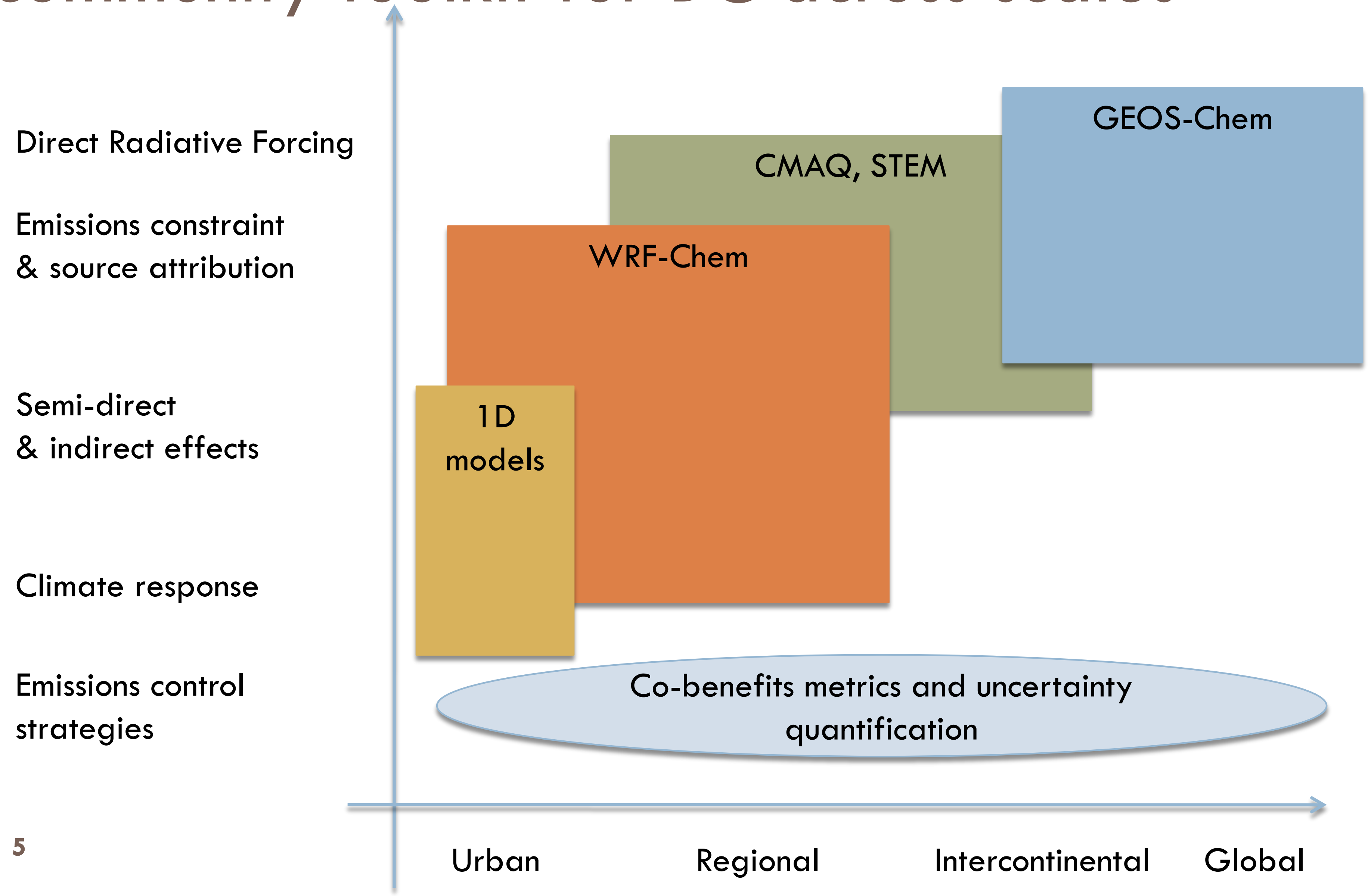
1. Rank and constrain the contributions of transport, deposition, aerosol properties, and emissions to uncertainty in estimates of BC distributions in urban and remote areas and of BC radiative forcing.
2. Improve model representation of BC distributions at urban to regional scales through assimilation 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

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: WRFPlus-Chem adjoint, WRFDA-Chem 4DVAR

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

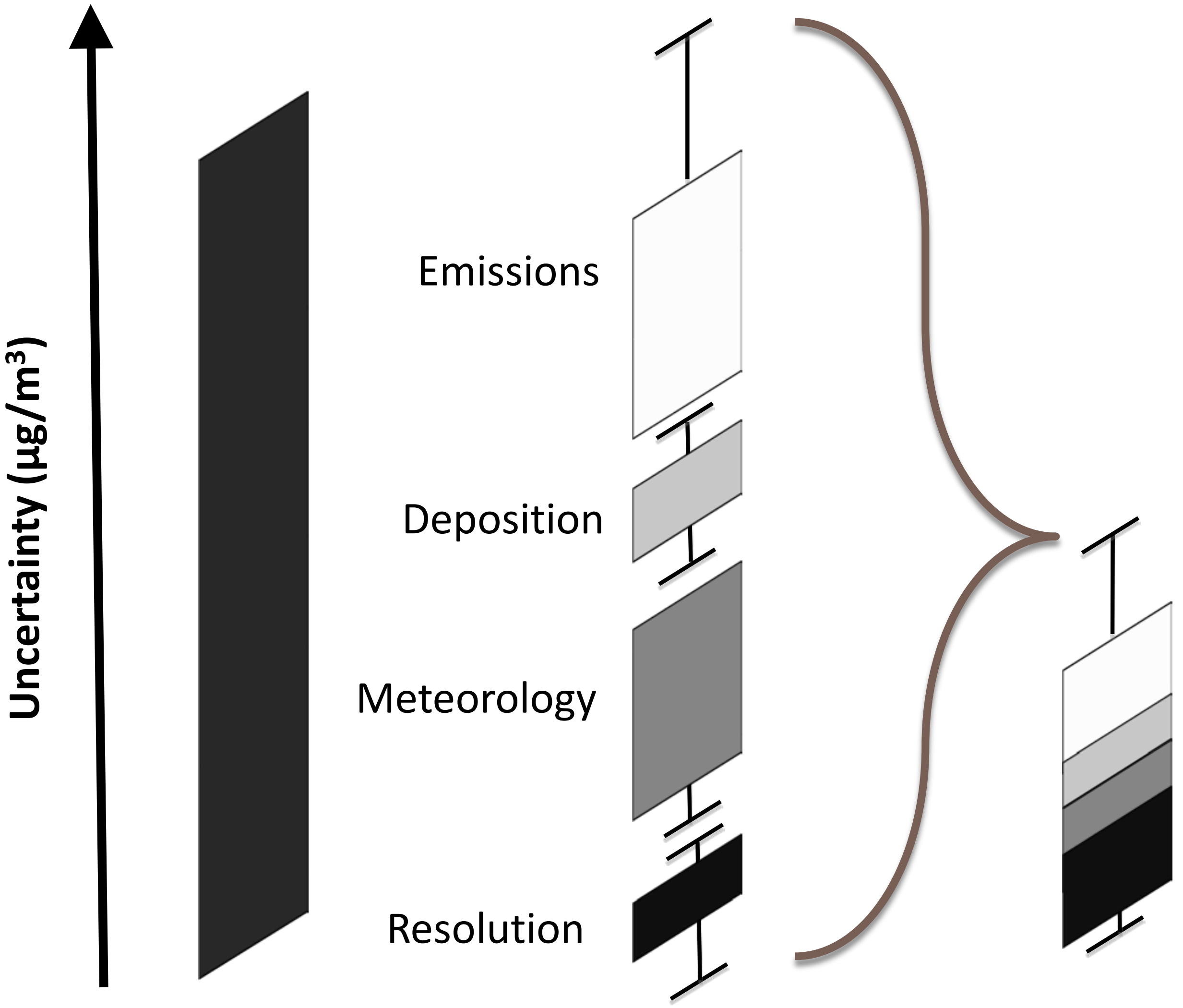


Uncertainty Assessment & Constraint

① **Total uncertainty**

② **Adjoint sensitivities quantify uncertainties**

③ **4DVAR constrained uncertainty**

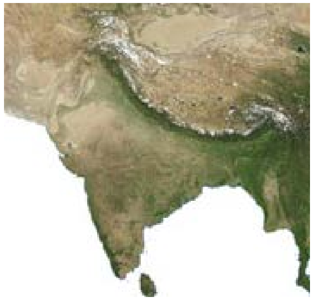


Constraint on:

- **emissions**
- **concentrations**
- **radiative forcing**

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

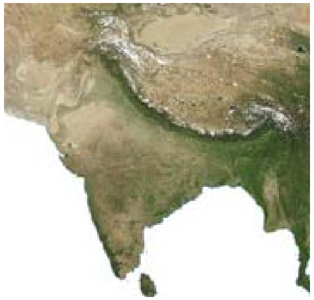
AND THEN, SCIENCE HAPPENED

BASIC & APPLIED
GLOBAL & REGIONAL
TOOLKIT & RESEARCH RESULTS

2015-2016

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

- ✓ Constrain uncertainty in BC emissions & vertical distributions using in situ observations
- + **Rim Fire + fire attribution + tornadogenesis**



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

- ✓ Constrain large, highly uncertain emissions inventories
- + **Eastern China Haze AQ:climate feedbacks**
- + **Geostationary assimilation + Central Asia BC**

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 + **Megacity co-benefits metrics**

ASSIMILATING AAOD TO IMPROVE BLACK CARBON EMISSIONS & CONCENTRATIONS

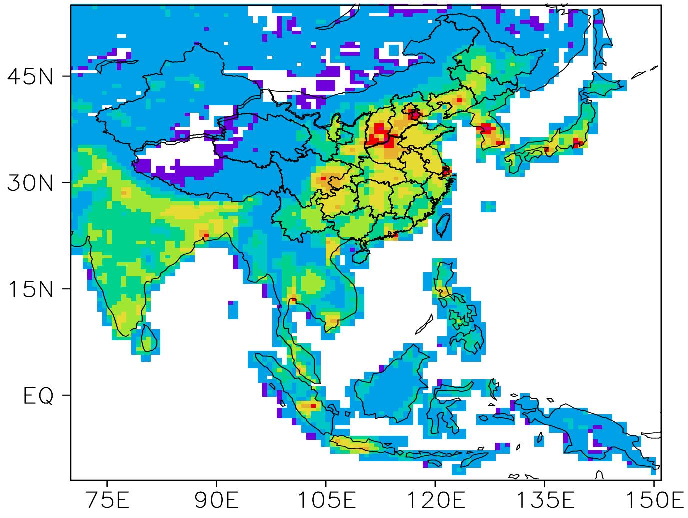
Zhang, L., D. K. Henze, G. A. Grell, G. R. Carmichael, N. Bousserez, Q. Zhang, J. Cao, and Y. Mao, Constraining black carbon aerosol over Southeast Asia using OMI aerosol absorption optical depth and the adjoint of GEOS-Chem, *Atmos. Chem. Phys.* 15, 10281-10308, doi:10.5194/acp-15-10281-2015.

Li Zhang, CU-Boulder

Uncertainties in Anthropogenic BC Emissions

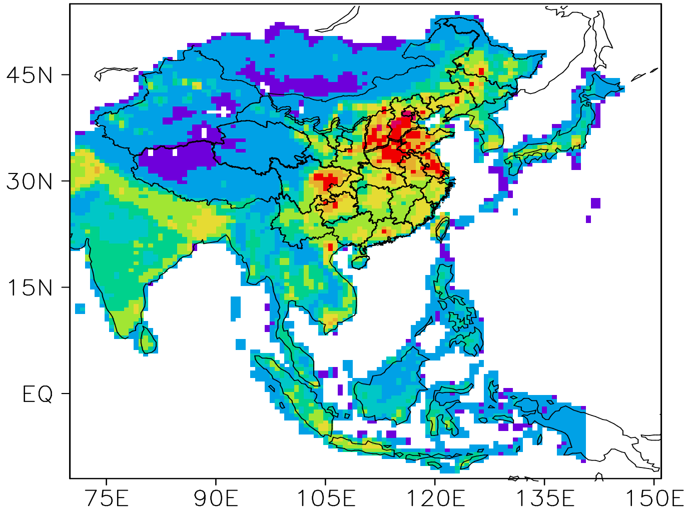
@ 0.67° x 0.5°

Bond, 1.0°x1.0°, 2000



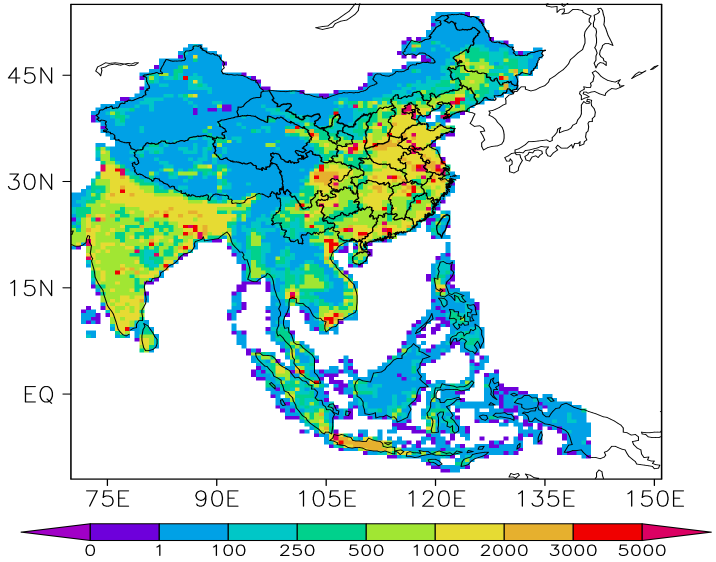
(Bond et al., 2007)

INTEX-B, 0.5°x0.5°, 2006



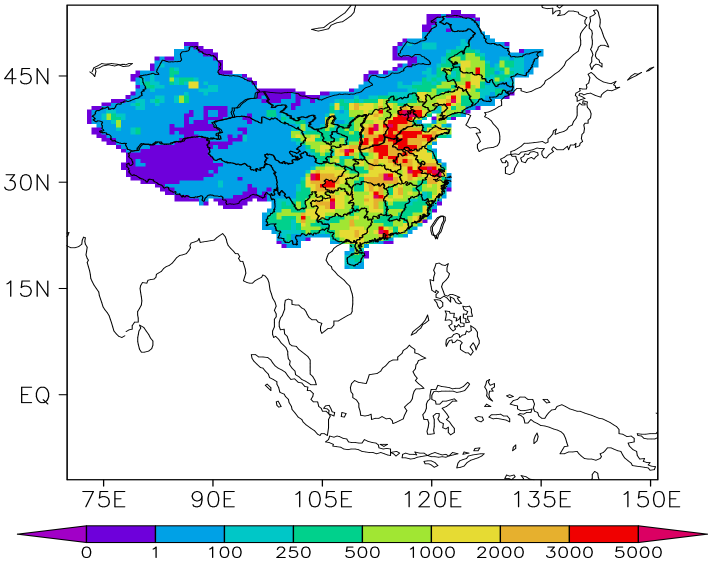
(Zhang et al., 2009)

SEAC^{4}RS, 0.1°x0.1°, 2012



(Lu et al., 2011)

MEIC, 0.5°x0.5°, 2010



(Zhang et al., 2012)

Mg BC/yr

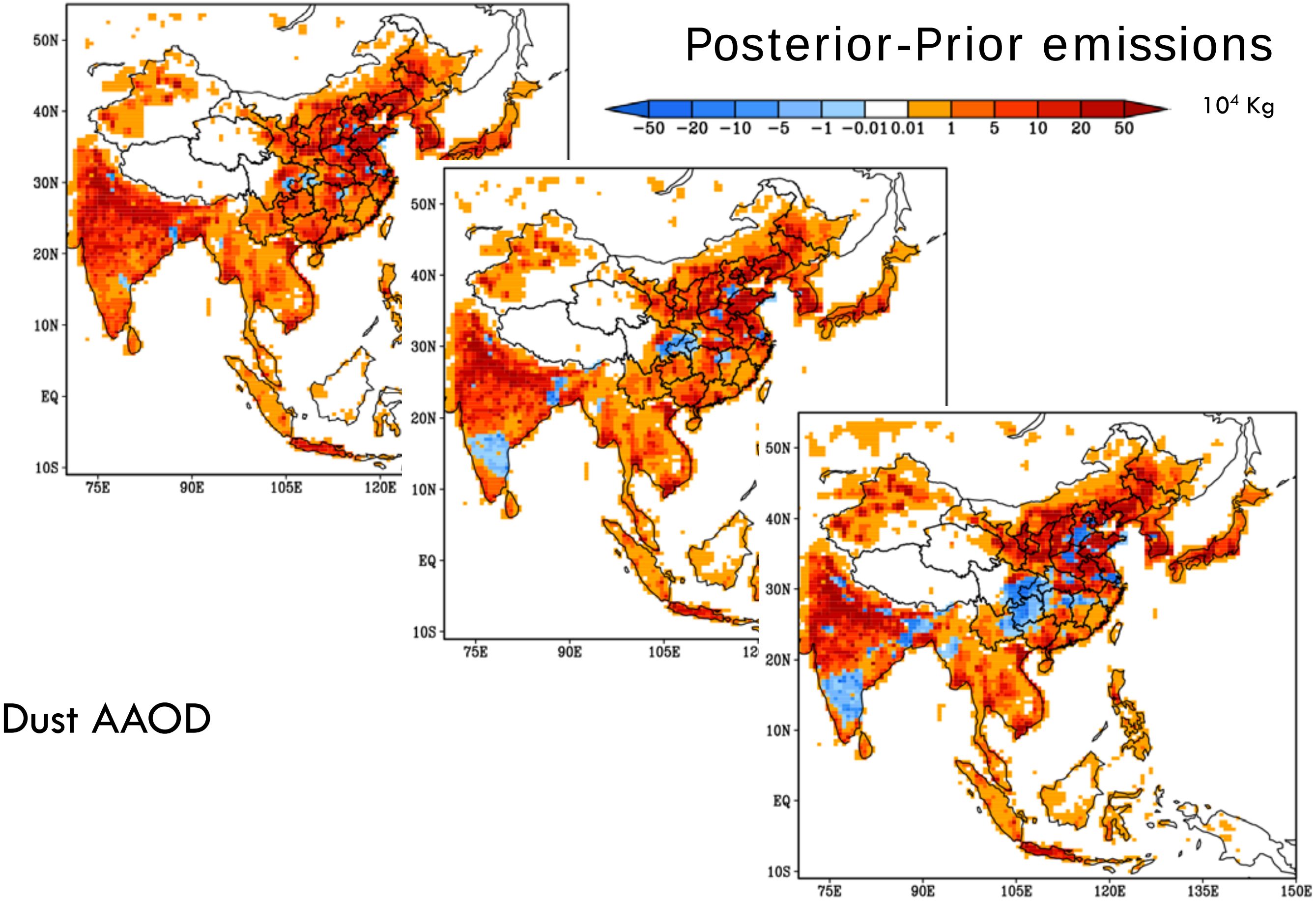
Grid-scale BC emissions constraints

How to isolate BC when assimilating AAOD?

Use model
BC/total AAOD
in each layer

Use model
BC/total AAOD
in each column

Use model
absolute OC and Dust AAOD
in each column



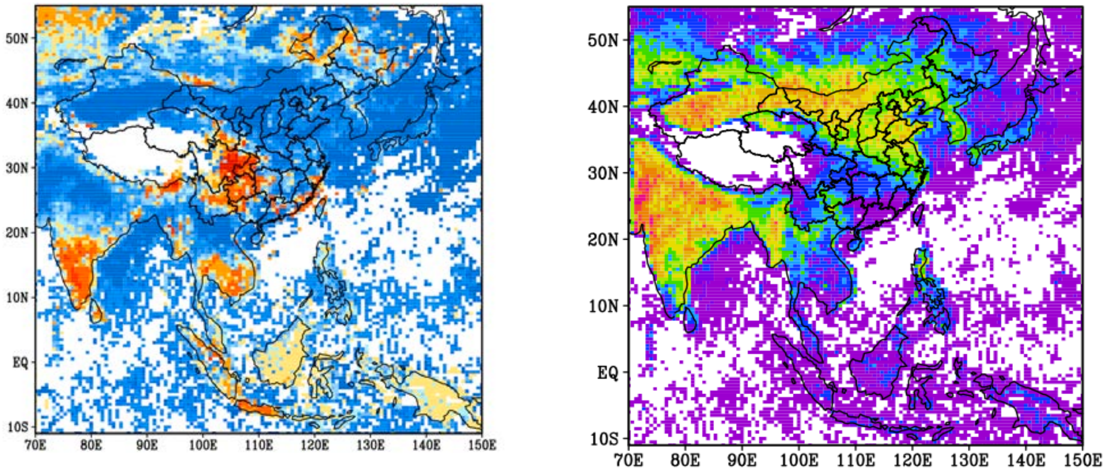
Posterior-Prior emissions

Use OMI retrieval aerosol classification: smoke, sulfate, dust
(Torres et al., 2013)

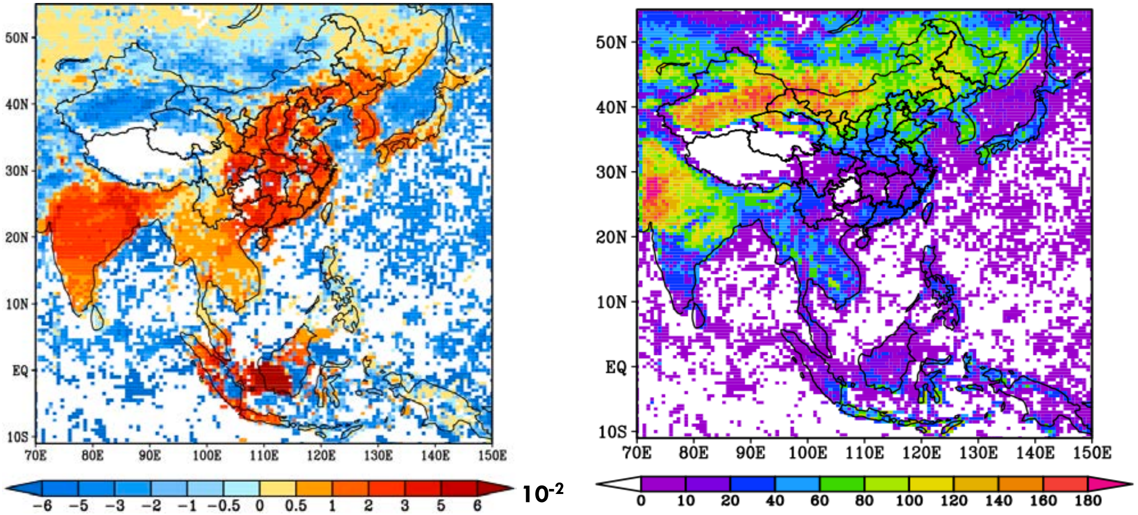
Seasonal, spatial differences in AAOD GEOS-Chem simulation vs. OMI retrieval

April

GEOS-Chem minus OMI **OMI observed data counts**



October



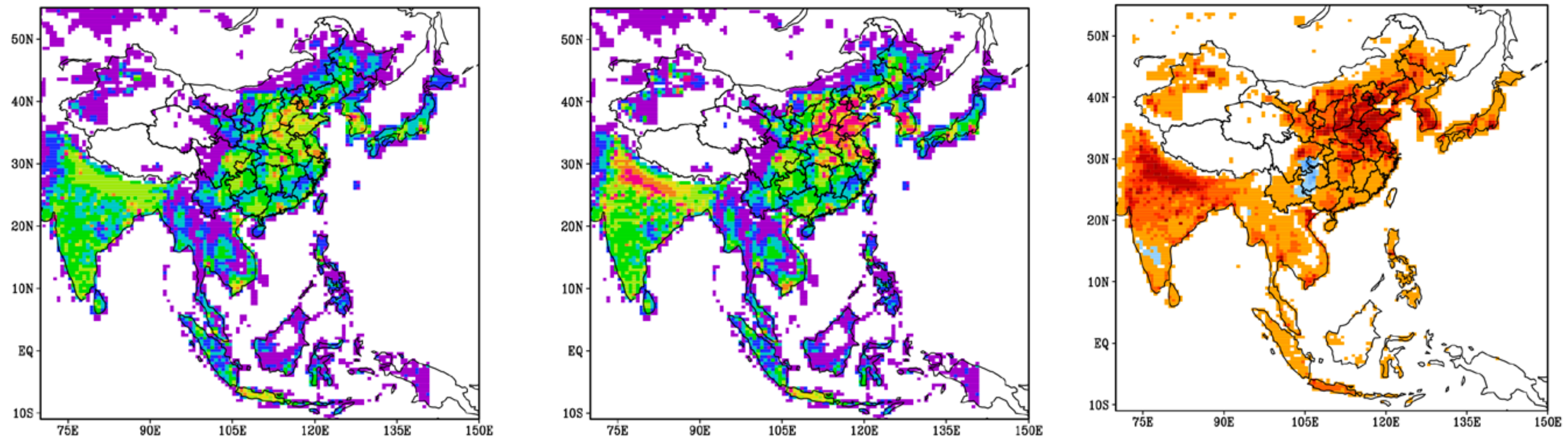
OMI aerosol absorption optical depth (AAOD) is an atmospheric column measurement of absorbing aerosol particles [Torres et al., 2007], which provides much better spatial and temporal coverage to constrain BC.

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

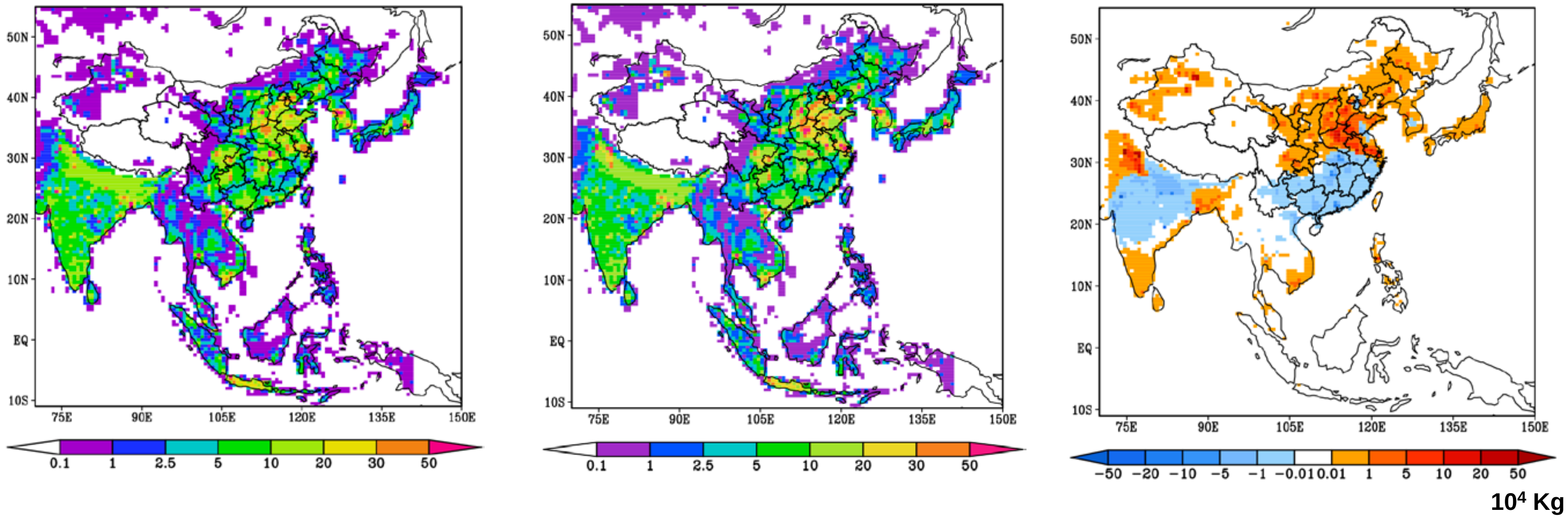
Anthropogenic emissions optimized using GEOS-Chem adjoint + MEIC_SEAC^{4}RS

April

Priori **Posteriori** **Posteriori - Priori**



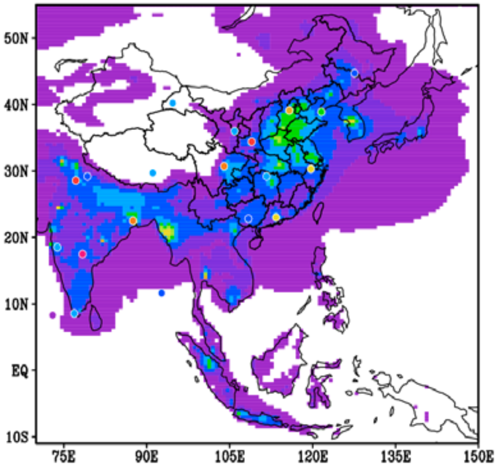
October



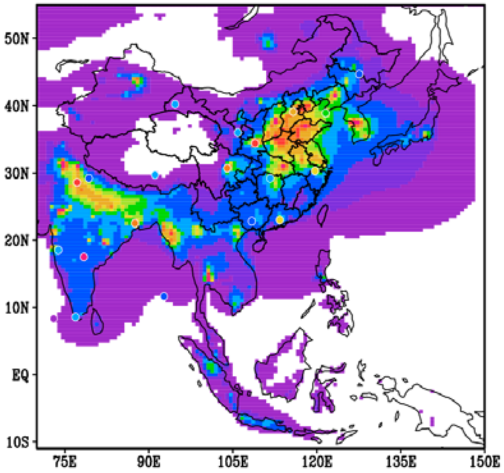
Optimized Surface BC Concentrations

April

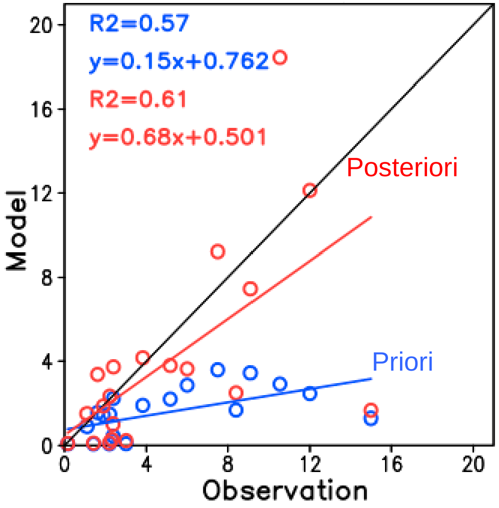
Priori



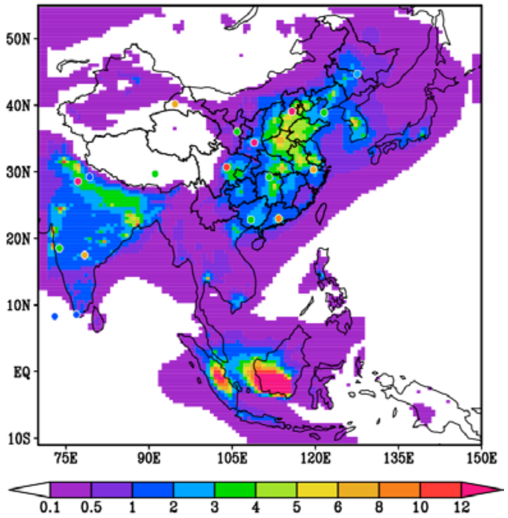
Posteriori

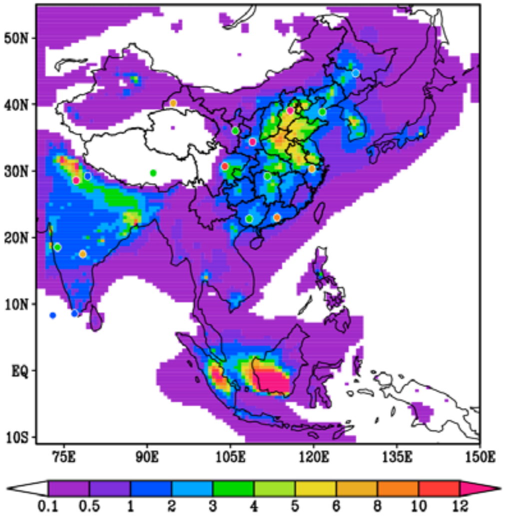


μg/m^3

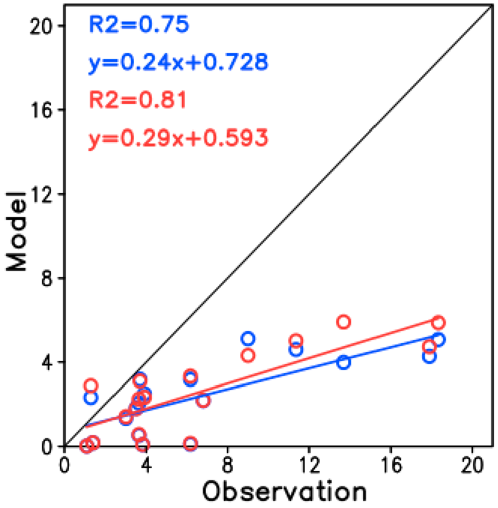


October





μg/m^3



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

1. **Science: attribution & reduction in uncertainty**
   - Seasonal: higher anthropogenic emissions after optimization (up to 500%), BB increase significant, spatially variable
   - Observational counts near sources determine effectiveness of inversion
   - Extension to U.S. long-term trends (submitted)
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 & surface obs

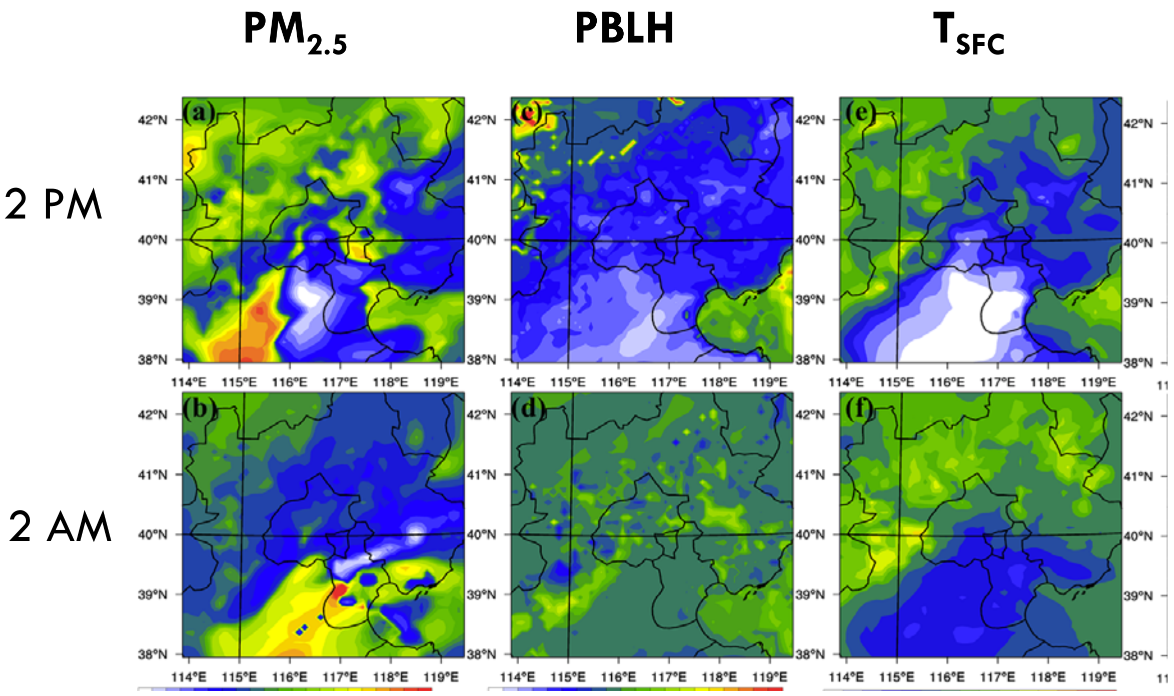
WINTERTIME HAZE IN CHINA: BC IMPACTS ON HAZE CONDITIONS, OBSERVATIONAL ASSIMILATION ON HEALTH IMPACTS

Gao, M., Guttikunda, S.K., Carmichael, G.R. , Wang, Y., Liu, Z., Stanier, C.O. Health Impacts and Economic Loss Assessment of the 2013 Severe Haze Event in Beijing. *Science of the Total Environment*. Vol 511, pp. 553-561, doi 10.1016/j.scitotenv.2015.01.005, 2015.

Gao, M., Carmichael, G. R., Wang, Y., Saide, P. E., Yu, M., Xin, J., Liu, Z., and Wang, Z.: Modeling study of the 2010 regional haze event in the North China Plain, *Atmos. Chem. Phys.*, 16, 1673-1691, doi:10.5194/acp-16-1673-2016, 2016.

Meng Gao, University of Iowa

Eastern China Wintertime Haze in WRF-Chem:
2010 (mechanism & BC feedbacks), 2013 (assimilation, health, valuation)



Findings:

- Secondary inorganic 70% of $PM_{2.5}$ mass, but BC absorption matters: up to 50% of net aerosol feedbacks
- Aerosol feedbacks important: lower PBL, less sun, change in surface temperature, wind speed/direction, net increase in $PM_{2.5}$
- January 2013 haze: 690 premature deaths, 45K acute bronchitis, 24K asthma cases
- $254 MM losses = 0.08% of Beijing GDP

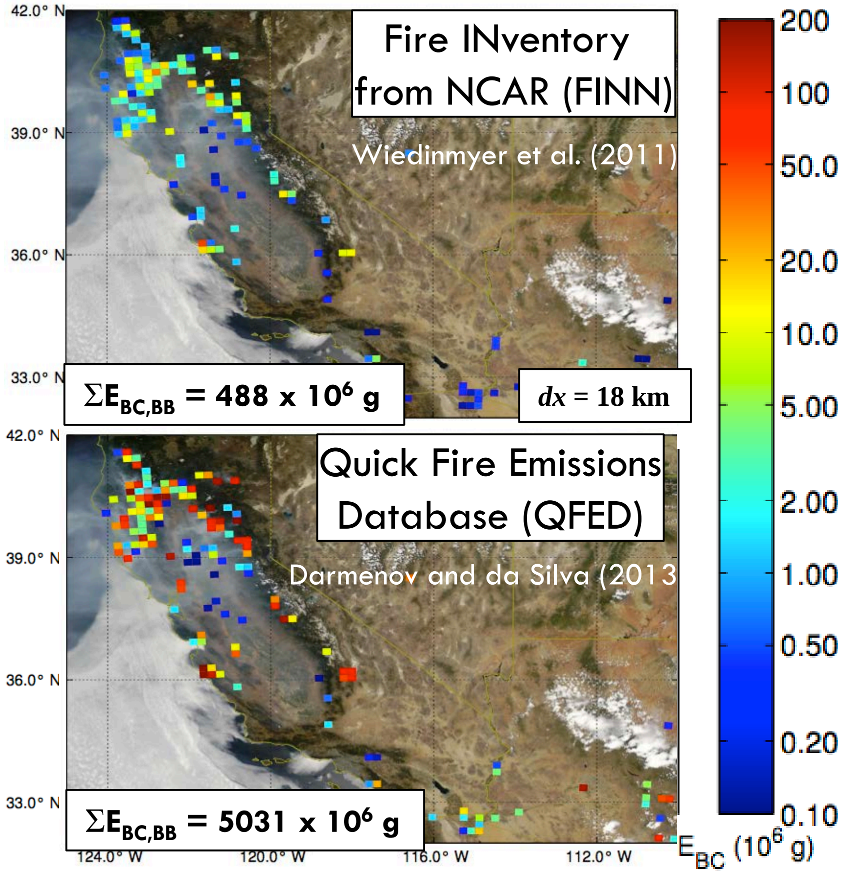
DEVELOPMENT & INITIAL APPLICATION OF THE WRF ADJOINT FOR BC: FOREST FIRE SMOKE DURING ARCTAS-CARB

Guerrette, J., and D. K. Henze, Development and application of the WRFPLUS-Chem online chemistry adjoint and WRFDA-Chem assimilation system, *Geosci. Mod. Devel.*, 8, 1857-1876, doi:10.5194/gmd-8-1857-2015.

Guerrette, J., and D. K. Henze (2016), Four dimensional variational inversion of black carbon emissions during ARCTAS-CARB with WRFDA-Chem, *Atmos. Chem. Phys. Discuss.*, doi:10.5194/acp-2016-573, in review.

J.J. Guerette, CU-Boulder

Biomass burning emissions: uncertainty abounds



Fire INventory from NCAR (FINN)

Wiedinmyer et al. (2011)

$\Sigma E_{BC,BB}$ = **488 x 10^6 g**

dx = 18 km

Quick Fire Emissions Database (QFED)

Darmenov and da Silva (2013

$\Sigma E_{BC,BB}$ = **5031 x 10^6 g**

BC Emissions, Jun 20-27, 2008:

× 10 spread similar to:

- Zhang et al. (2014)
  (7 inventories in Sub-Saharan Africa)
- Fu et al. (2012)
  (2 inventories in Southeast/East Asia)

ANTHROPOGENIC:
National Emission Inventory (NEI2005)

$\Sigma E_{BC,ANT}$ = **548 x 10^6 g**

Bayesian Inversion Framework

$\boldsymbol{x}$ – control variable
y^{o} – observations
y – modeled observations
$\mathbf{B}$ – Background covariance
$\mathbf{R}$ – Model/Obs. covariance

Bayesian Posterior

$$P(\boldsymbol{x}|\boldsymbol{y}^{o}) \propto P(\boldsymbol{x})\ P(\boldsymbol{y}^{o}|\boldsymbol{x})$$

Gaussian distributions:

1. Prior

3D: $\boldsymbol{x} \in \mathcal{R}^{n_x \times n_y \times n_t}$

$$P(\boldsymbol{x}) \propto \exp\left[-\frac{1}{2}\left(\boldsymbol{x}-\boldsymbol{x}^{b}\right)^{\mathrm{T}}\mathbf{B}^{-1}\left(\boldsymbol{x}-\boldsymbol{x}^{b}\right)\right]$$

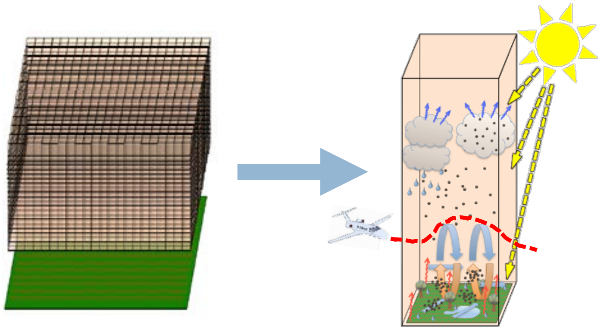
2. Model/Obs. mismatch

4D, sparse

$$P(\boldsymbol{y}^{o}|\boldsymbol{x}) \propto \exp\left[-\frac{1}{2}(\boldsymbol{y}-\boldsymbol{y}^{o})^{\mathrm{T}}\mathbf{R}^{-1}(\boldsymbol{y}-\boldsymbol{y}^{o})\right] \qquad \boldsymbol{y} = G(\boldsymbol{x})$$

Model + Observation Operator

2D (spatial) + 1D (temporal) fields of chemical fluxes



WRFDA-Chem Model Family

$G(x)$

WRF: Advection, diffusion, PBL mixing, convection, microphysics, radiation

[Skamarock et al. (2008)]

-Chem: Chemical transformation, advection, emission, fire plume rise, dry/wet deposition, vertical mixing (PBL and cumulus)

[Grell et al. (2005)]

$\mathbf{G}\delta\boldsymbol{x}, \mathbf{G}^{\top}\delta\boldsymbol{y}$

WRFPLUS: Tangent Linear **(TLM)** and Adjoint **(ADM)** models for meteorology

[Zhang et al. (2013)]

-Chem: ADM/TLM of PBL transport, emissions, dry deposition, and GOCART aerosols

[Guerrette and Henze (*GMD*, 2015)]

$\mathbf{B}, \mathbf{R}, \mathbf{A}\boldsymbol{q}$

WRFDA: 4D-Var for meteorology (initial and boundary conditions), many in-situ and remote obs. types

[Barker et al. (2005); Huang et al. (2009); Zhang et al. (2014)]

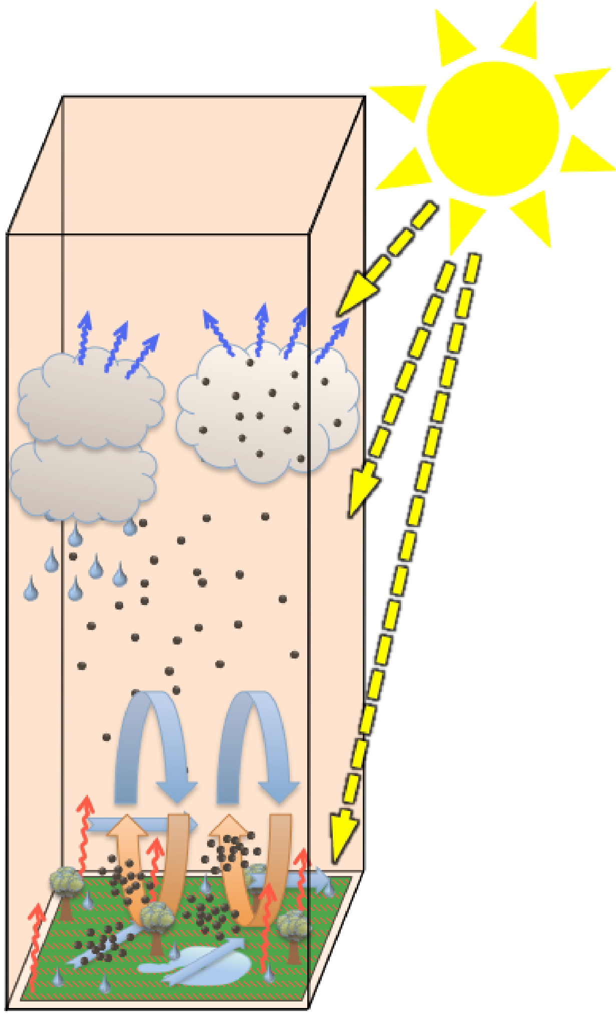
-Chem: 4D-Var for chemical emissions control variables and in-situ observations

[Guerrette and Henze, in review, *ACPD*]

WRF-Chem Adjoint Development

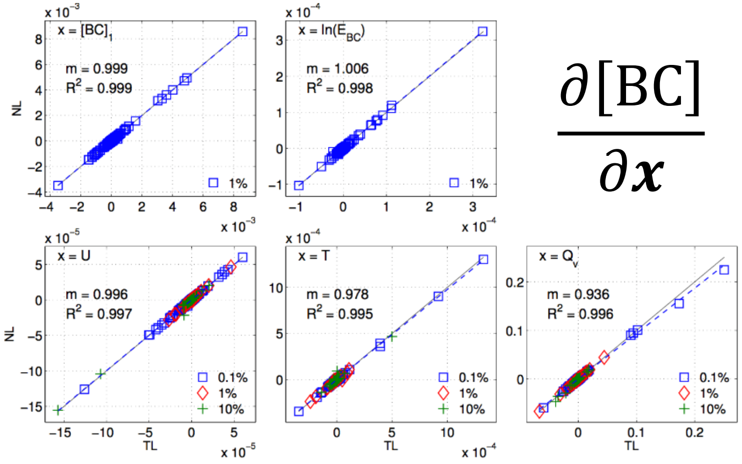
Adjoint: chemical transport

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



Development milestones

- Implemented ADM/TLM
- Verified gradients by comparison to finite difference approximations
- Calculated model/observation variance
- Reduced memory requirements for simulations with $\Delta t > 6\text{hr}$ using second order checkpointing



$$\frac{\partial[\mathrm{BC}]}{\partial \boldsymbol{x}}$$

$$\mathrm{diag}(\mathbf{R})_i = {\sigma_i^o}^2 = \sigma_{\mathrm{model},i}^2 + \sigma_{\mathrm{instrument},i}^2$$

Stochastic variance from 156 ensemble members

June 22, 2008 ARCTAS-CARB Case Study

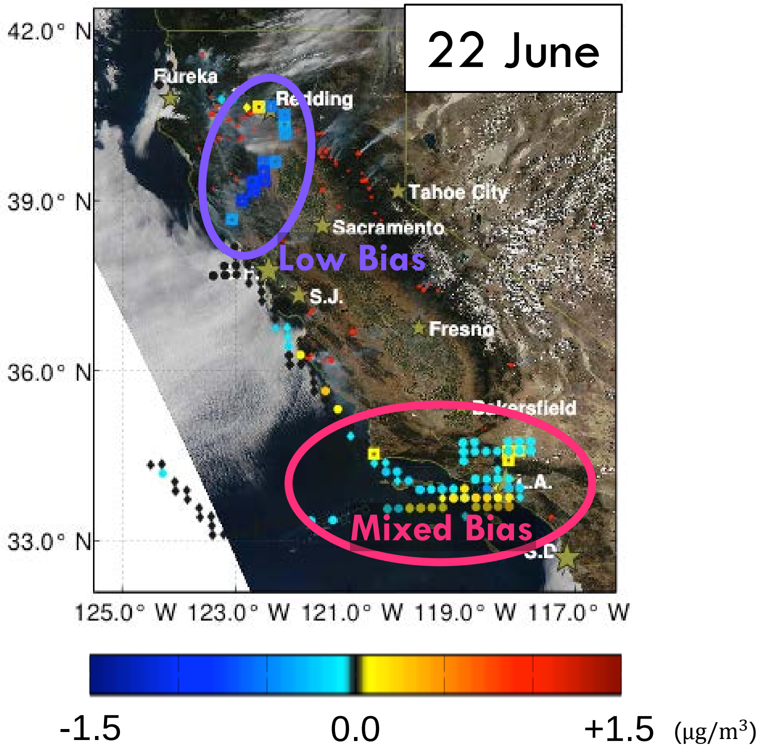
- BC measurements
  - NASA DC8 SP2 on 22 June
  - 241 grid-scale measurements

  [Kondo et al., 2011; Sahu et al., 2012]

- Domain
  - 18 km, 80 × 80 × 4
- Prior emissions
  - FINN biomass burning emissions, x3.8 relative uncertainty
  - NEI2005 anthro. emissions, x2.0 relative uncertainty
  - Assumed temporal and spatial error correlations

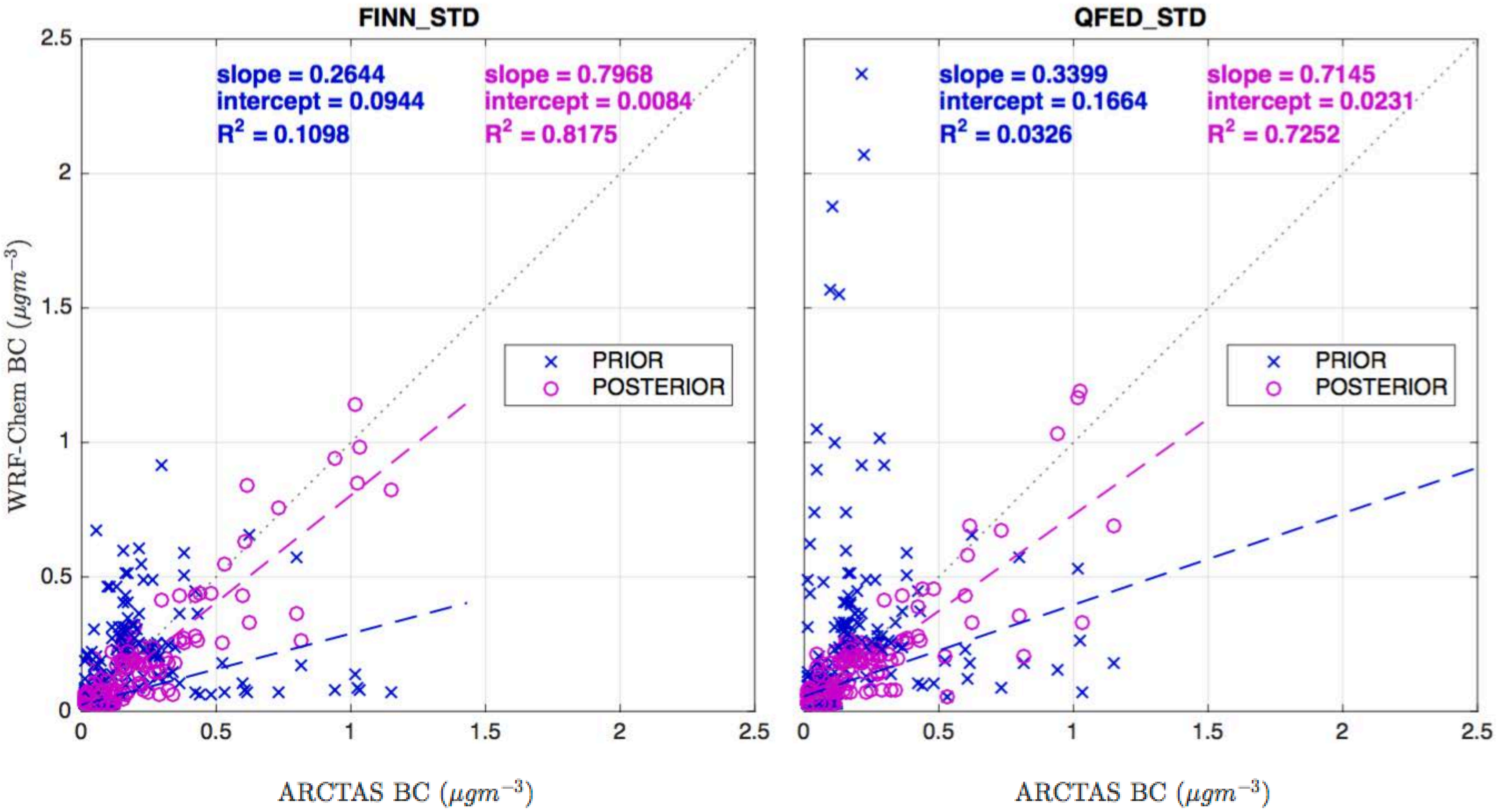
- Inversion Configuration
  - 5 outer iterations x10 inner iteration for $\boldsymbol{x}^a$
  - 1 outer iteration x50 inner iterations for $\mathbf{P}^a$
  - 24 hour assimilation window from 00Z, 22 June

MODEL− OBS $= \boldsymbol{y} - \boldsymbol{y}^o$



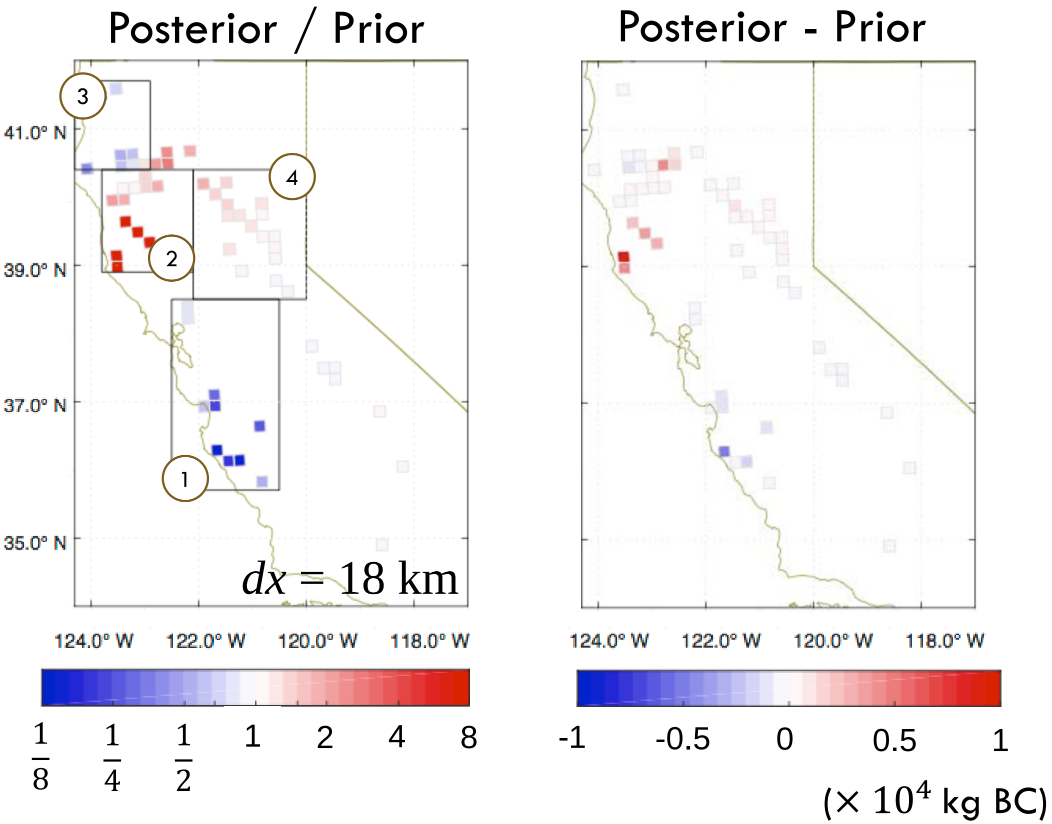
[Guerrette and Henze, 2015, GMD]

22 June model, 4DVAR, inversion x2 emissions inventories



[Guerrette and Henze, in review, ACP]

Biomass Burning BC Constraint



- Relative increments are correlated in space (as expected; $L_{x,y} = 36$ km)
- Absolute increments are disperse, collocated with large priors or large residual errors
- Consistent sign of increments across broad areas due to sparse observations + enforced emission correlation

[Guerrette and Henze, in review, ACPD]

Take Home Points: WRFDA-Chem Adjoint

1. Tools: Developed adjoint of NWP + chemistry model. WRFDA-Chem 4D-Var is **fully functional** for BC and other tracer emission inversions
   These tools lay the foundation for 4D-Var in a coupled meteorology chemistry model and for operational air quality forecasting
2. Decision Support: Local/regional source attribution
3. Science: Enables determination of model process vs. emission contributions to errors

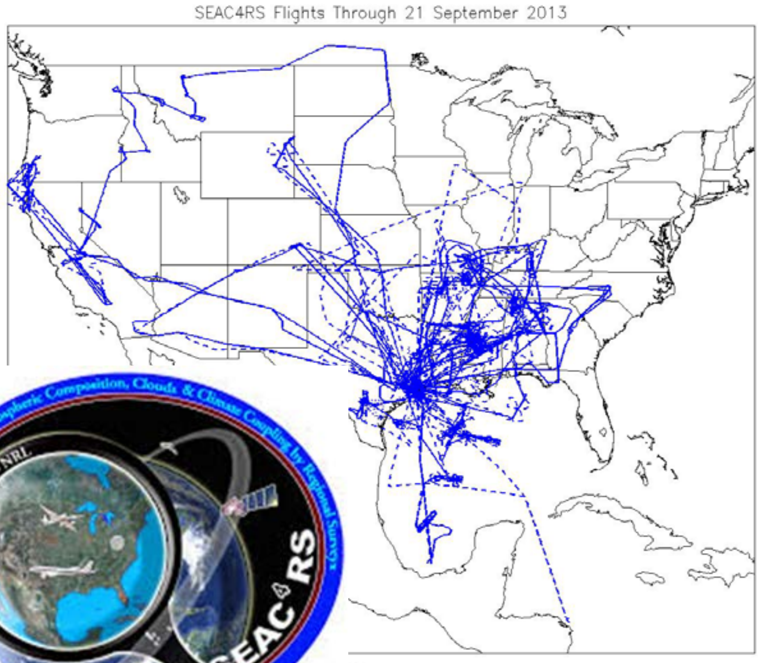
ASSIMILATION OF NEXT GENERATION GEOSTATIONARY RETRIEVALS & MULTI-PLATFORM INVERSION OF WILDFIRE EMISSIONS

Saide, P. E., Kim, J., Song, C. H., Choi, M., Cheng, Y., and Carmichael, G. R.: Assimilating next generation geostationary aerosol optical depth retrievals can improve air quality simulations, *Geophys. Res. Lett.*, 2014GL062089, doi:10.1002/2014gl062089.

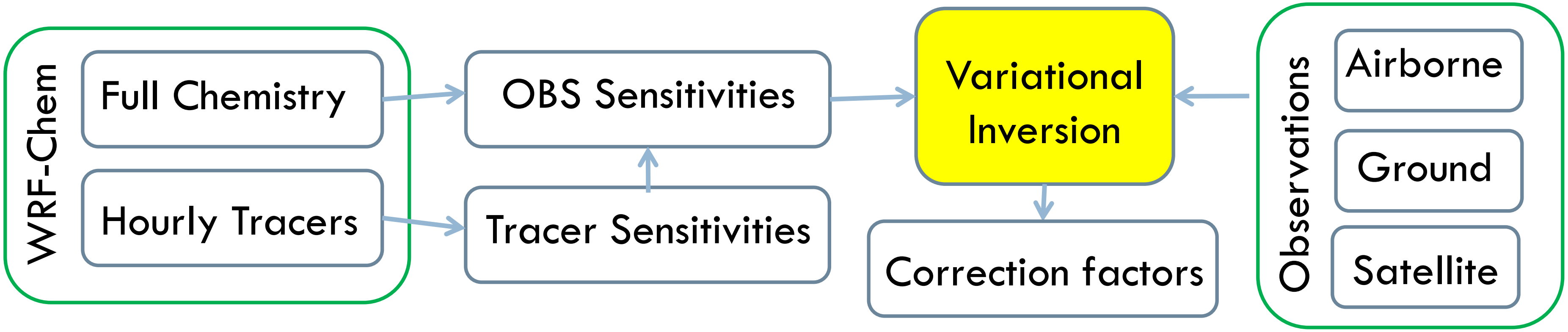
Saide, P.E., Peterson, D., da Silva, A., Anderson, B., Ziemba L.D., Diskin, G., Sachse, G., Hair, J., Butler, C., Fenn, M., Jimenez, J.L., Campuzano-Jost, O., Perring, A., Schwarz, J., Markovic, M.Z., Russell, P., Redemann, J., Shinozuka, Y., Streets, D.G., Yan, F., Dibb, J., Yokelson, R., Toon, O.B., Hyer, E, Carmichael, G.R., Revealing important nocturnal and day-to-day variations in fire smoke emissions through a novel multiplatform inversion. *Geophys. Res. Lett.*, doi:10.1002/2015GL063737.

Pablo Saide

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



- WRF-Chem v3.5, 12km CONUS
- CBM-Z, 4 bin MOSAIC
- NRL AOD assimilated every 3h
- SEAC4RS in-situ + remote sensing ground observations assimilated



WRF-Chem

Full Chemistry

Hourly Tracers

OBS Sensitivities

Tracer Sensitivities

Variational Inversion

Correction factors

Observations

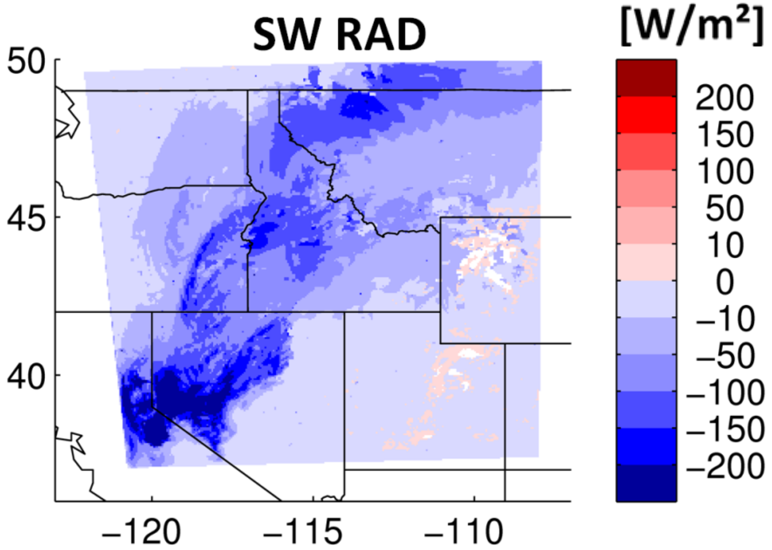
Airborne

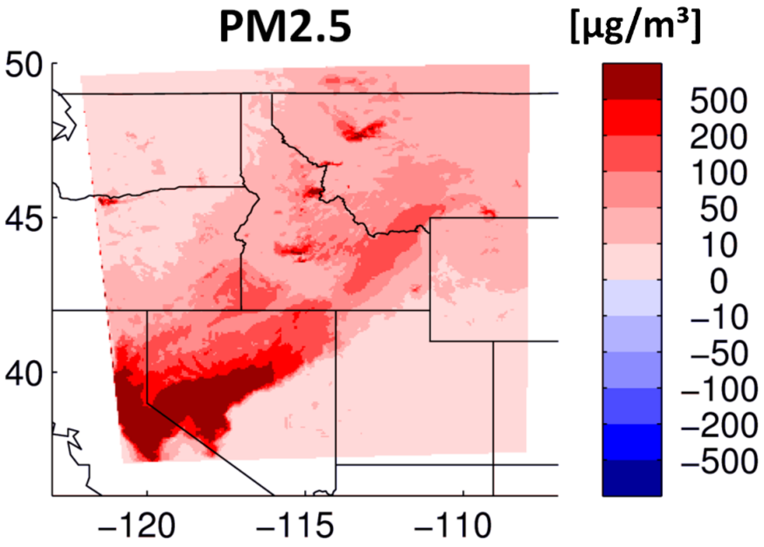
Ground

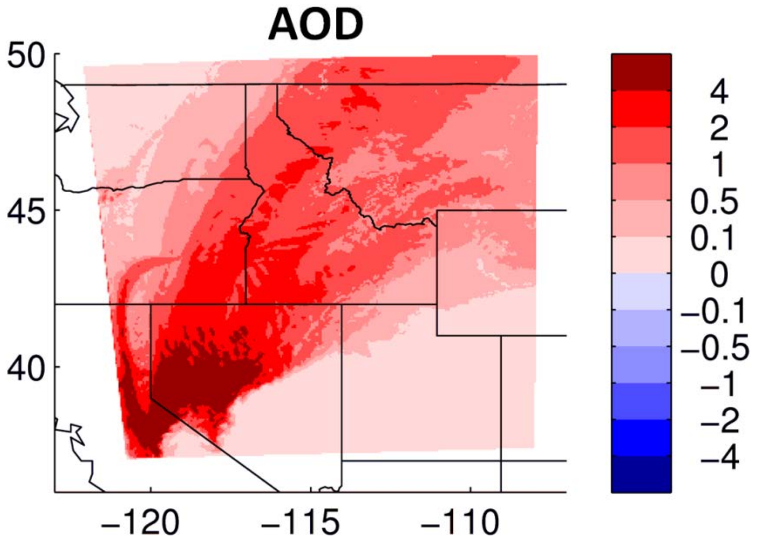
Satellite

Impacts on smoke $PM_{2.5}$, AOD, SLCF

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

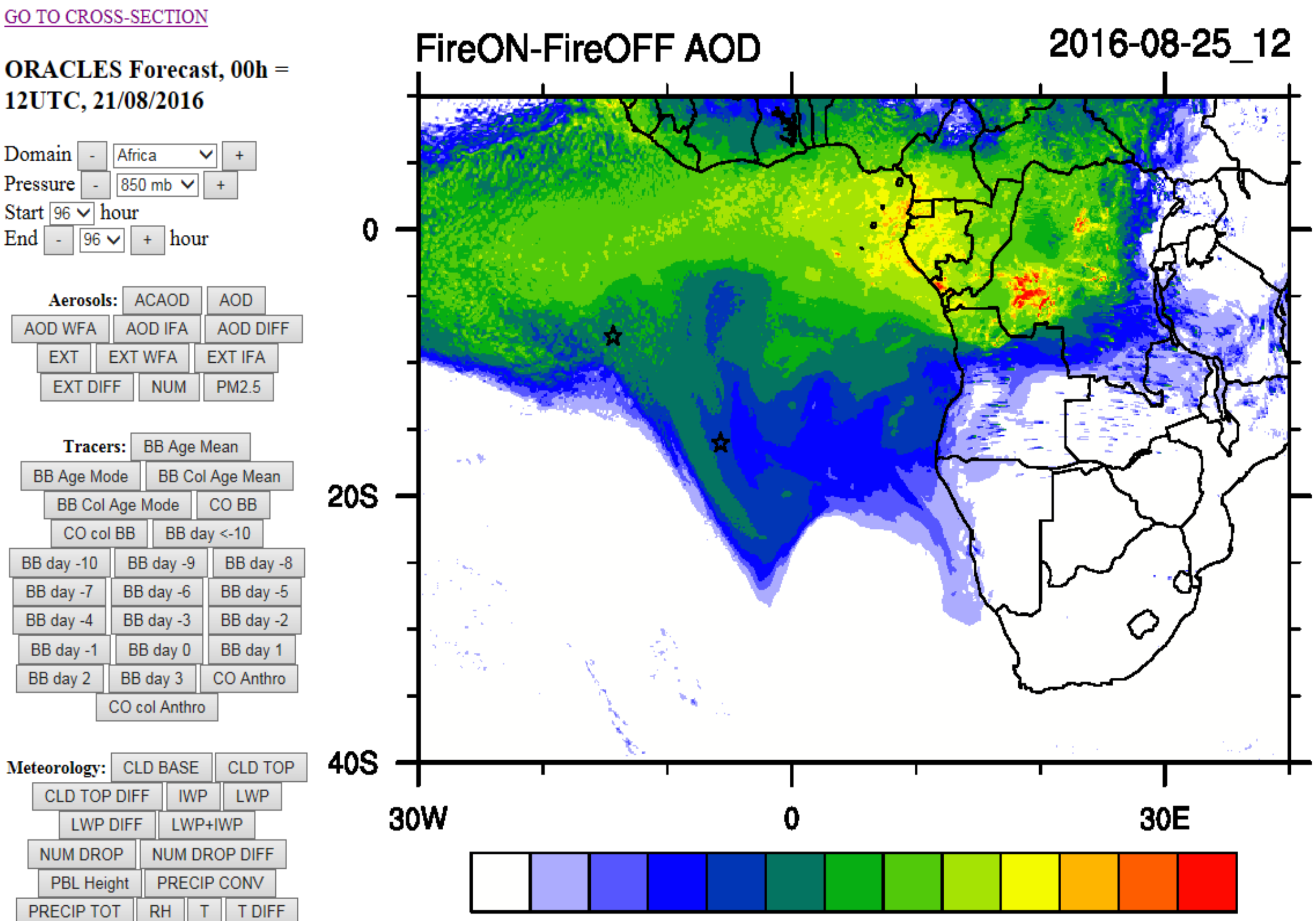






Operational real-time GSI assimilation & inversion in ORACLES forecasting

Instrumentation & Models NASA Earth-Venture-Suborbital-2 project



GO TO CROSS-SECTION

ORACLES Forecast, 00h = 12UTC, 21/08/2016

Domain Africa

Pressure 850 mb

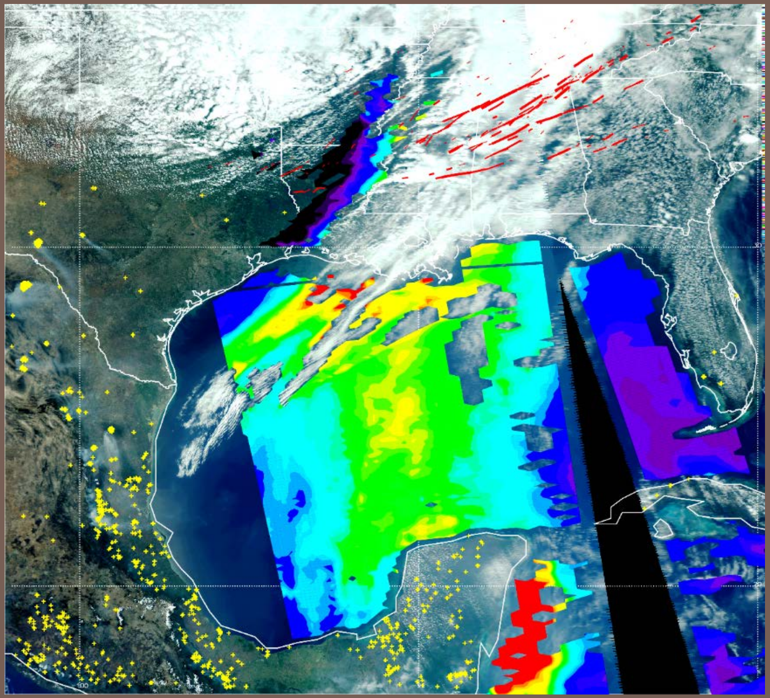
Start 96 hour

End 96 hour

Take Home Points: GSI Assimilation

1. Science
   - Constraining fire emissions with multiple data sources can better characterize fires, improve AQ predictions
   - Assimilating next gen geostationary AOD improves AQ forecasts
2. Tools
   - Attribution + inversion in coupled AQ + climate model using tracer + concentration + climate sensitivities
   - Practical additions to GSI + any model
3. Decision Support
   - Fast track to better inputs for monitor siting, forecasting, SIP, policy analysis applications

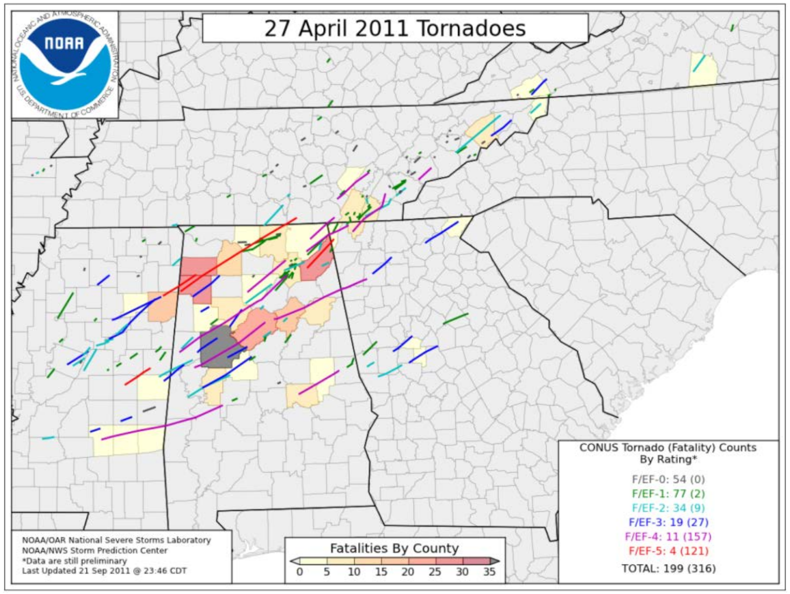
LINKS BETWEEN BIOMASS BURNING SMOKE & TORNADO LIKELIHOOD: FROM REGIONAL TO CLOUD-RESOLVING SIMULATIONS

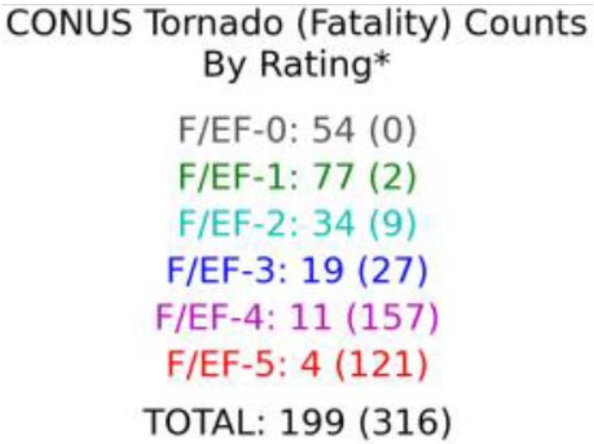


Saide, P.E., S. N. Spak, R. B. Pierce, J. A. Otkin, T. K. Schaack, A. K., Heidinger, A. M. da Silva, M. Kacenelenbogen, J. Redemann and G. R. Carmichael, Central American biomass burning smoke can increase tornado severity in the US. Geophys. Res. Lett. 42, doi:10.1002/2014GL062826.

Pablo Saide, NCAR ASP/ACOM

Case Study: 27 April 2011 outbreak





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)

BAMS

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

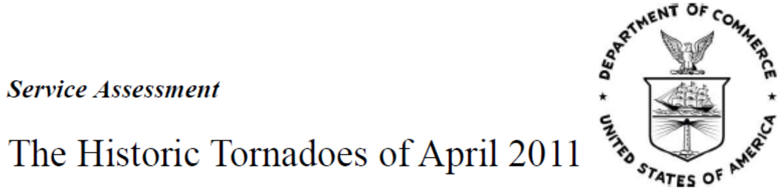
Weather – April 2012, Vol. 67, No. 4

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

Charles A. Doswell III[1,2], Gregory W. Carbin[3] and Harold E. Brooks[4]

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-



Service Assessment

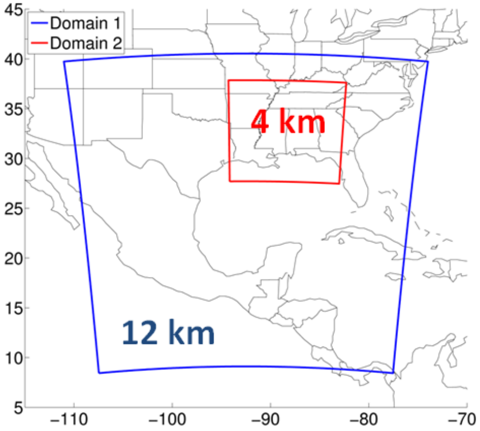
The Historic Tornadoes of April 2011

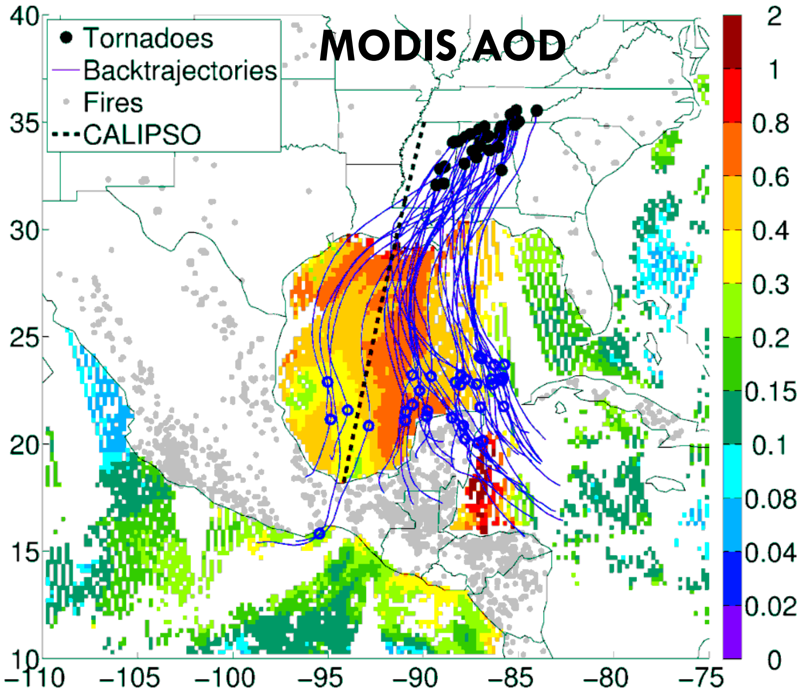
DEPARTMENT OF COMMERCE
UNITED STATES OF AMERICA

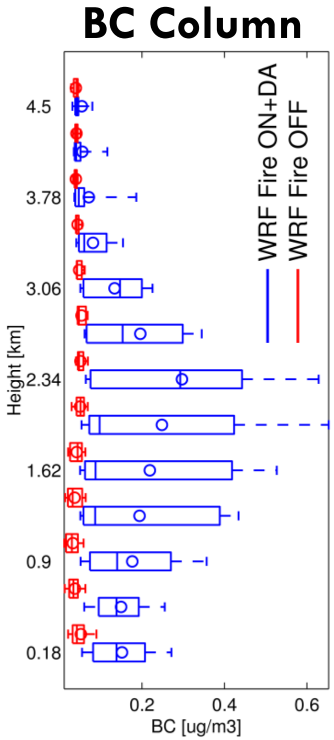
“By many metrics, the tornado outbreak on 27 April 2011 was the most significant outbreak since 1950”

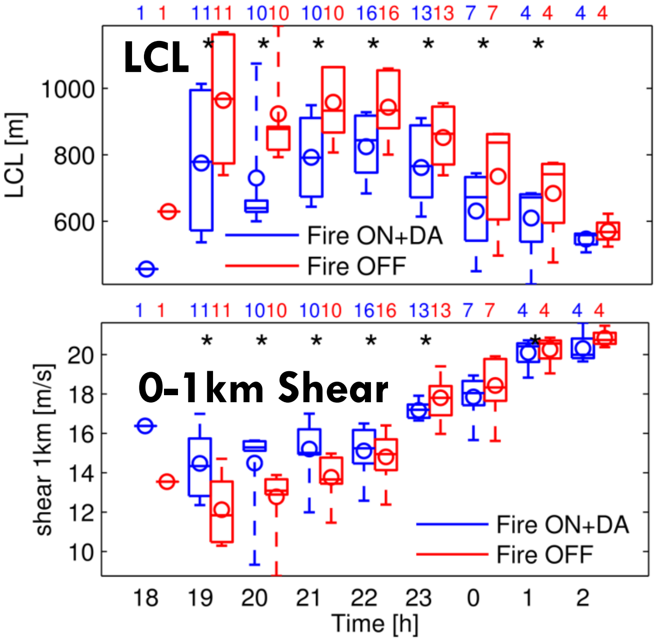
Where there's smoke…

WRF-Chem simulations indicate that the presence of smoke during this event results in lower cloud bases and stronger low-level wind shear which indicate higher probability of tornadogenesis and tornado intensity and longevity.









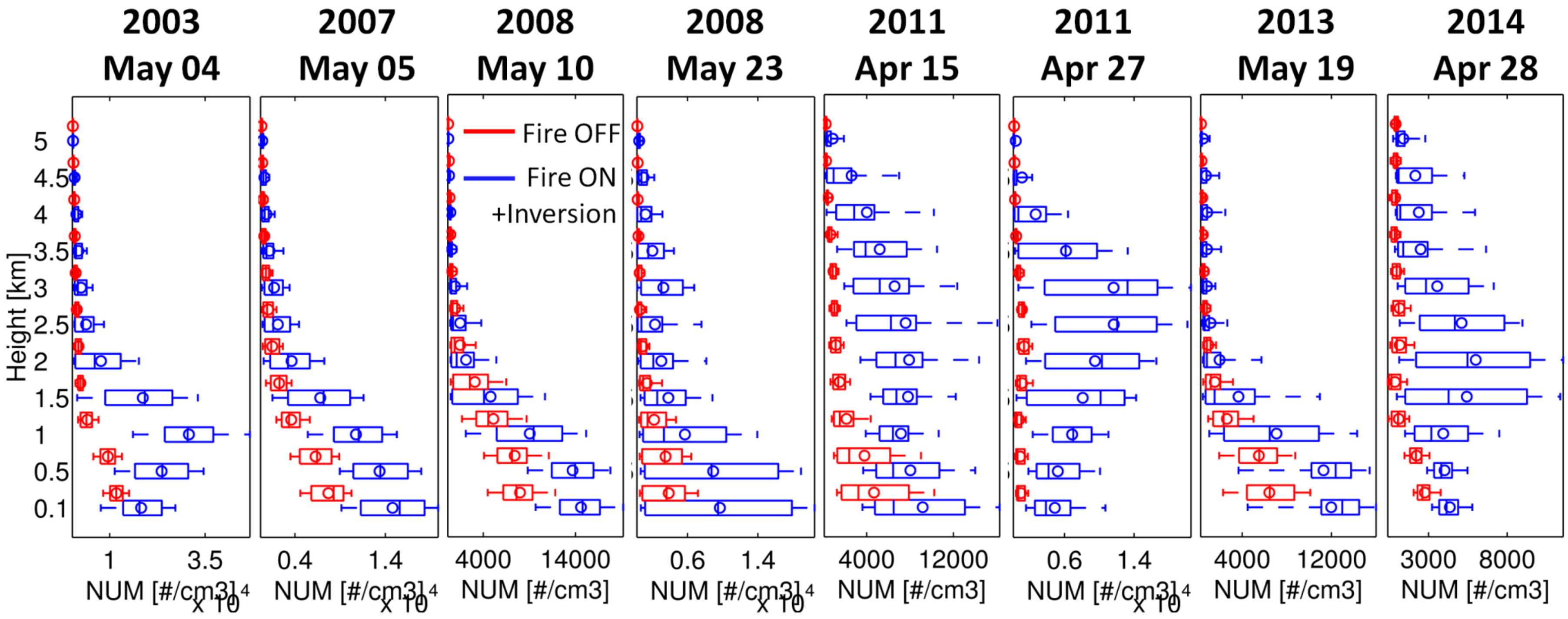
Why?

- Optical thickening of shallow clouds due to increase CCN
- Enhancing of the capping inversion due to soot absorption

Saide et al., GRL 2015b

Analyzing a decade of outbreaks

Updated near-operational NWP approach for SLFC & regional attribution: WRF with aerosol-aware microphysics (AAM) (Thompson and Eidhammer, 2014) with WRF-Chem primary emissions

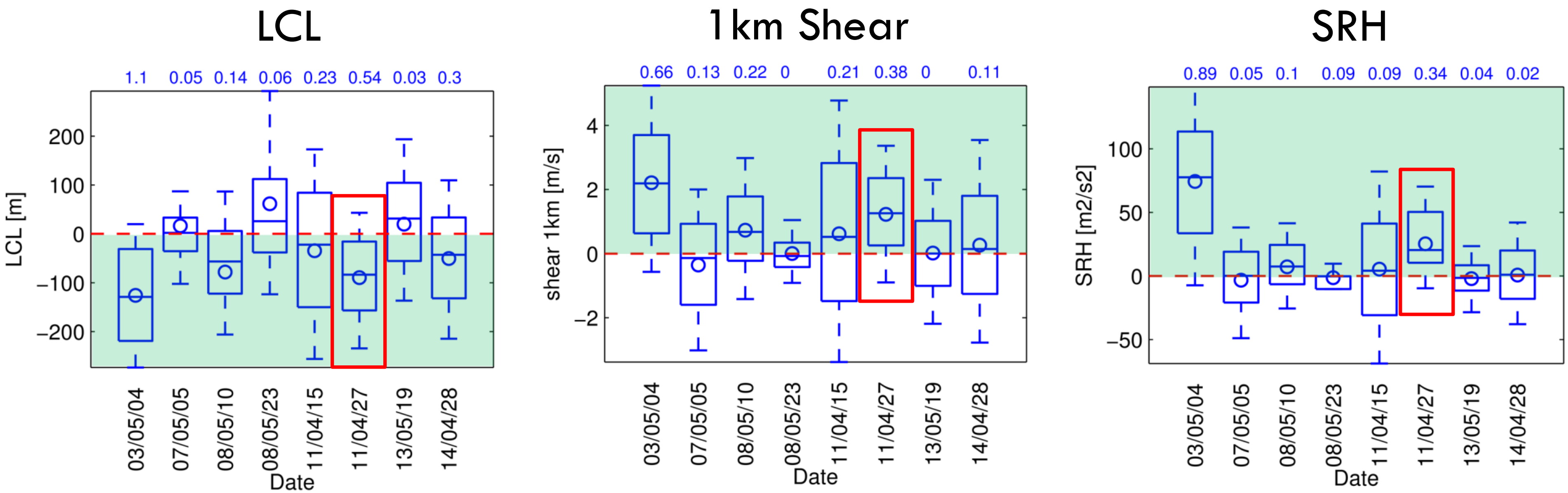


Aerosol Number concentration [#/cm3]

Saide et al., JGR 2016

Found: how, when smoke impacts

- Large spread in smoke effects on environmental conditions, from negligible impacts to large intensification.
- 27 Apr 2011 intensification consistent with WRF-Chem MOSAIC



LCL

1km Shear

SRH

FIRE ON+INVERSION – FIRE OFF

Saide et al., JGR 2016

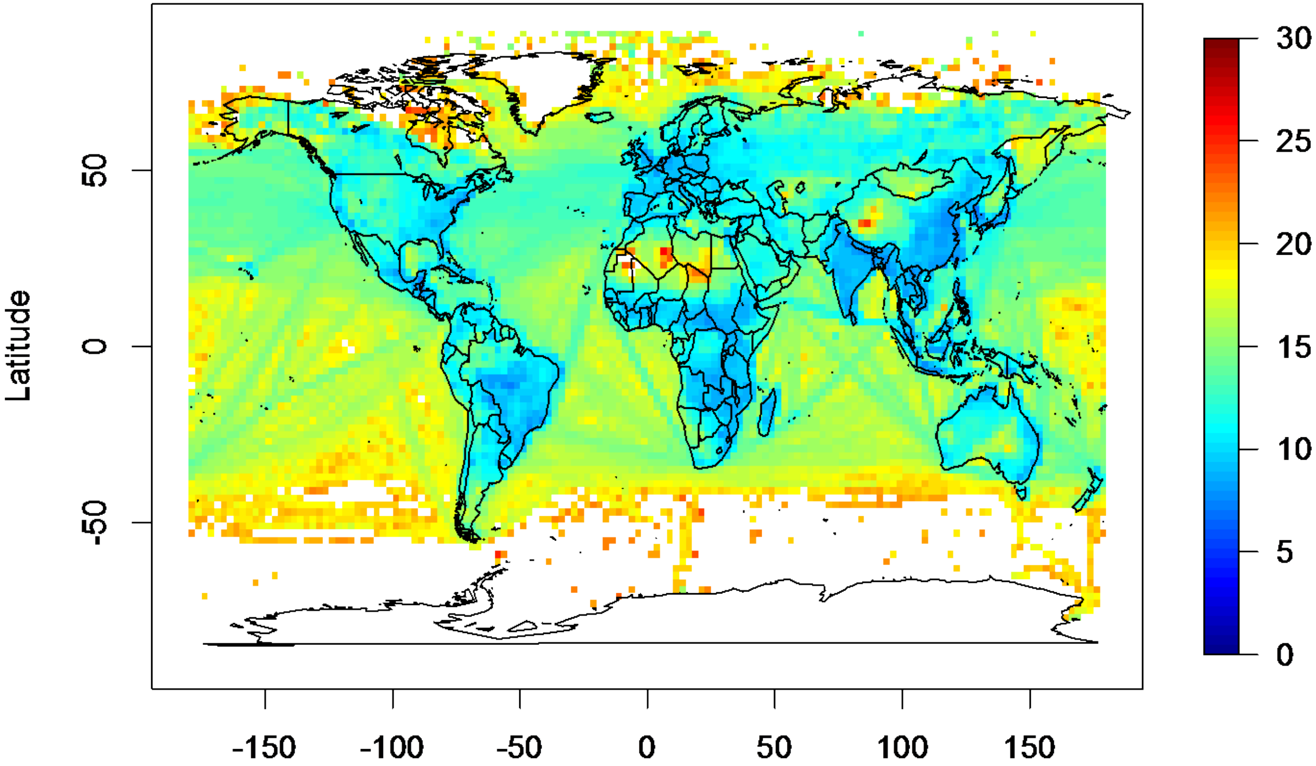
🟩 : Higher likelihood of tornado formation and intensity

ADJOINT METRICS FOR AIR QUALITY & CLIMATE CO-BENEFITS

SN Spak, DK Henze, F Lacey, EA Minor, GR Carmichael. Global disparities in health and climate co-benefits from air pollution control policies. In preparation.

RCP2000 sensitivities: SLCF

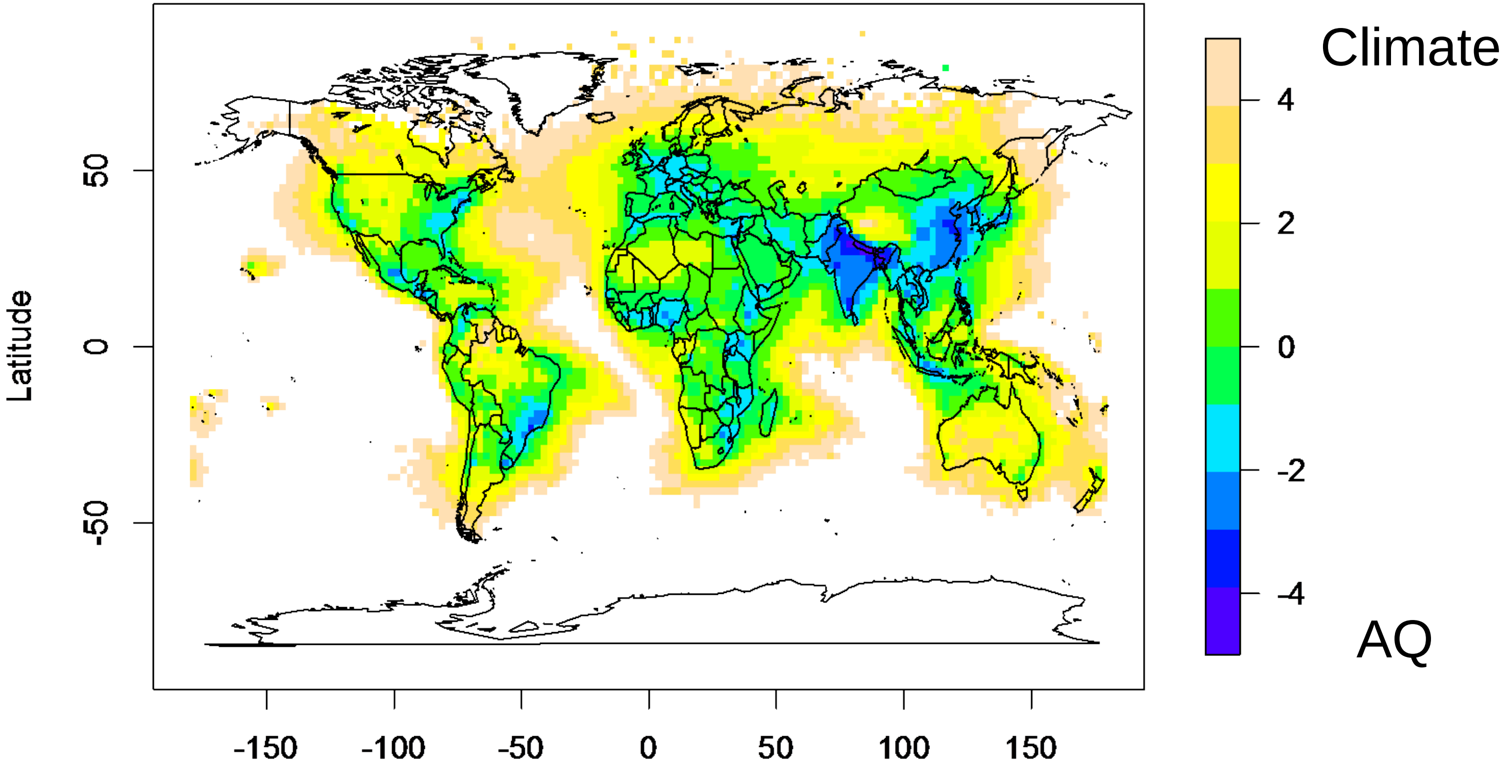
Global BC DRF : emissions
(W/m^2/kg/year, log scale)



$$Elasticity_{SLFC} = \frac{! \; SLFC \, / \, SLFC}{! \; Emissions[SLFCA] \, / \, Emissions[SLFCA]} = \frac{! \ln SLFC}{! \ln Emissions[SLFCA]}$$

Where to focus BC on climate vs AQ?

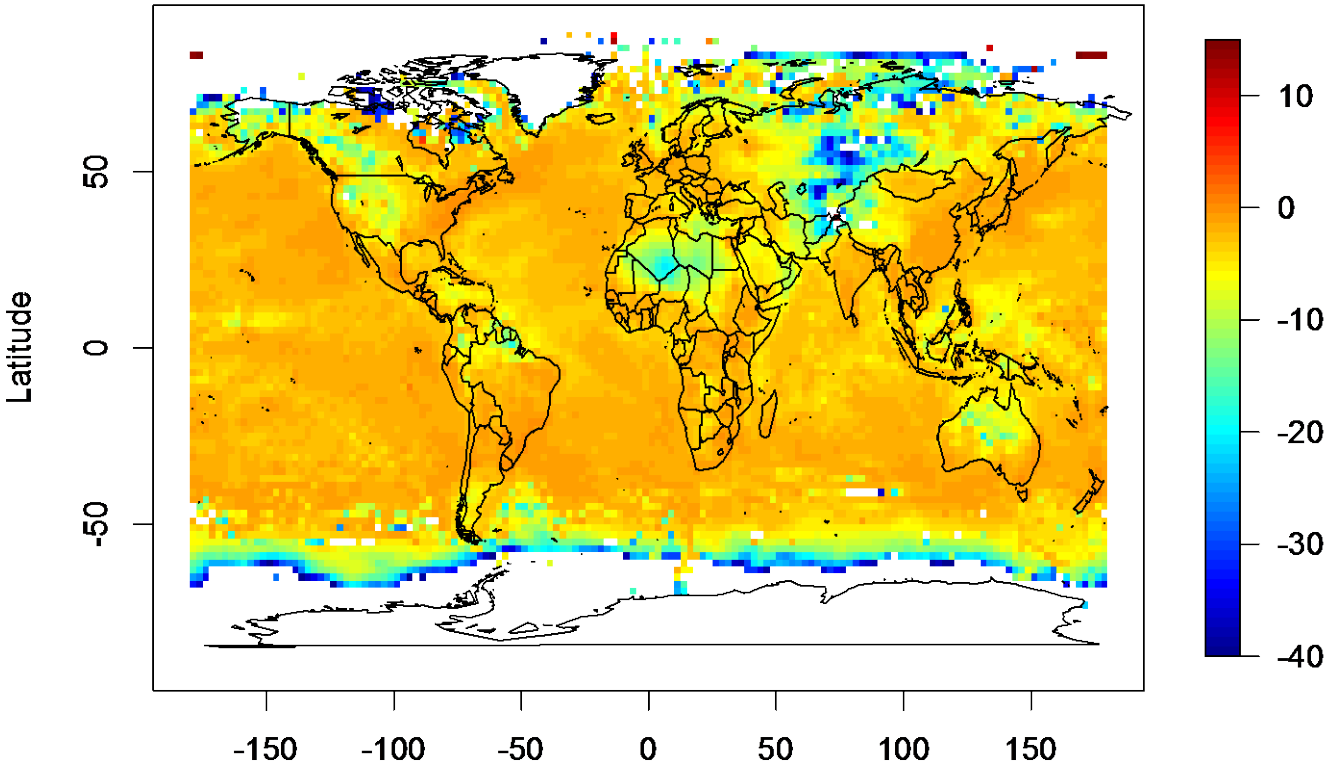
Global BC DRF by latitude band : Population-weighted BC
(W•m/µg, log scale)



$$Forcing\_Amplifier_{SLFCA} = \frac{! \ln SLCF[SLFCA]}{! \ln Concentration[SLFCA]} = \frac{Elasticity_{SLFC}}{Elasticity_{SLFCA}}$$

Design policies to reflect urban/regional differences in sources, mixtures, impacts?

Global BC:SO_2 Emissions Reduction Efficiency



Manage the ratio

Reduce BC

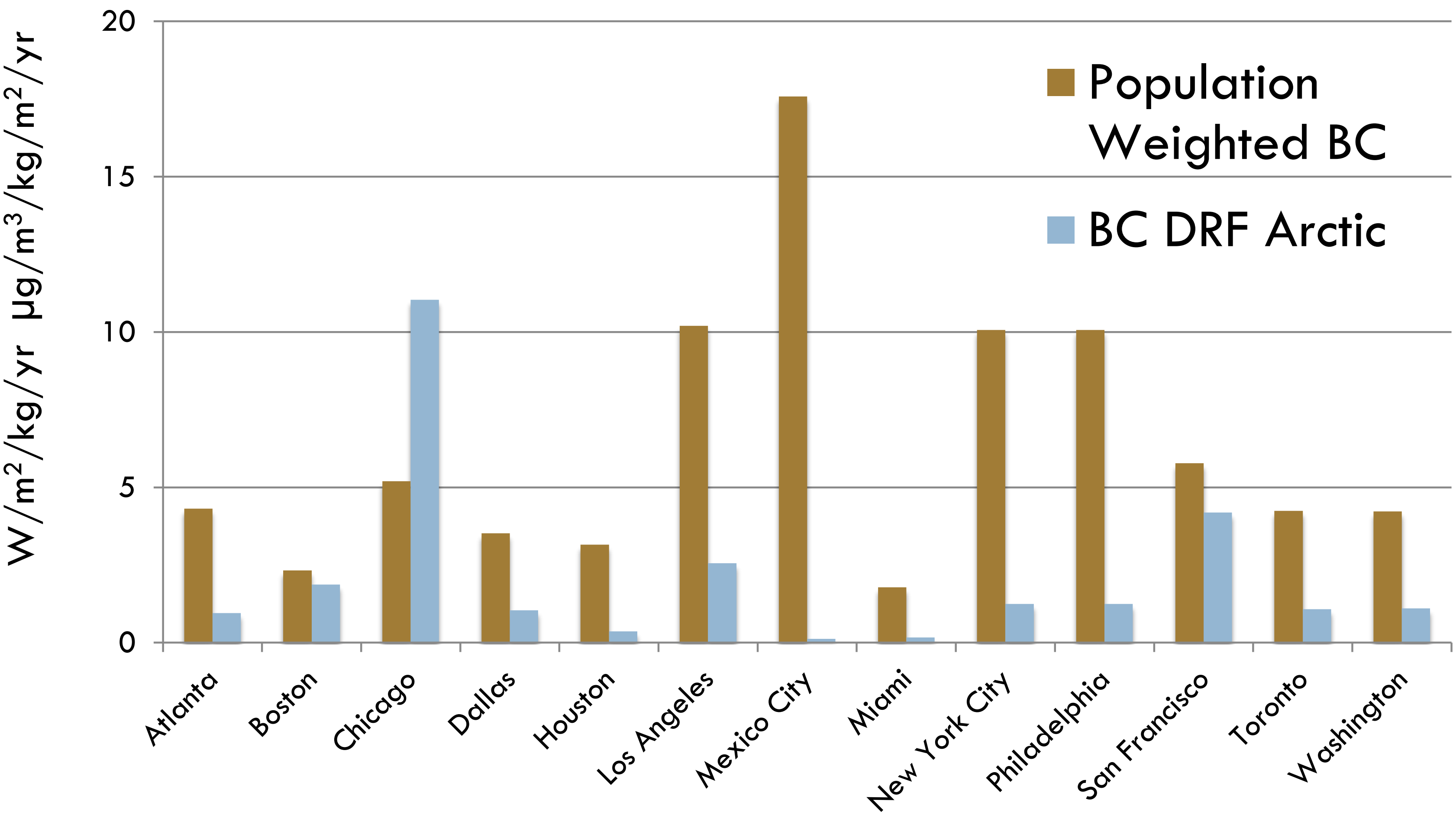
$$\mathit{Emissions\_Reduction\_Efficiency}_{SLFCA1,SLFCA2} = \frac{\mathit{Forcing\_Amplifier}_{SLFCA1}}{\mathit{Forcing\_Amplifier}_{SLFCA2}}$$

The 75 Largest Cities

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

North American Cities



Conclusions: Science

- Start here: emissions are the greatest parametric uncertainty, and readily reduced through assimilation, globally, across scales
- Nested solutions: constraining biomass burning emissions represents a potential fast track to improve rates + spatial/temporal attribution for other sectors, globally, across scales
- Climate surprises: BC direct + indirect SLCF can influence tornado likelihood, severity

Conclusions: 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
- Shared experimental recipes for BC sensitivity, DA, attribution using AQ + climate models in real world conditions, averages, extremes
- Synergies between non-linear sensitivity tools & emerging observing systems for understanding and reducing uncertainties in BC

Conclusions: Decision support

- Adjoint co-benefits metrics: just add emissions to identify where and how to most quickly improve climate & AQ together
- BC SLFC:AQ and BC:SO_2 management vary by orders of magnitude globally and among megacities
- Trans-boundary BC-specific SLFC may have broad environmental policy implications

Thank you!

Publications

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.

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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.

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Saide, P. E., Kim, J., Song, C. H., Choi, M., Cheng, Y., and Carmichael, G. R.: Assimilating next generation geostationary aerosol optical depth retrievals can improve air quality simulations, *Geophys. Res. Lett.*, 2014GL062089, 10.1002/2014gl062089, 2014.

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Gao, M., Guttikunda, S.K., Carmichael, G.R. , Wang, Y., Liu, Z., Stanier, C.O. Health impacts and economic loss assessment of the 2013 severe haze event in Beijing. *Sci. Tot. Environ.* 511, 553-561, doi 10.1016/j.scitotenv.2015.01.005, 2015.

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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, and K.-N. Liou, Variational estimates of black carbon emissions in the western United States, *Atmos. Chem. Phys.*, 5, 7685-7702, doi:10.5194/acp-15-7685-2015.

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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. *Geophys. Res. Lett., doi:* 10.1002/2015GL063737.

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Forthcoming

Submitted

Guerrette, J., and D. K. Henze (2016), Four dimensional variational inversion of black carbon emissions during ARCTAS-CARB with WRFDA-Chem, *Atmos. Chem. Phys. Discuss.*, doi:10.5194/acp-2016-573, in review.

Zhang, L., D. K. Henze, G. A. Grell, O. Torres, H. Jethva, L. N. Lamsal, What factors control the trend of increasing AAOD over the United States in the last decade?

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Qi, L., *et al*. Sources of springtime surface black carbon in the Arctic: an adjoint analysis.

Xu, J., *et al*., Source attribution of Arctic black carbon constrained by aircraft and surface measurements.

Spak, S.N., D.K. Henze, *et al*. Global disparities in health and climate co-benefits from air pollution control policies.