Examining Air Quality-Meteorology Interactions on Regional to Hemispheric Scales

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Air Pollution-Meteorology Interactions

N. Minnesota fire smoke over Chicago, 2011

New Delhi, January 2015

AQI at U.S. Embassy: ~180-250

Phoenix, 2014: Dust Storm

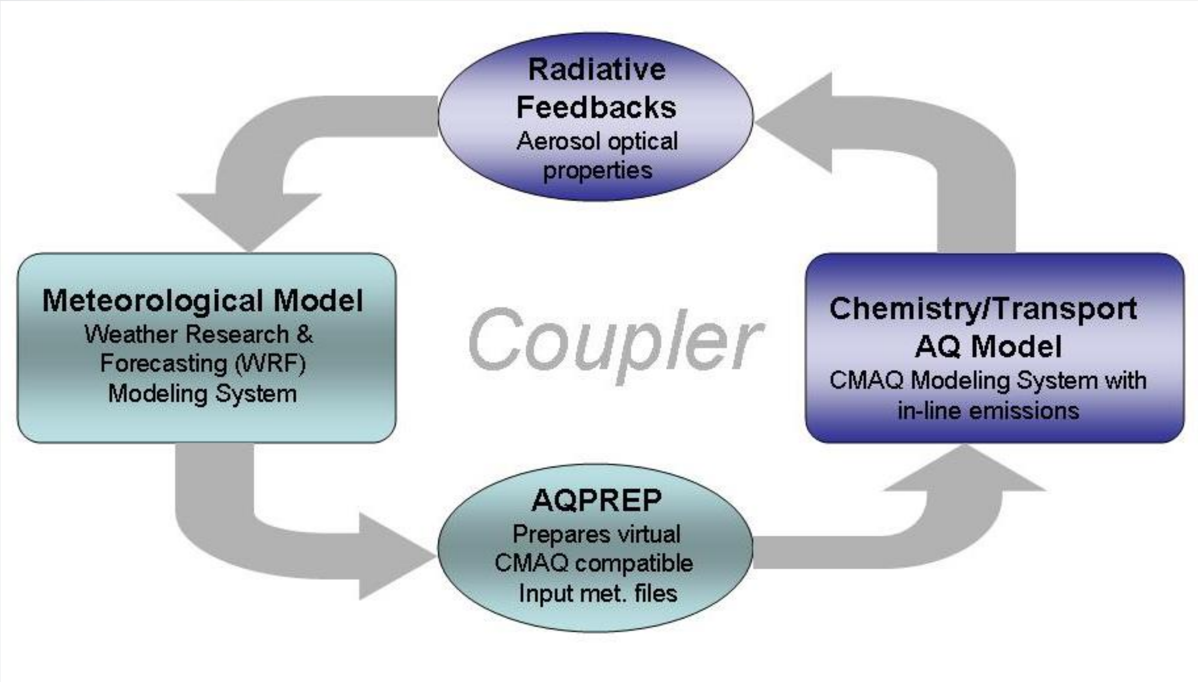
Beijing, December 2011; $PM_{2.5}$ ~ 260 $\mu g/m^3$

2-Way Coupling of Atmospheric Dynamics & Chemistry: Rationale

- ***Represent and assess the potentially important radiative effects of pollutant loading*** on simulated dynamical features and air quality
  - Many compounds contribute to poor air quality as well as climate change (e.g., O_3 and aerosols)
  - ***Need tools to simultaneously address both issues and their interactions***

- Concurrent meteorology and chemistry-transport calculation
  - ***High frequency communication*** between dynamical and chemical calculations
    - Higher temporal integration (Dt << 1 hour) is necessary at finer horizontal grid resolutions (Dx < 10 km).
    - ***Such high rates of data exchange are not practical using I/O disk files***
  - ***Potentially improve*** representation of variability in predicted air quality (and human exposure) at fine resolutions

Coupled WRF-CMAQ: Design & Features



Aerosol Optics & Feedbacks

- Refractive indices for each wavelength based on
  - Composition and size distribution
  - SO_4^{2-}, NO_3^-, NH_4^+, Na^+, Cl^-, EC, POA, anthropogenic and biogenic SOA, other primary, water
- RRTMG Shortwave radiation scheme
- Effects of aerosol scattering and absorption on photolysis
- Effects of O_3 on long-wave radiation

Effects on grid-scale clouds

Flexible **design of model coupling allows**

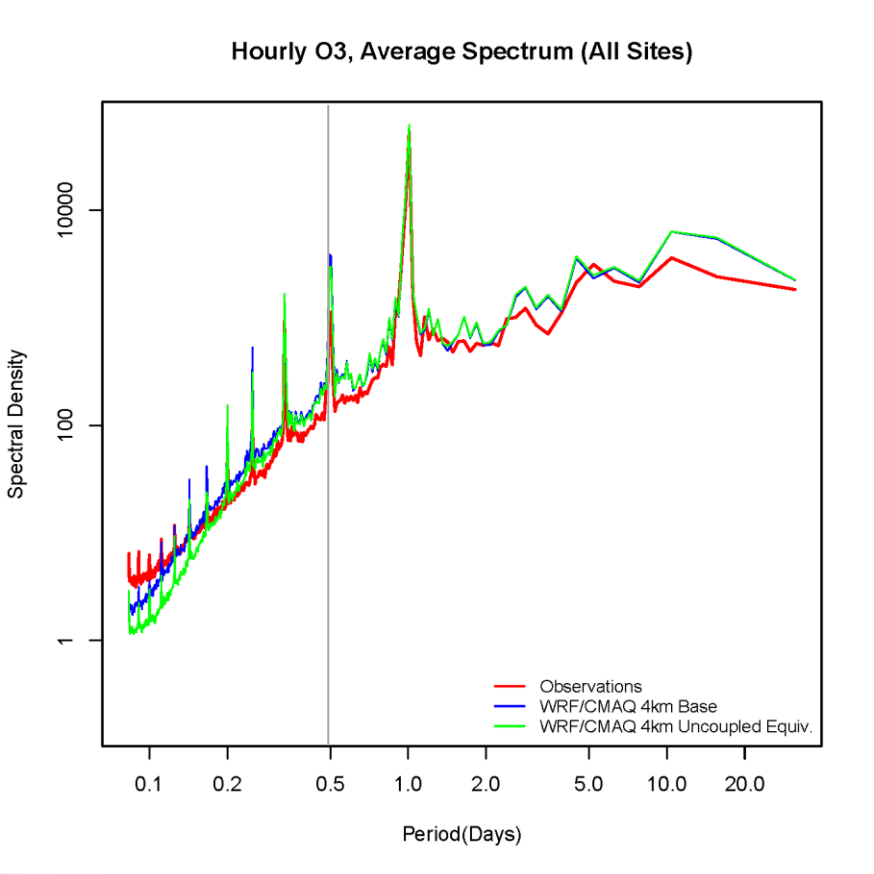
- data exchange through memory resident buffer-files
- flexibility in frequency of coupling
- identical on-line and off-line computational paradigms with minimal code changes
- both WRF and CMAQ models to evolve independently;

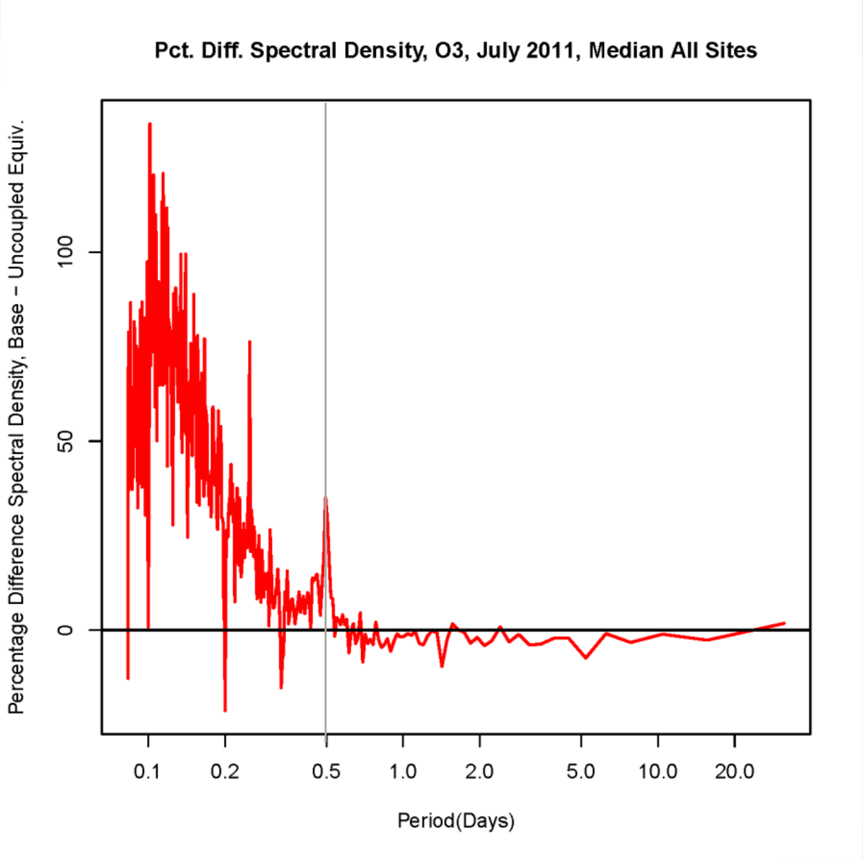
➡ *Maintains integrity of WRF and CMAQ*

Does frequency of coupling impact model predictions of pollutant concentration variations?

Comparison of coupled and “uncoupled” (hourly linkage) simulations at 4km

Model output data at 1-hr resolution

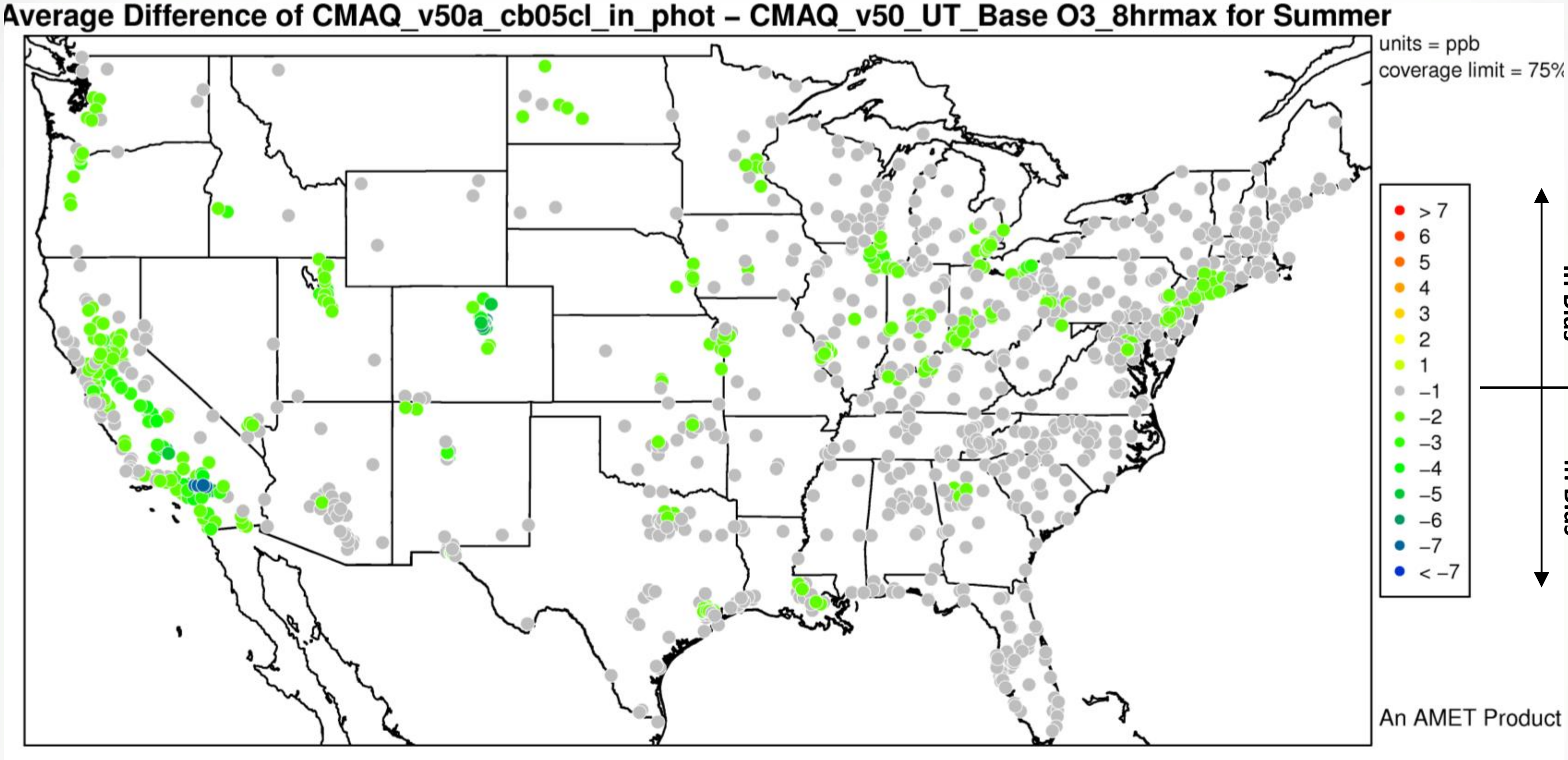




Higher variability in the intra-day spectral band when higher frequency meteorological information is used to drive the chemistry-transport calculations; little impact at time-scales > 12hrs

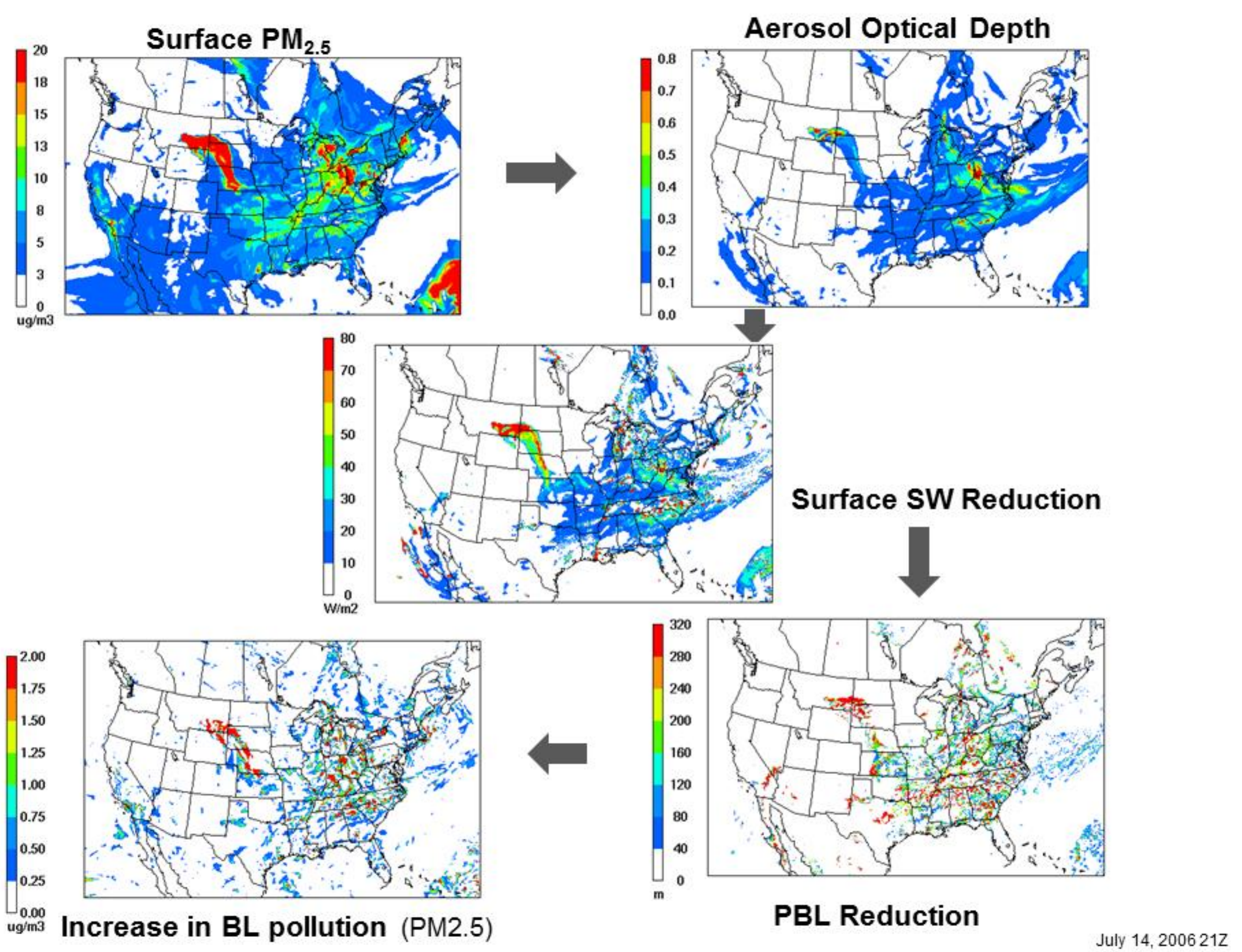
Aerosol Effects on Photolysis

Impact on simulated O_3: Difference in Bias



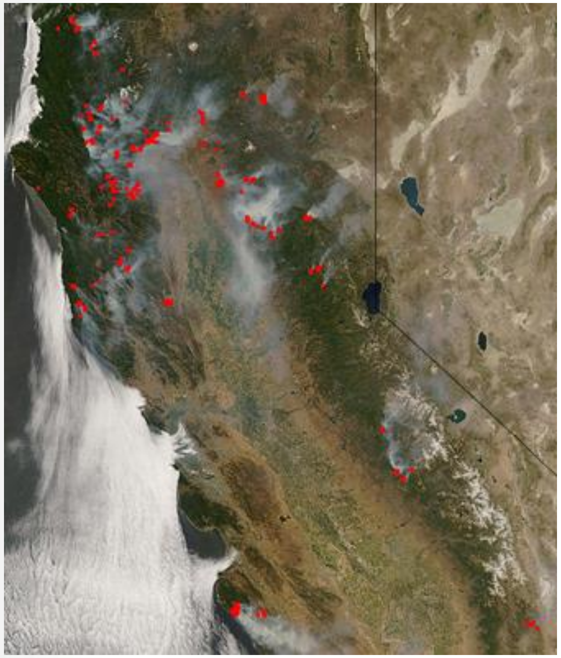
Reduction in bias in vicinity and downwind of source regions

Aerosol Direct Radiative Effects on Air Quality

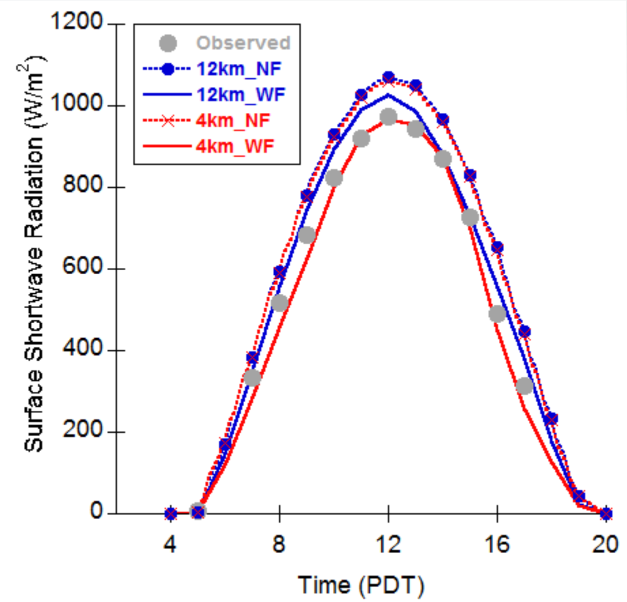


Case Study: California Wildfires

Widespread wildfires resulted in significant PM pollution during mid/late June 2008 in California and surrounding states



Surface shortwave radiation at Hanford



	O_3 (ppb)		$PM_{2.5}$ (μg/m³)		SWR (W/m²)		T (K)	
	NF	WF	NF	WF	NF	WF	NF	WF
ME	15.2	**14.6**	29.1	**28.6**	145.6	**112.5**	3.34	3.43
RMSE	20.2	**19.5**	48.1	**45.19**	184.2	**148.8**	4.87	**4.9**
R	0.69	0.69	0.45	**0.47**	0.86	**0.88**	0.77	**0.79**

Incorporation of feedbacks improves performance at locations impacted by smoke plumes

- ***Feedback effects can be important in conditions of high aerosol loading***

Multi-Decadal WRF-CMAQ Simulations

Horizontal

- Polar Stereographic projection
- **108 km resolution (187x187)**
- **Nested CONUS: 36km resolution**

Vertical

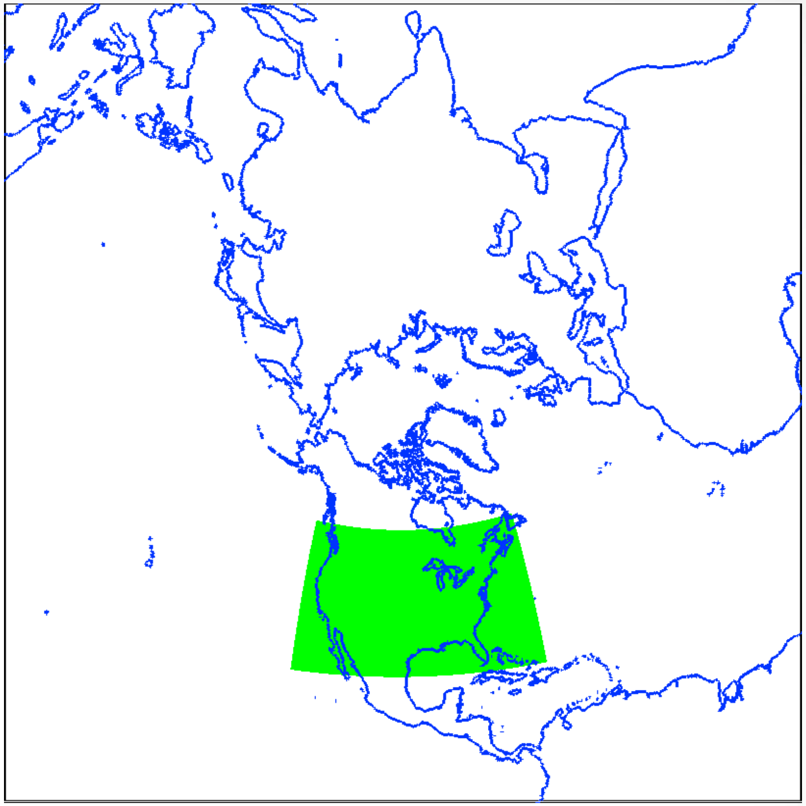
- 44 layers between surface & 50mb

Emissions

- NH: EDGARv4.2
- CONUS: Xing et al., 2013

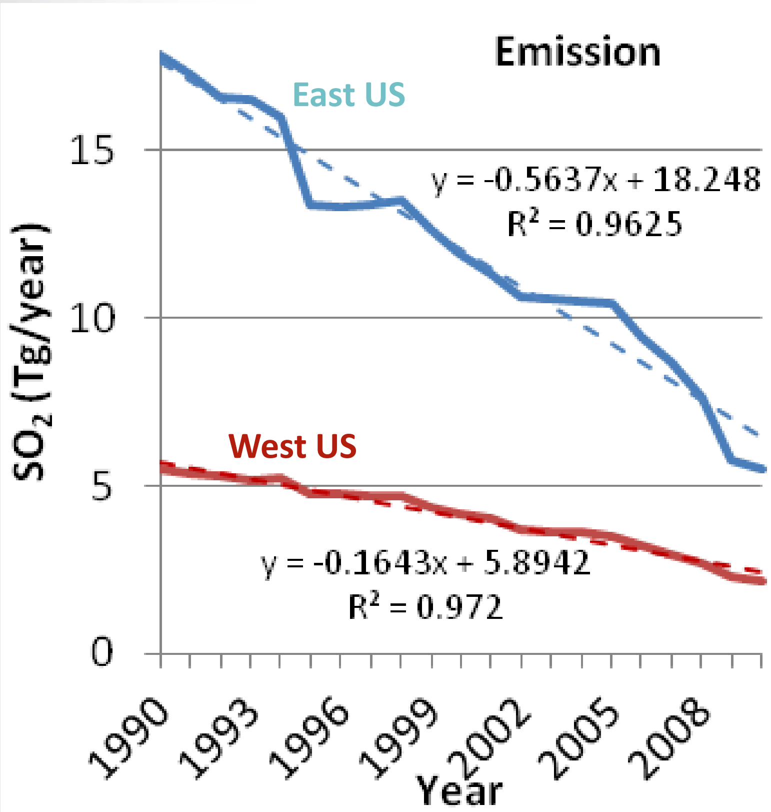
Time Period: 1990-2010

Simulations ***with*** and ***without aerosol direct radiative effects (ADRE)***

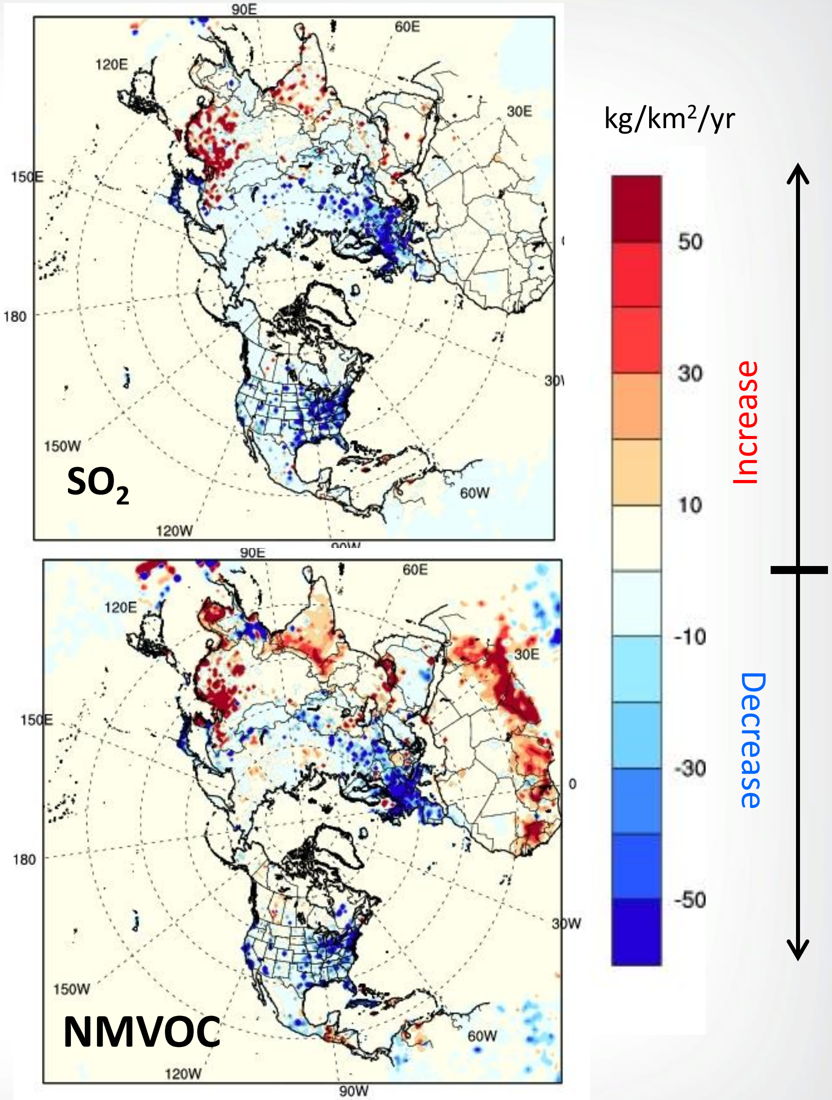


1990-2010 Emission Trends

U.S. Emission Trends

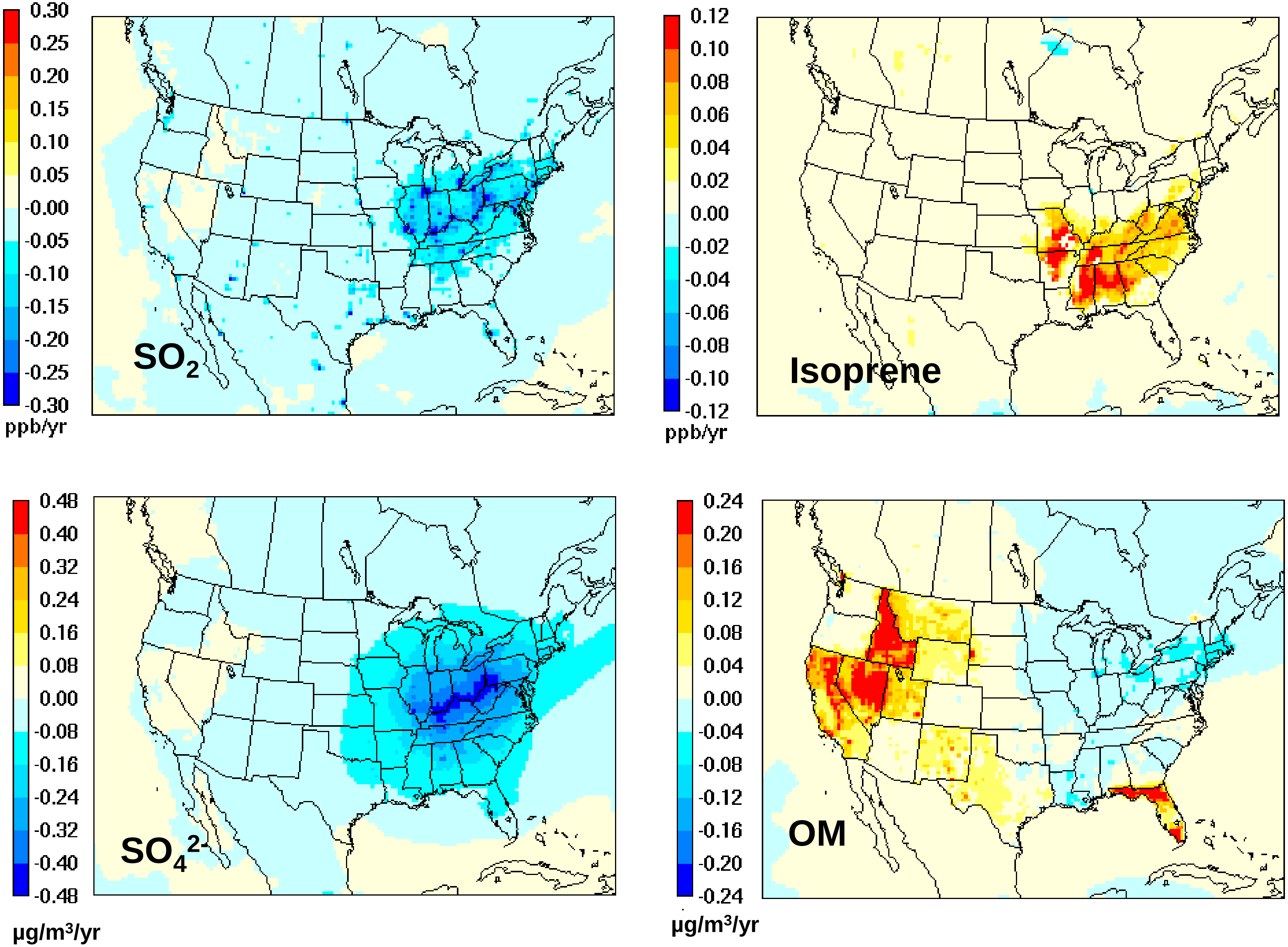


N. Hemisphere Emission Trends

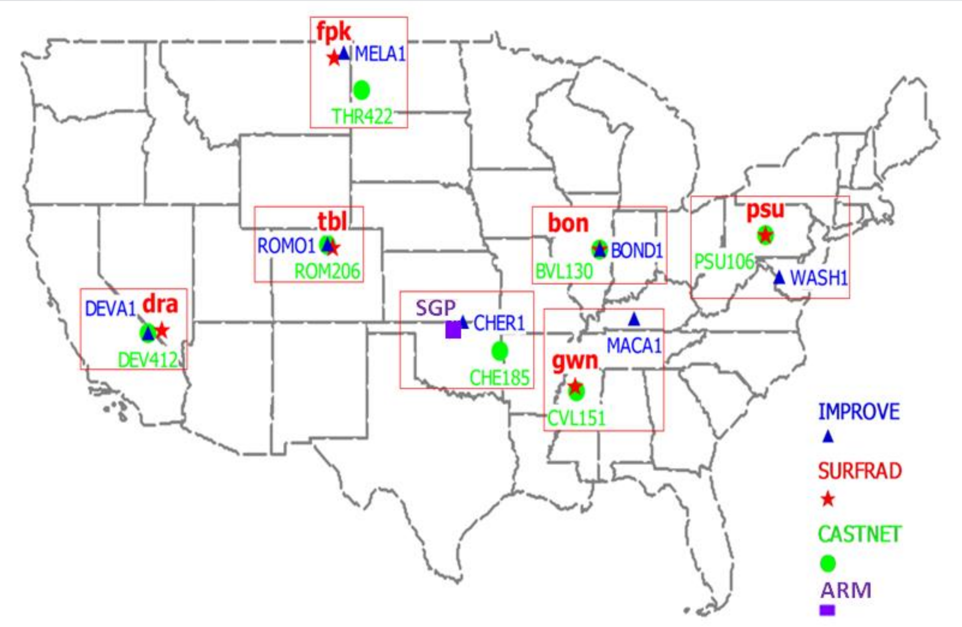


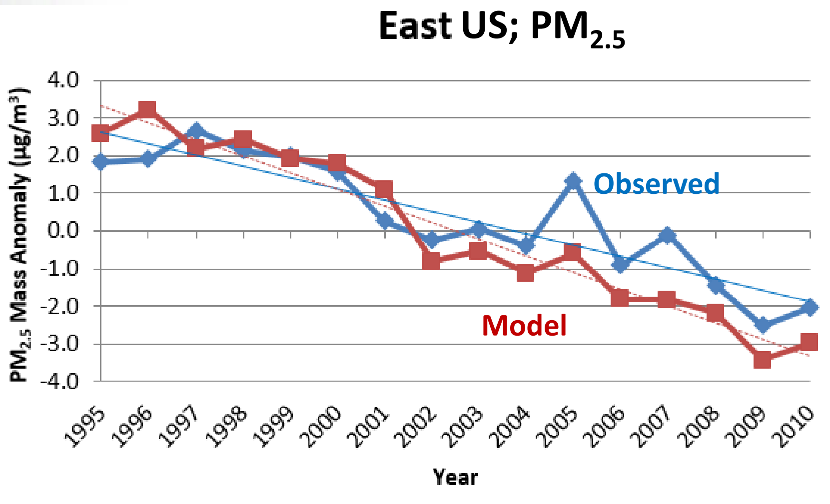
Xing et al., 2015 (ACP)

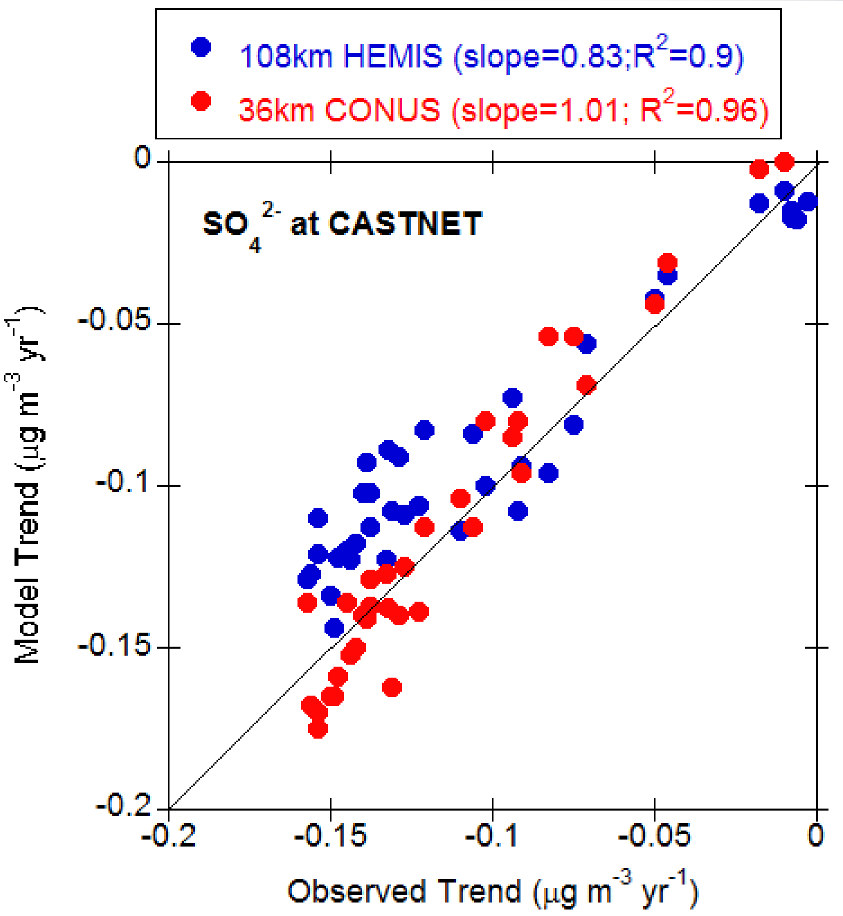
1990-2010 Summer (JJA) Trends in Aerosol Precursors & Constituents



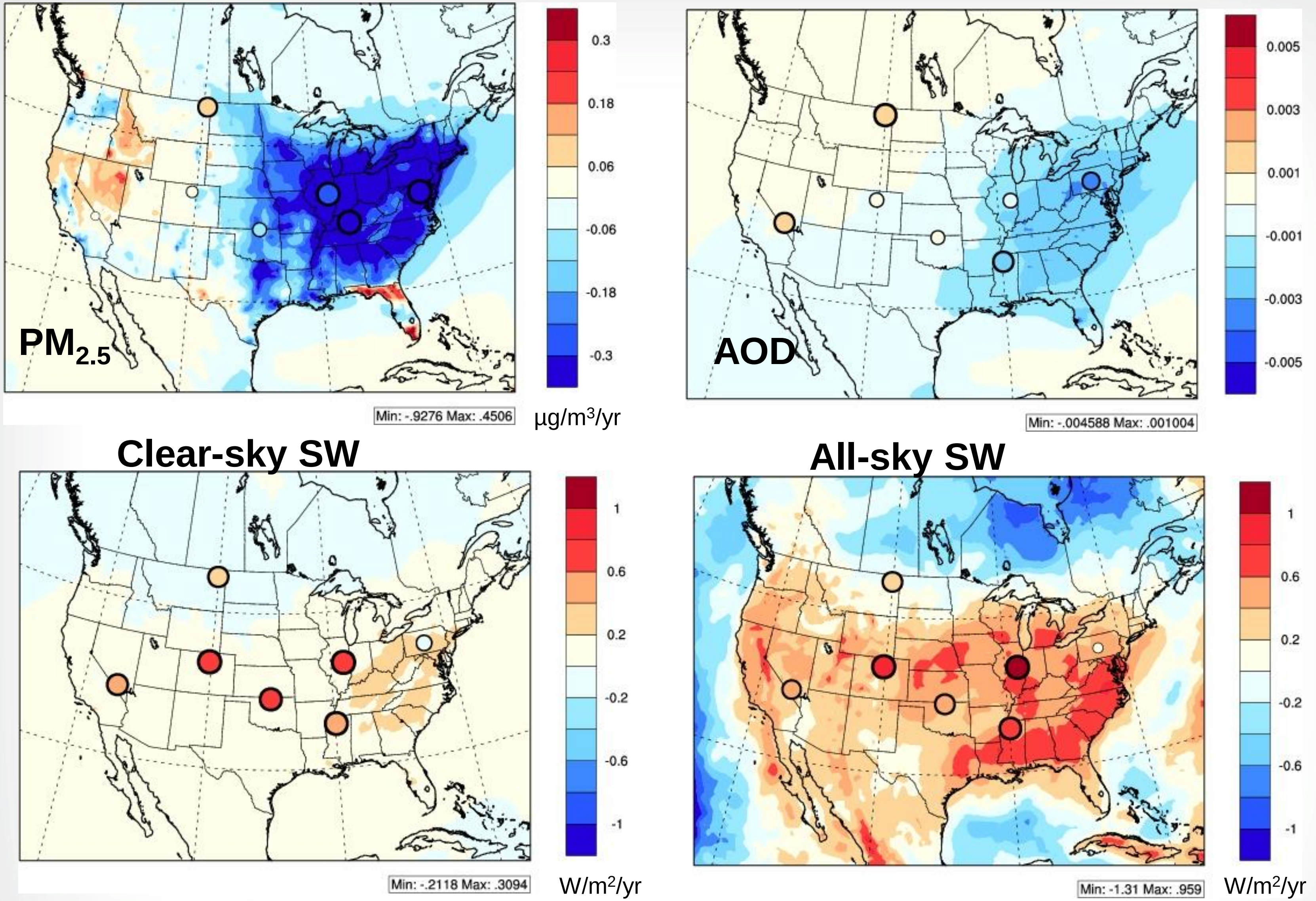
Comparison with Surface Measurements of Aerosols & Radiation







Model and Observed Annual Trends at Surface

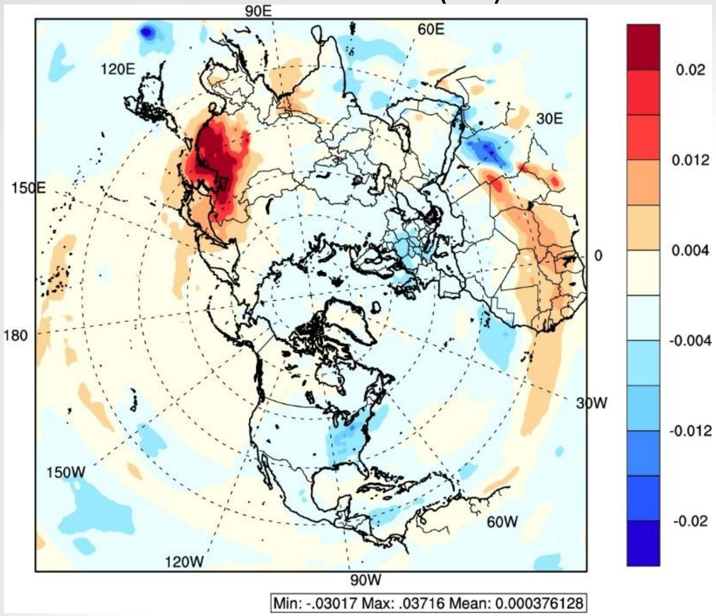


- Decreasing trends in $PM_{2.5}$, and AOD evident across the eastern U.S. in observations and model calculations
- Trends in clear-sky SW radiation show “brightening”, but are underestimated

Gan et al., 2015 (ACP)

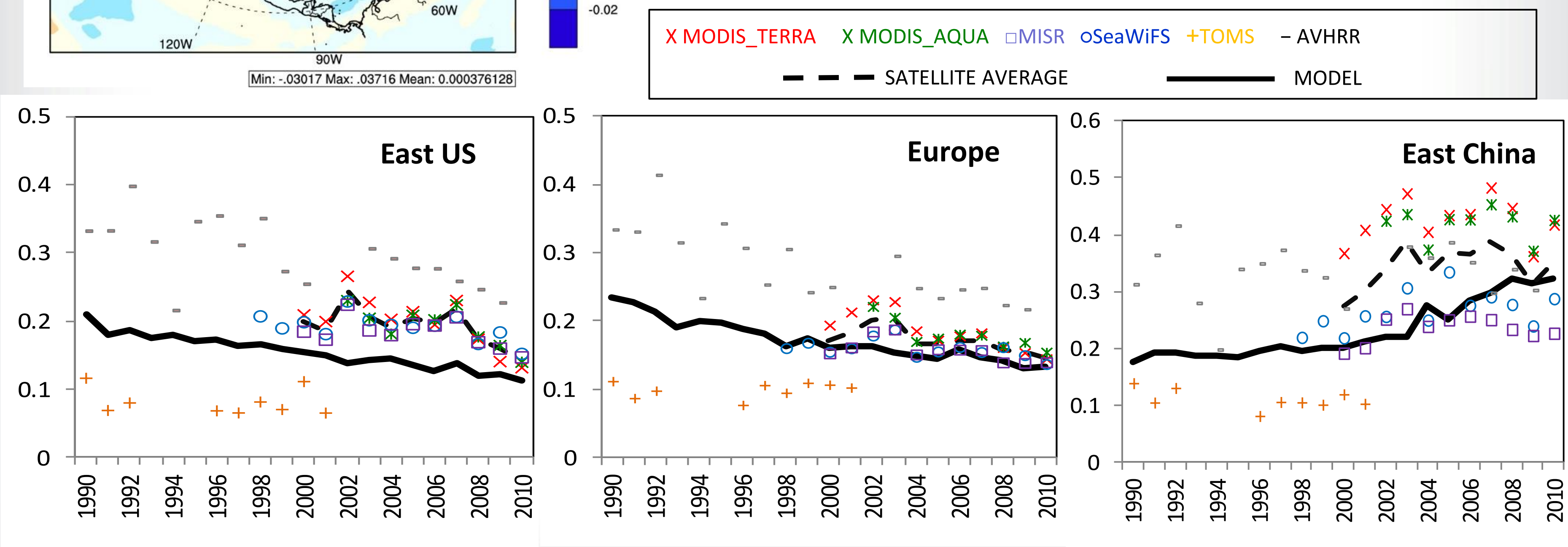
Simulated & Observed Trends: Aerosol Optical Depth

Model Trend: 2000-2010 (JJA)



Qualitatively consistent trends with recent satellite observations of trends of tropospheric aerosol burden:

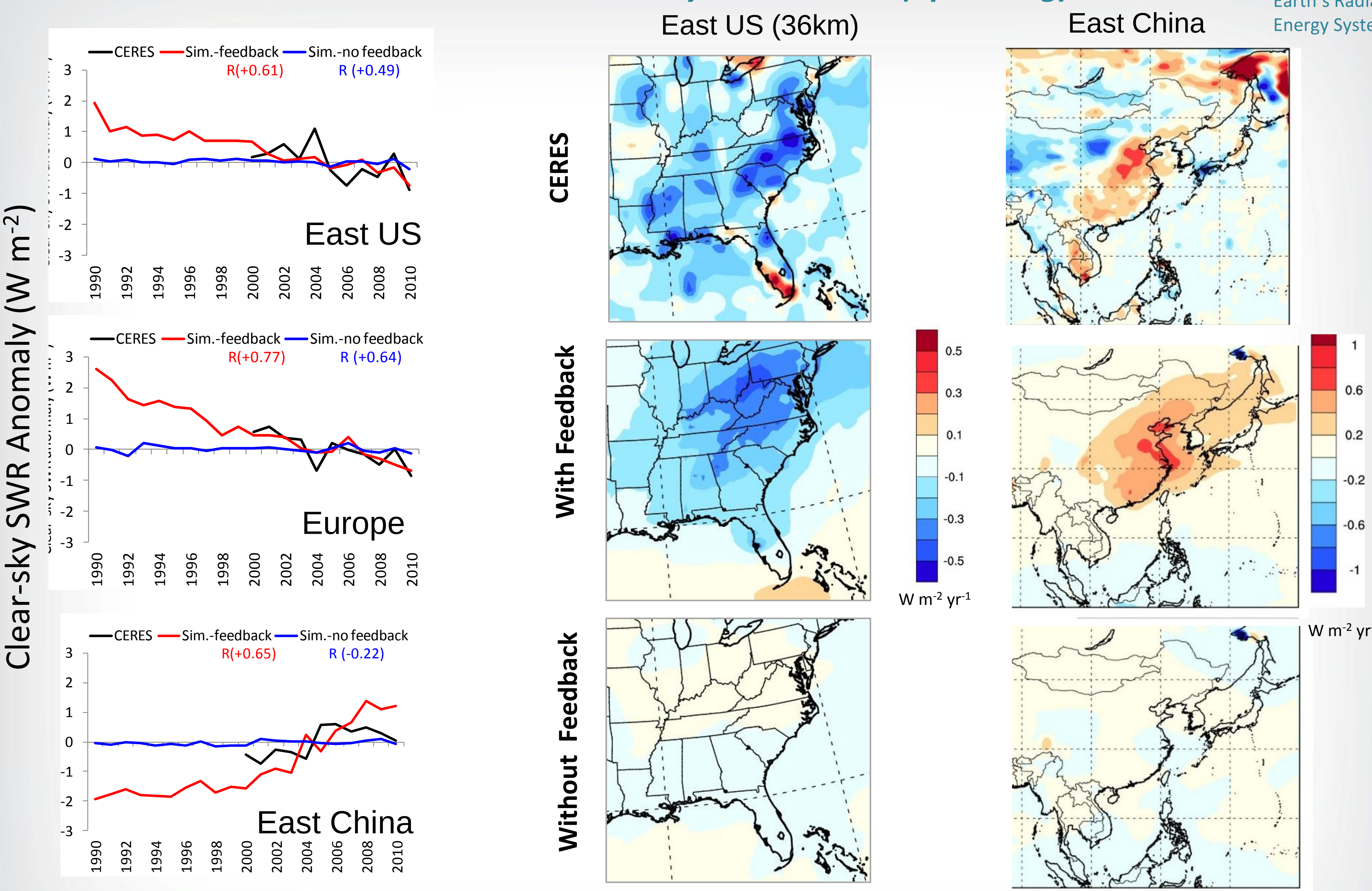
- ***Decrease*** *in aerosol burden across North America & Europe; evidence of increase in western NA*
- ***Increase*** *in aerosol burden across east China & north India*



Xing et al., 2015 (ACP)

Simulated and Observed Trends: *Clear-sky SWR at TOA (upwelling): 2000-2010*

Cloud & the Earth's Radiant Energy System

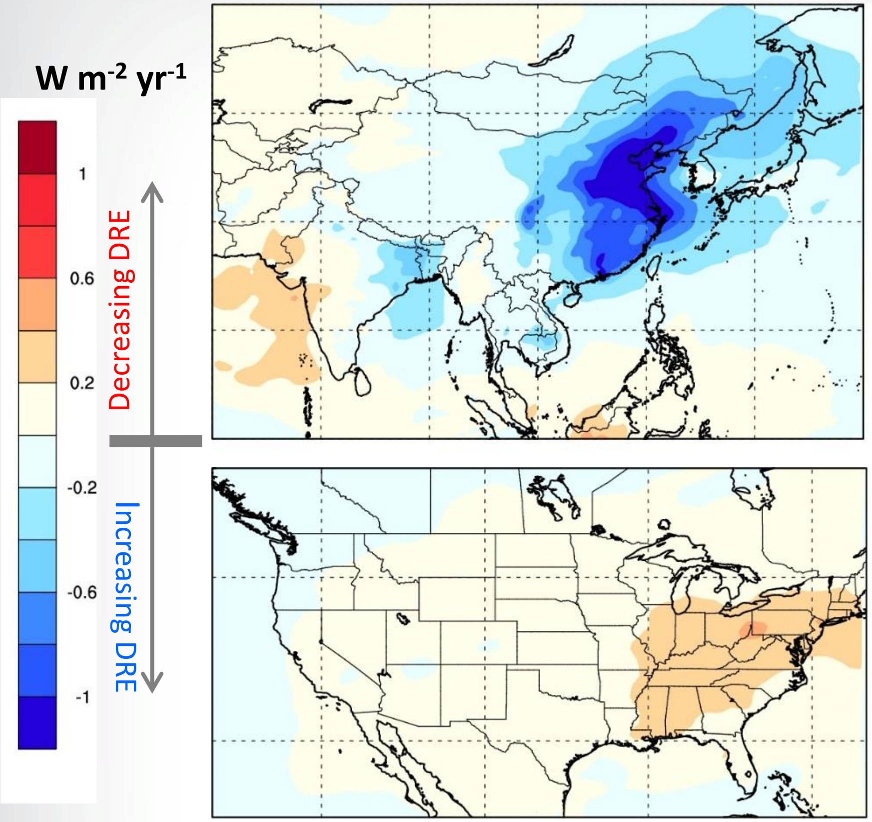


- Better agreement between modeled and observed trends when aerosol feedback effects are considered
- Lack of any trend and lower R in the "no-feedback" simulation, suggest trends in clear-sky radiation are influenced by trends in aerosol burden

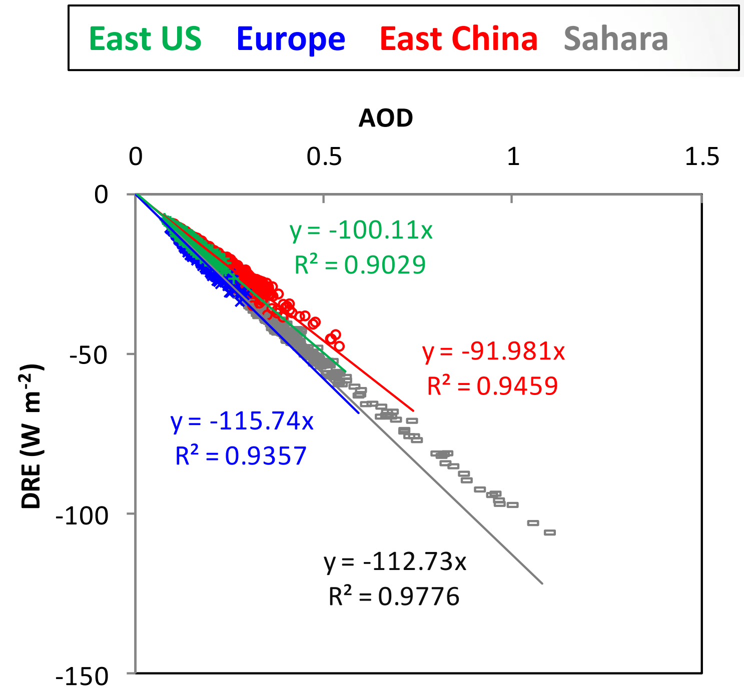
Trends in Direct Radiative Effect (DRE) at Surface: 2000-2010

ADRE = Clear-sky $SW_{Feedback}$ – Clear sky $SW_{No\ Feedback}$; is negative

Trend in summer-average ADRE



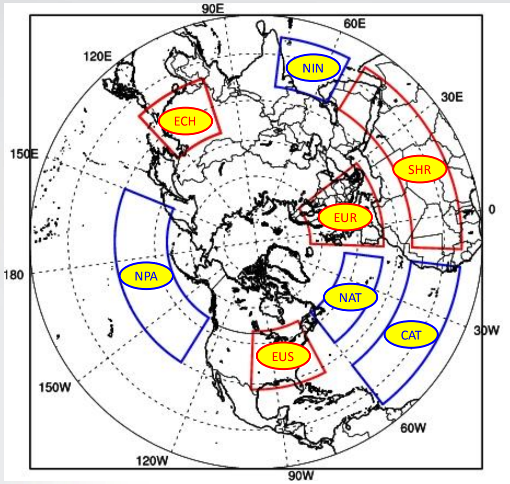
Daytime regional averages



- Spatial trends and direction strongly correlated with those in the aerosol burden
  - Increasing trend across large parts of Asia
  - Decreasing trend across large parts of N. America

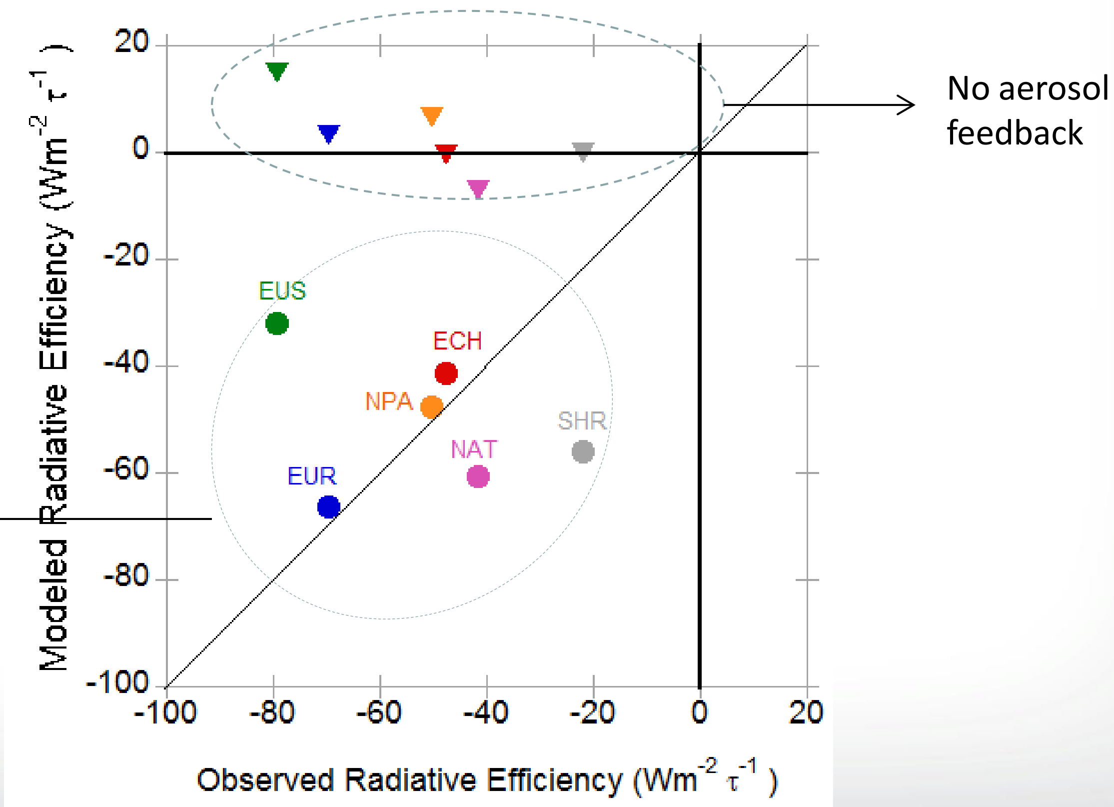
- Model estimates of DRE per unit AOD (*direct radiative efficiency*) is comparable across different regions
  - *Can these be inferred from observational data?*

Summertime Aerosol Direct Radiative Efficiency (Wm^{-2} per unit AOD)



- 2000-2010 data
- Observed clear-sky surface SWR from CERES; AOD from 4 EOS satellites retrievals available for grid cells within a region
- Slope of the SWR and AOD is estimate of the efficiency

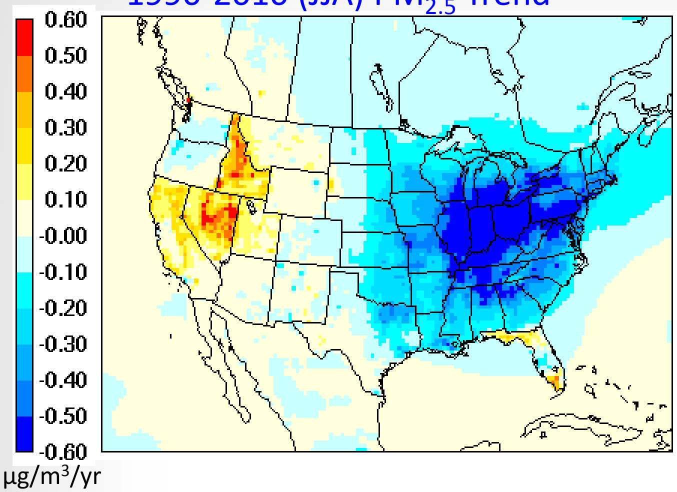
Comparison of Model and Observed Estimates



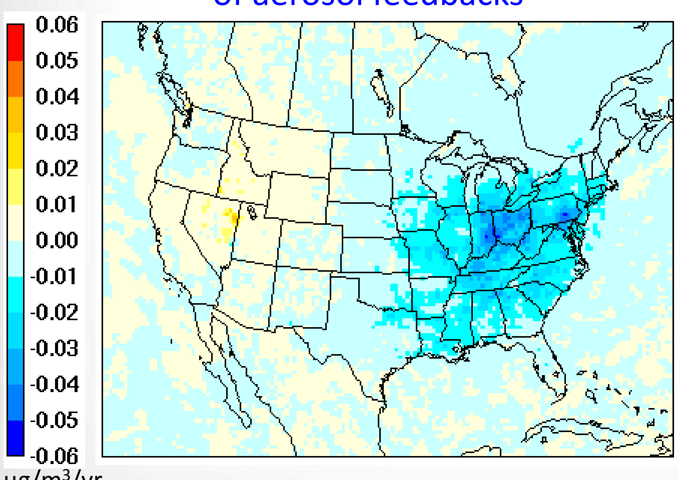
Impact of Aerosol DRE on Air Quality

ADRE impacts on cooling and ventilation modulate air quality

1990-2010 (JJA) $PM_{2.5}$ Trend

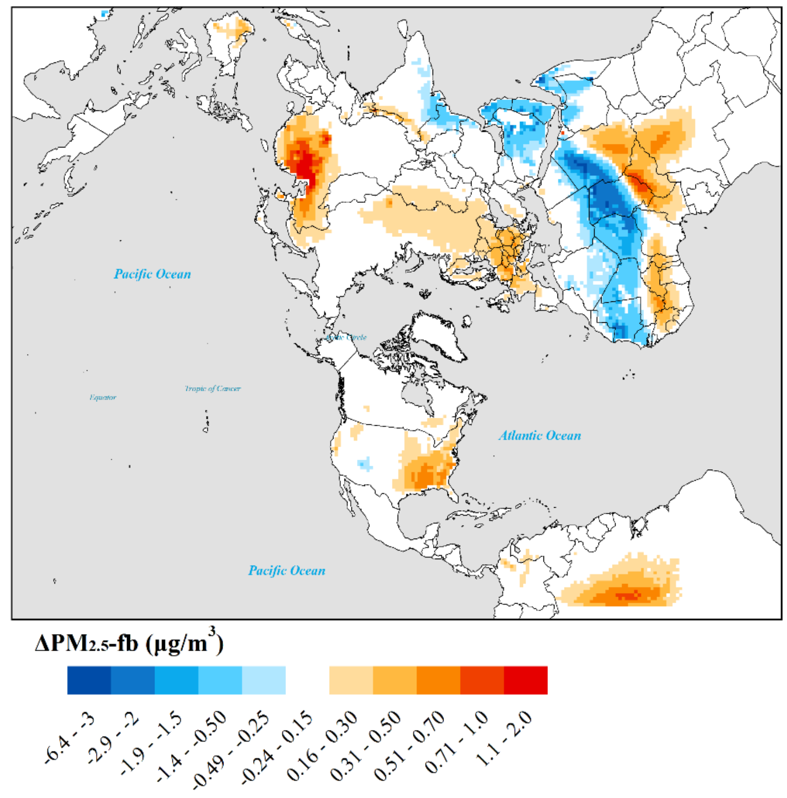


Change in $PM_{2.5}$ trend due to incorporation of aerosol feedbacks



Impacts magnitude of trends

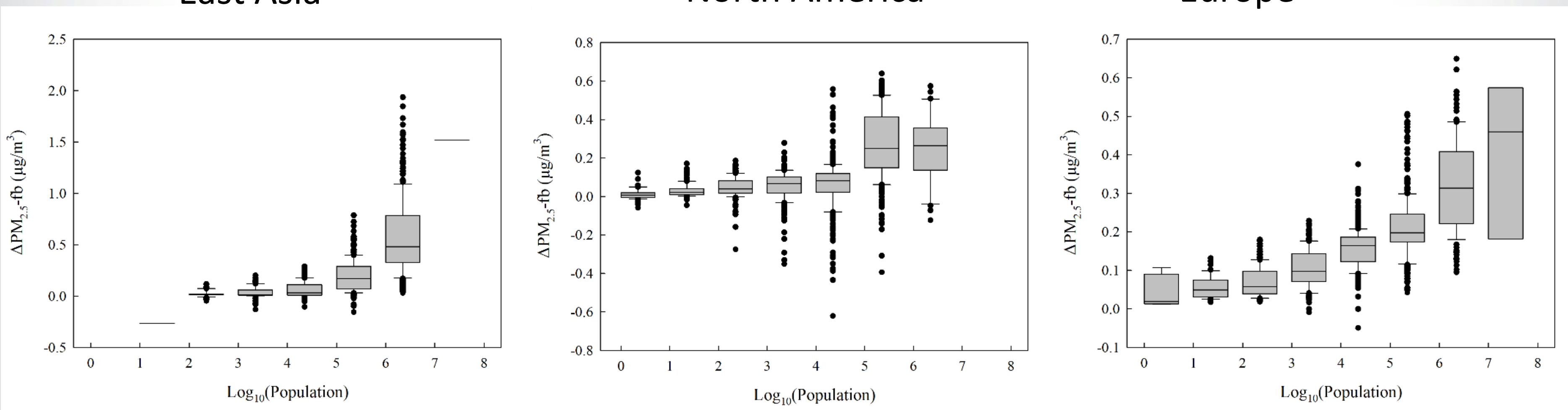
1990-2010 (JJA) $PM_{2.5}$ Change due to DRE



- $PM_{2.5}$ increases due to reduced ventilation
- In desert regions, possible reduction in wind speeds reduces emissions of wind-blown dust thereby reducing the PM burden in these regions

Distribution of surface $PM_{2.5}$ changes due to DRE as a function of population

East Asia | North America | Europe



- Regions of largest impact are in populated areas
- Feedback effects could be important for forecasting exposure of sensitive populations to poor air quality
- Feedback effects could be important for improving AQF skill in regions of increasing emissions

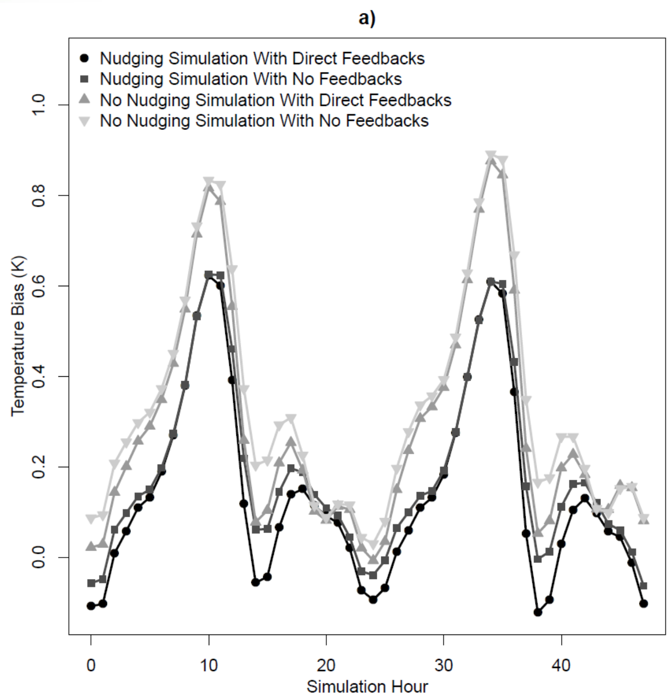
Extra slides

Does Nudging Impact the Representation of Feedback Effects?

June 20-July 31, 2006

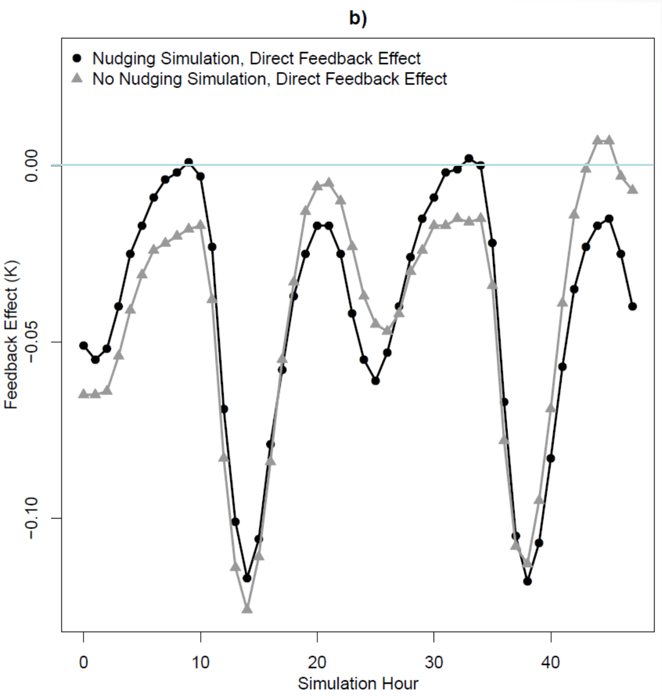
“Weak” nudging to temperature, winds, and water vapor mixing ratio above the PBL

2m T Bias averaged over the month



Direct Feedback Effects:

Feedback – No Feedback



- Without nudging, model errors are higher and tend to grow
- Bias in FB and no-FB runs are similar

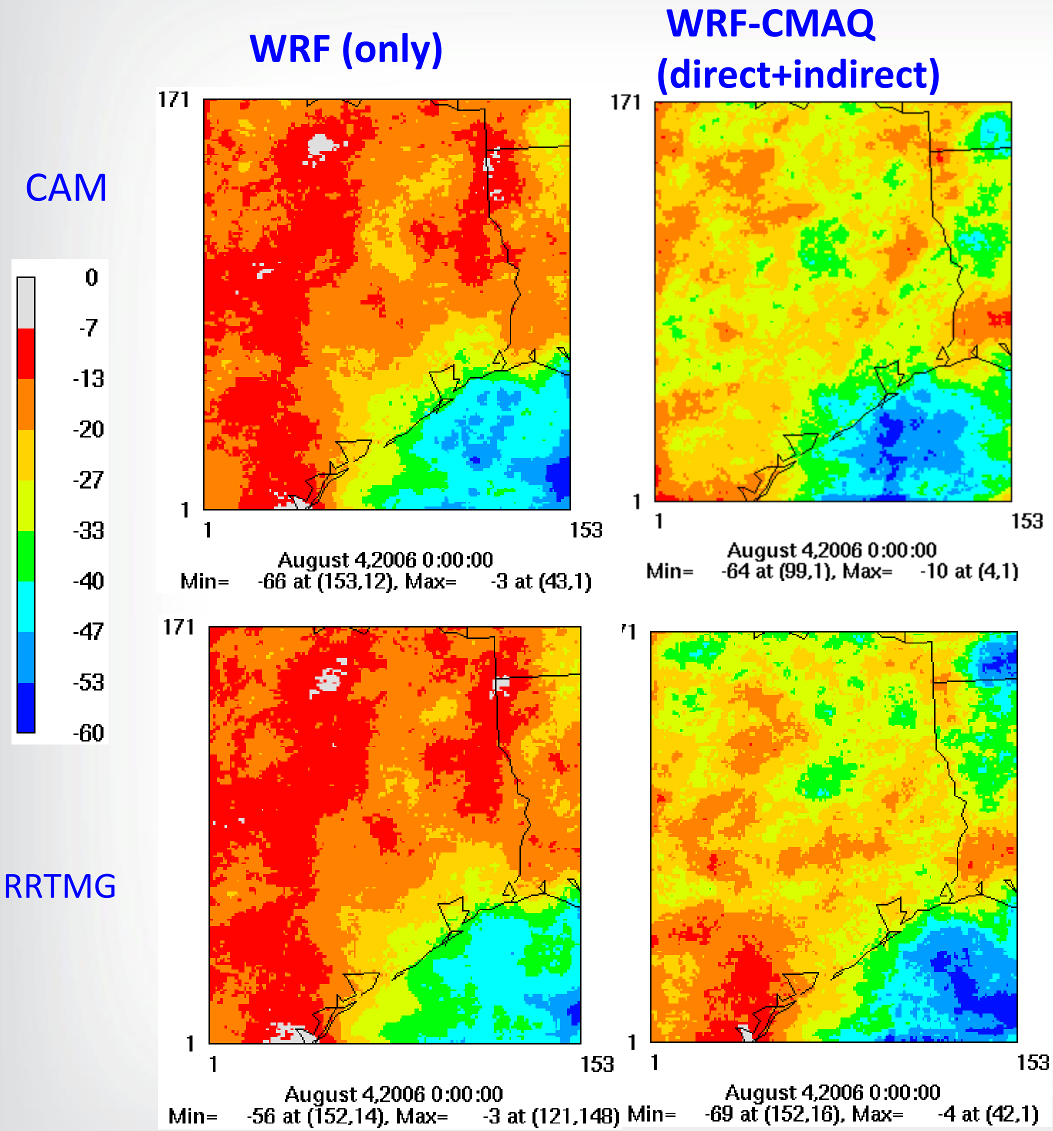
- Weak nudging has small impact on the simulated magnitude of peak aerosol direct radiative effects

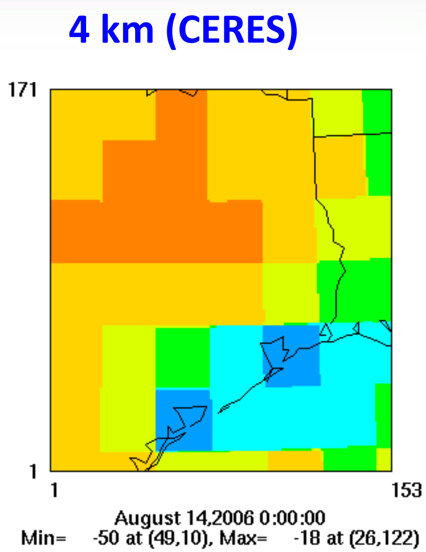
Hogrefe et al., 2015

Incorporating Aerosol Effects on Clouds

Shortwave Cloud Forcing: Comparison with CERES

SWCF= reflected SW_{clr}-reflected SW_{tot} at TOA, *Negative*





Obs (CERES)	-33.3	NMB (%)
CAM		
WRF-CMAQ (DI)	-31.6	-5
WRF (only)	-25.4	-24
RRTMG		
WRF-CMAQ (DI	-30.9	-7
WRF (only)	-23.8	-28

Yu et al., ACP, 2014