Simulating and Analyzing Long-Term Changes in Emissions, Air Quality, Aerosol Feedback Effects and Human Health

J. Xing[1,+], C.-M. Gan[1,*], C. Wei[1,^], J. Wang[1,+], D. Wong[1], G. Pouliot[1], K. Foley[1], C. Hogrefe[1], J. Pleim[1], and R. Mathur[1]

[1] Computational Exposure Division, NERL, ORD, EPA, , Research Triangle Park, NC

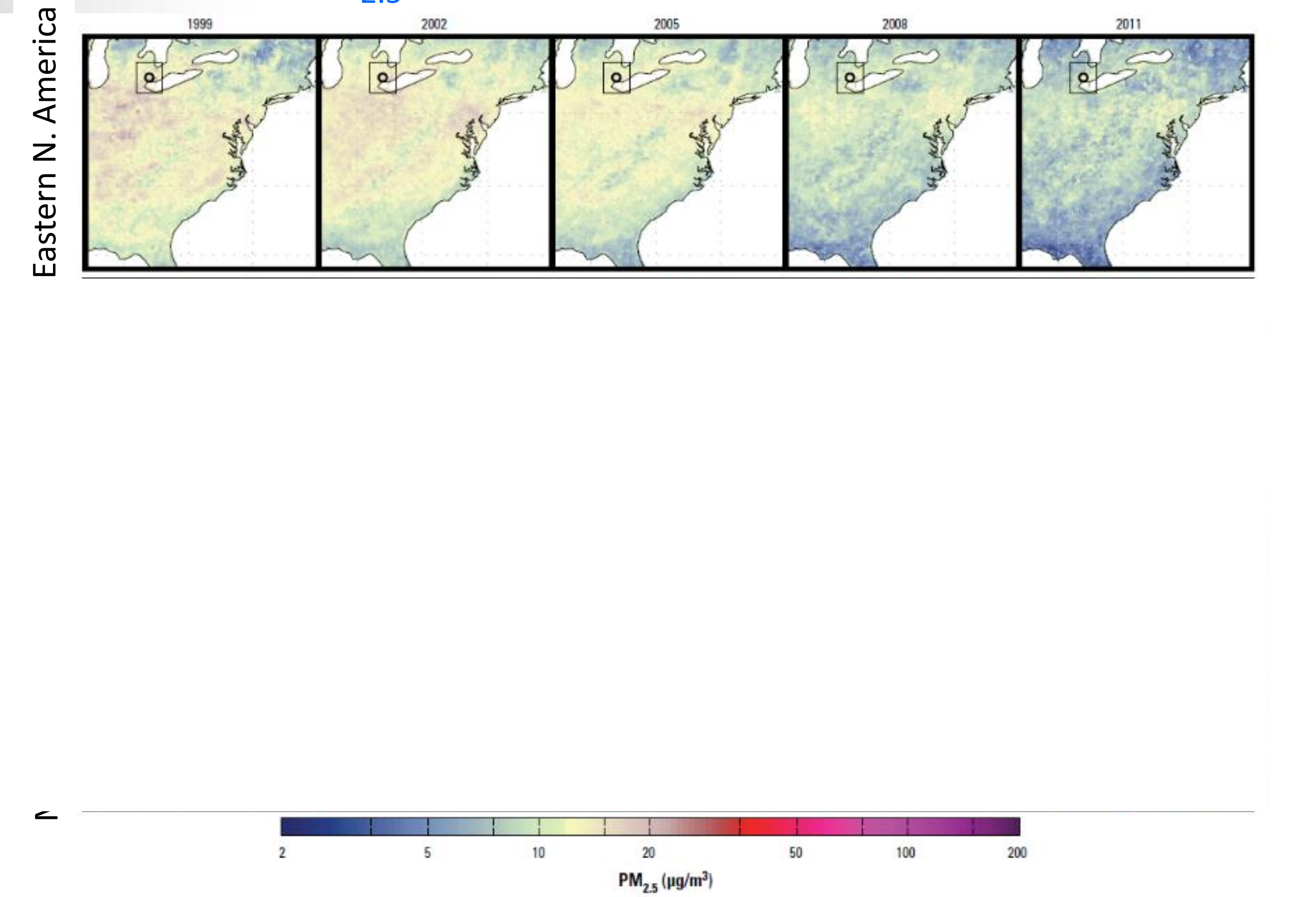
[+] Tsinghua University, Beijing, China

[*] Now at CSRA, Research Triangle Park, NC

[^] Now at Max Planck Institute for Chemistry, Mainz, Germany

Motivation

PM$_{2.5}$ Concentrations from 1999-2011



van Donkelaar et al, Environmental Health Perspectives, 2015

- Significant and diverging trends in emissions and air quality have occurred over the past decades
- These trends in air quality can have impacts on aerosol/radiation interactions and air pollution related mortality
- Modeling systems accounting for the spatially hetereogeneous changes in emissions and air quality and incorporating aerosol/radiation interactions can help to better quantify these impacts

→ perform long-term simulations over both North America and the entire Northern Hemisphere with the coupled WRF-CMAQ model

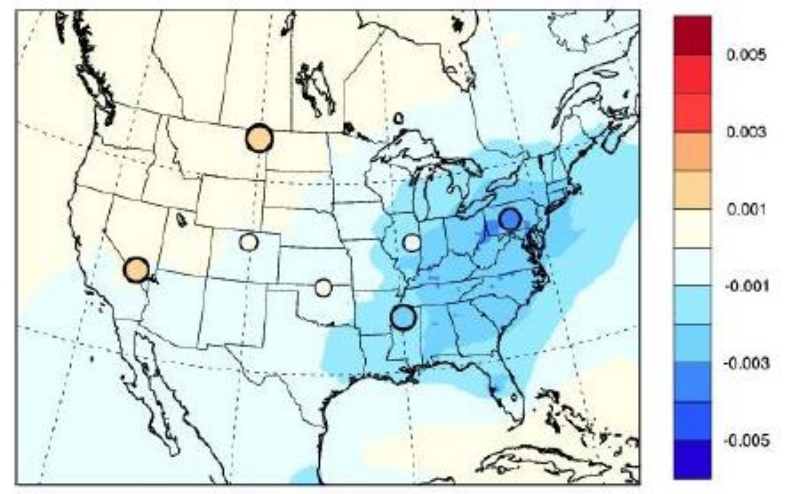
Continental-Scale WRF-CMAQ Simulations

WRF-CMAQ two-way model

–WRF3.4: NARR Reanalysis data; RRTMg radiation scheme, ACM2 (Pleim) PBL, PX LSM.

–CMAQ5.0: CB05-AERO6 chemistry, inline photolysis, inline dust emission module.

–Two-way coupling captures aerosol direct effects (ADE) by transferring CMAQ aerosol information available to RRTMg in WRF



Domain:

✓36×36 km resolution over the CONUS

✓35 layers from surface to 100mb

Period:

✓ from 1990 to 2010

Emissions:

✓ *Xing et al. (2013)*

Boundary Conditions:

✓ *Hemispheric WRF-CMAQ simulations (Xing et al., 2015 a,b,c)*

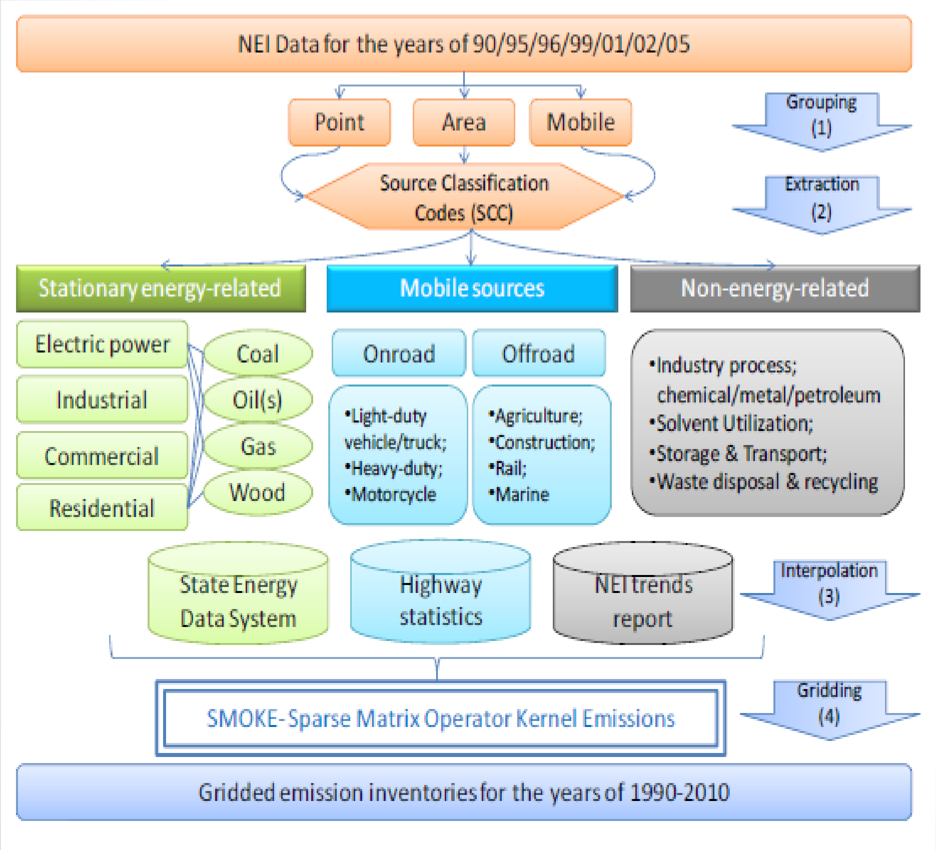
Scenarios:

✓ No feedback (turn off the aerosol direct effects)

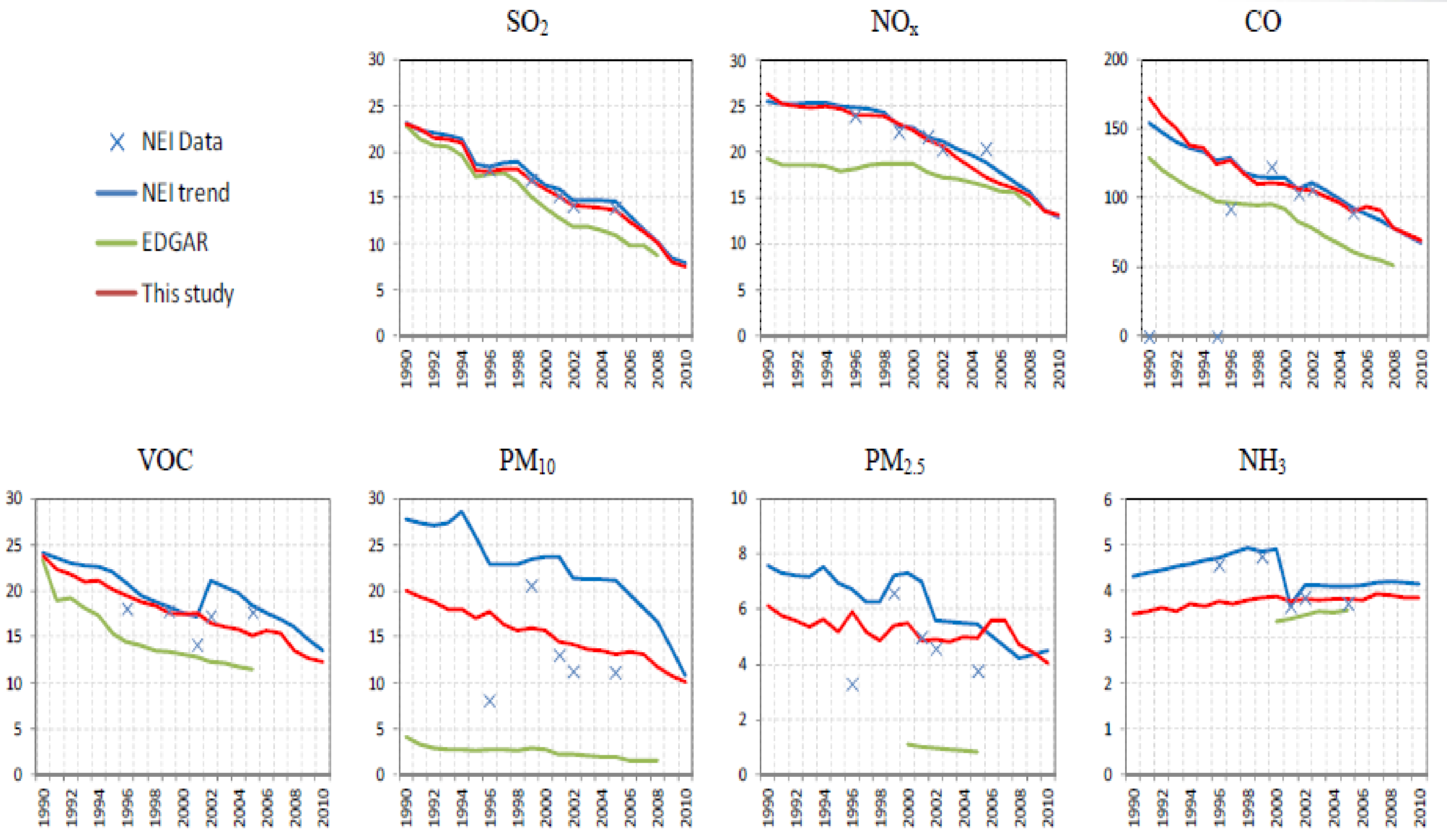
✓ with feedback

Changes in U.S. Emissions

Constructed internally consistent 1990 – 2010 model-ready emission dataset based on available emission inventories, activity data, emission factors and control technologies

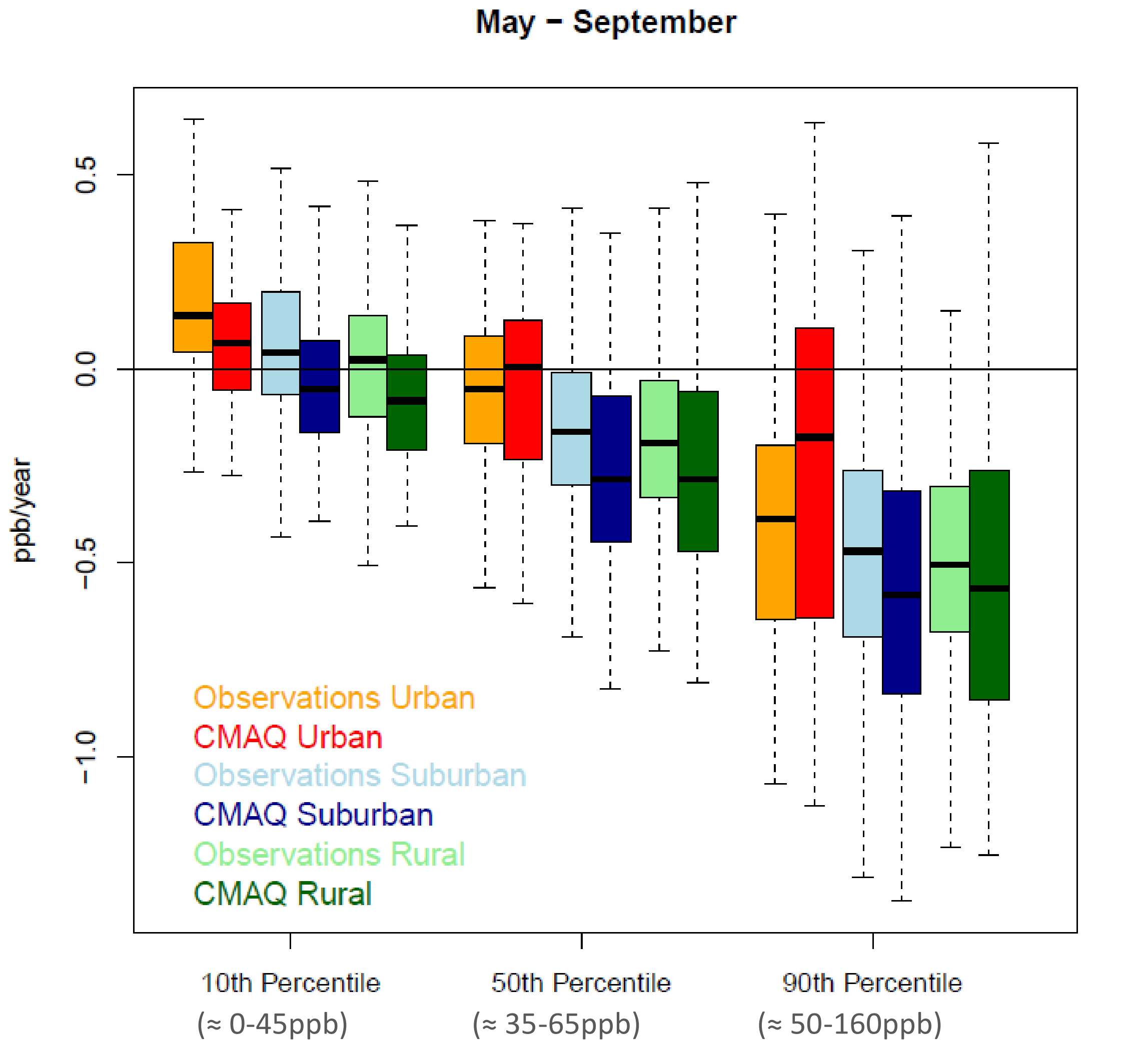


Trends in US Emissions (Tg/year)



Xing et al., Historical gaseous and primary aerosol emissions in the US from 1990 to 2010, Atmos. Chem. Phys., 2013.

Trends in Summer Daily Maximum 8-hr Ozone

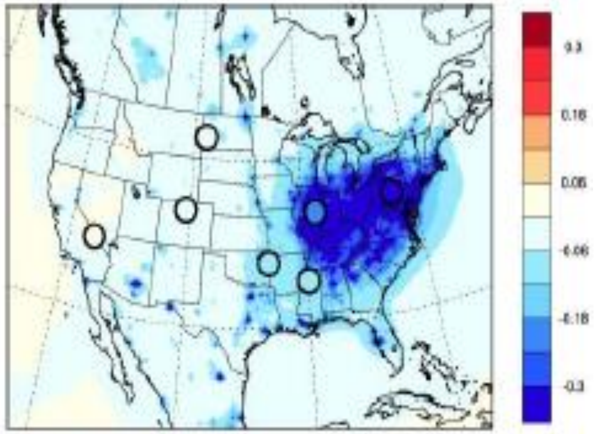


- Decreasing trends for 90th percentile and flat or increasing trends for 10th percentile in both observations and model simulations
- Trends are more negative for rural and suburban sites compared to urban sites and the model picks up this difference.
- At rural and suburban sites, modeled trends tend to be somewhat more negative than the observed trends.

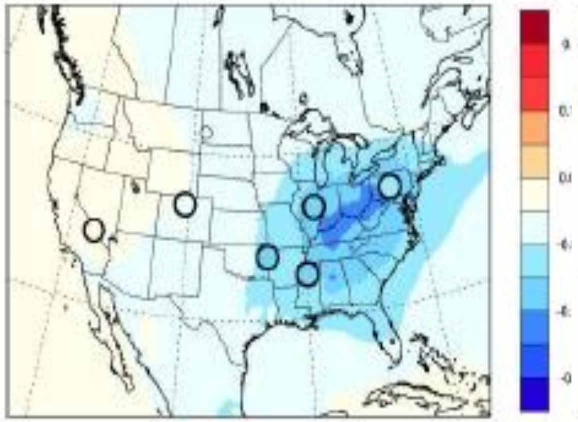
Foley et al., A Comparison of Observed and Simulated 1990 – 2010 U.S. Ozone Trends, A&WMA 108th Annual Conference, Raleigh, NC, June 25th, 2015

Observed and Simulated Trends in Air Quality 1995 - 2010

CASTNET SO2



CASTNET Sulfate



IMPROVE Sulfate

CASTNET Nitrate

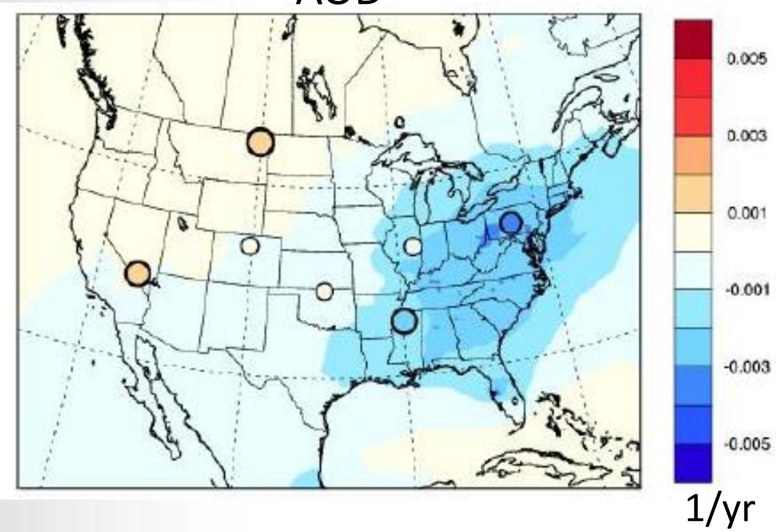
IMPROVE Nitrate

- Substantial decreases in observed and WRF-CMAQ simulated pollutant concentrations
- The greatest decreases occurred over the Eastern U.S.
- The model simulations tend to capture the magnitude and spatial variability of observed trends

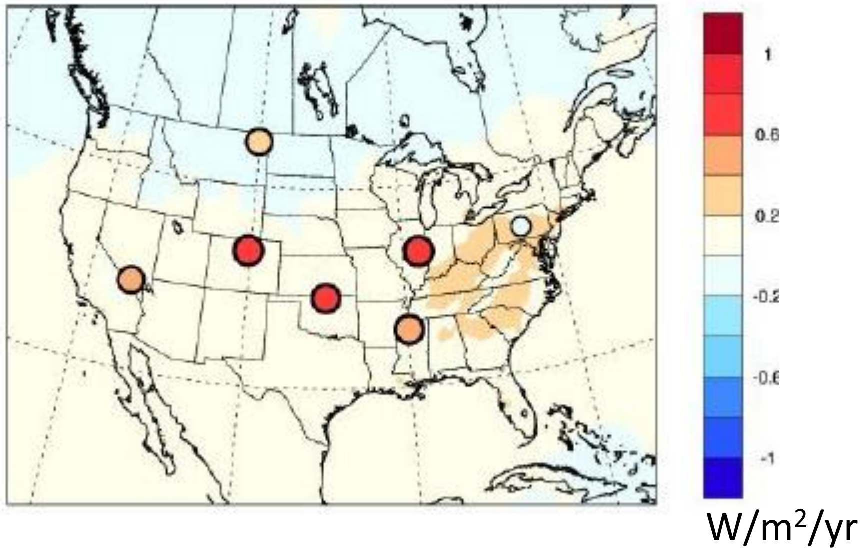
Gan et al., Assessment of long-term WRF–CMAQ simulations for understanding direct aerosol effects on radiation “brightening” in the United States, Atmos. Chem. Phys., 2015.

Observed and Simulated Trends in AOD and Radiation (Observations are from SURFRAD)

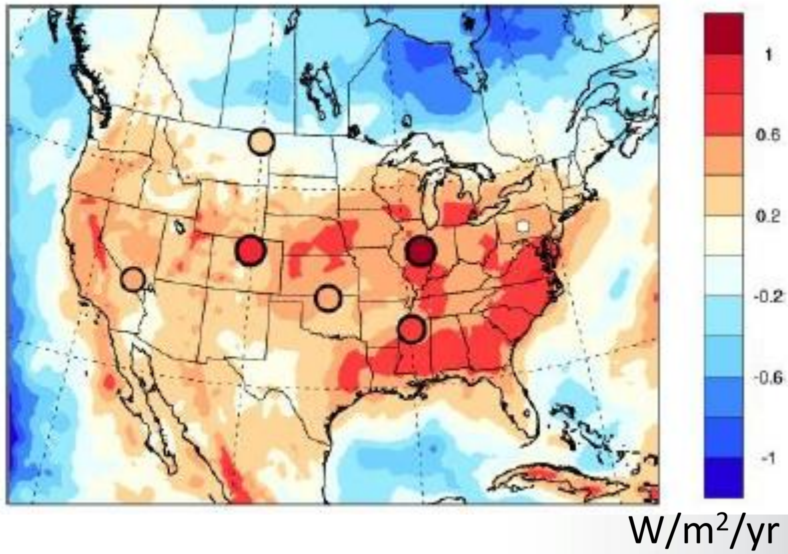
AOD



Clear-Sky Shortwave Radiation



All-Sky Shortwave Radiation



- Decreasing AOD in areas of decreasing surface $PM_{2.5}$ concentrations, i.e. Eastern U.S.
- Associated increases in clear-sky and all-sky radiation

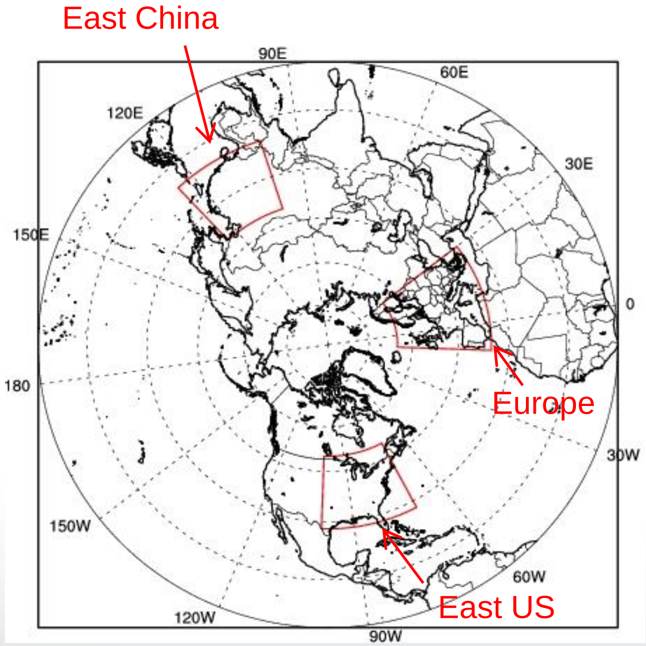
Gan et al., Assessment of long-term WRF–CMAQ simulations for understanding direct aerosol effects on radiation "brightening" in the United States, Atmos. Chem. Phys., 2015.

Hemispheric WRF-CMAQ Simulations

Hemispheric WRF-CMAQ two-way model

–WRF3.4: NCEP/NCAR Reanalysis data with 2.5 degree spatial and 6-hour temporal resolution; NCEP ADP Operational Global Surface/ Upper Air Observations with 6 hour intervals, MODIS land-use type, RRTMg radiation scheme, ACM2 (Pleim) PBL, PX LSM.

–CMAQ5.0: CB05-AERO6 chemistry, tropopause ozone calculated from potential vorticity, inline photolysis, inline dust emission module.



Domain:

✓108×108 km resolution over the northern hemisphere

✓44 layers from surface to 50mb

Period:

✓ from 1990 to 2010 (JJA, summer)

Scenarios:

✓ No feedback (turn off the aerosol direct effects)

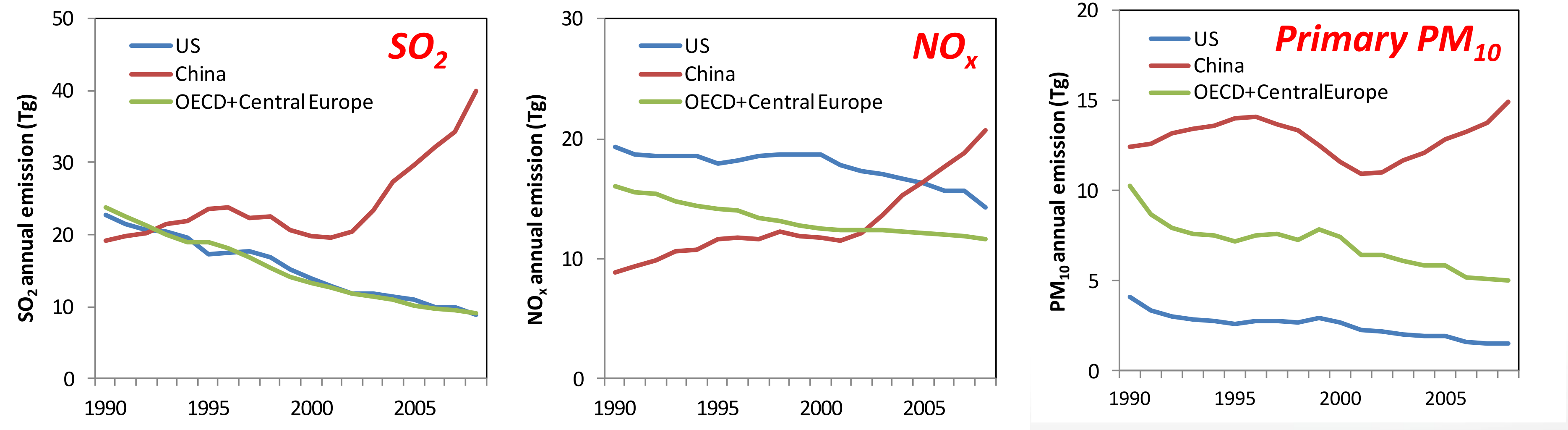
✓ with feedback

Hemispheric Emission Trends

Emissions for Hemispheric WRF-CMAQ model

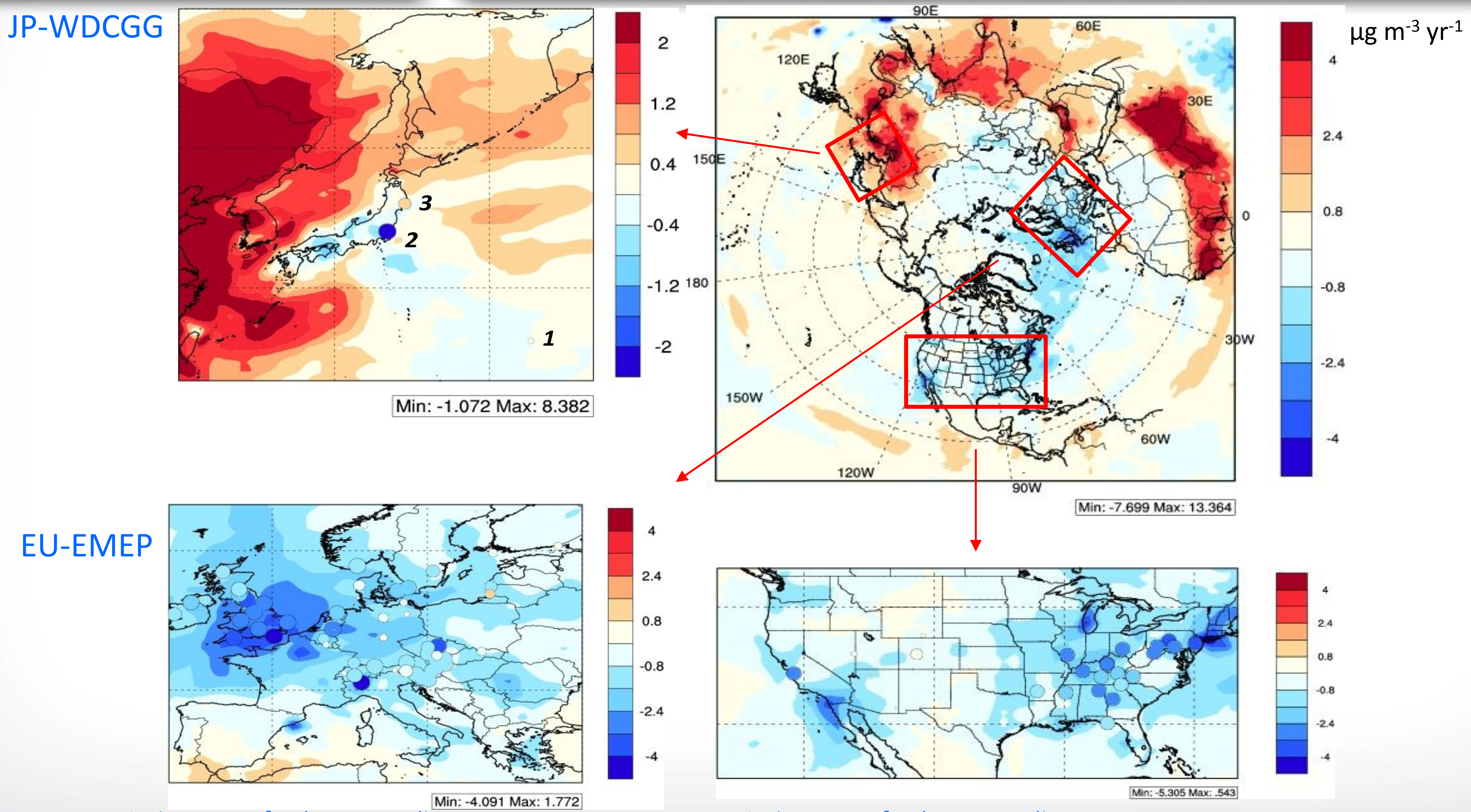
- ✓ **Anthropogenic emissions** were derived from EDGAR (Emission Database for Global Atmospheric Research);
- ✓ **Biogenic** VOC and lightning NOx emissions were obtained from GEIA (Global Emission Inventory Activity);
- ✓ **Temporal distribution** was based on EDGAR default profiles;
- ✓ **Speciation** was based on standard SMOKE profiles;
- ✓ **Vertical allocation** was based on SMOKE plume-rise and EMEP profiles.

1990-2008 emissions in China, US and Europe from EDGAR



Striking contrast in emission trends between developed and developing countries

Trends in Annual Maximum of Daily Maximum 8-hr Ozone (1990-2010)



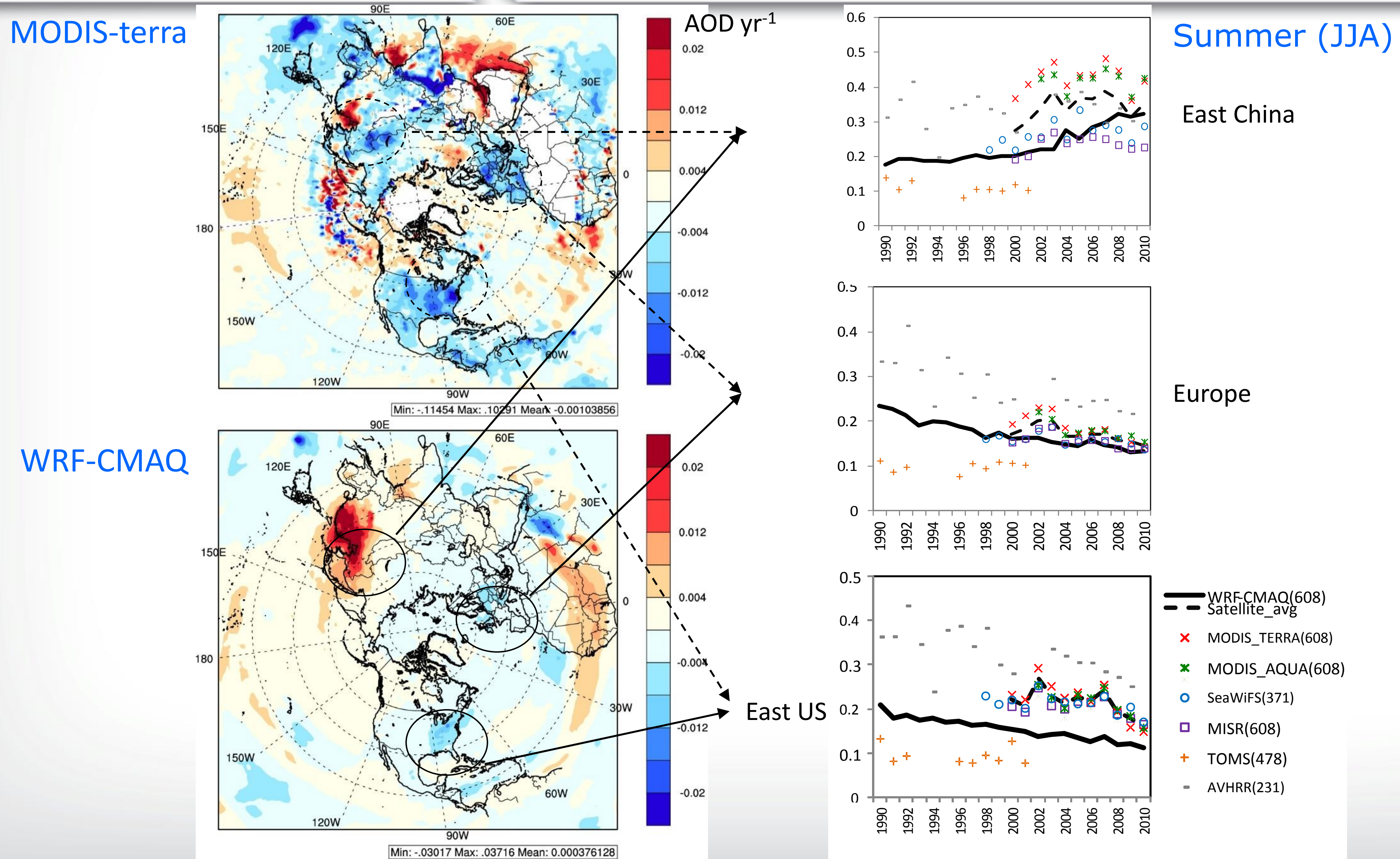
Obs ($-1.07 \mu g\ m^{-3}\ yr^{-1}$, $-0.74\%\ yr^{-1}$)
Sim($-1.31 \mu g\ m^{-3}\ yr^{-1}$, $-0.87\%\ yr^{-1}$)

Obs ($-1.86 \mu g\ m^{-3}\ yr^{-1}$, $-1.10\%\ yr^{-1}$)
Sim($-0.95 \mu g\ m^{-3}\ yr^{-1}$, $-0.64\%\ yr^{-1}$)

US-CASTNET

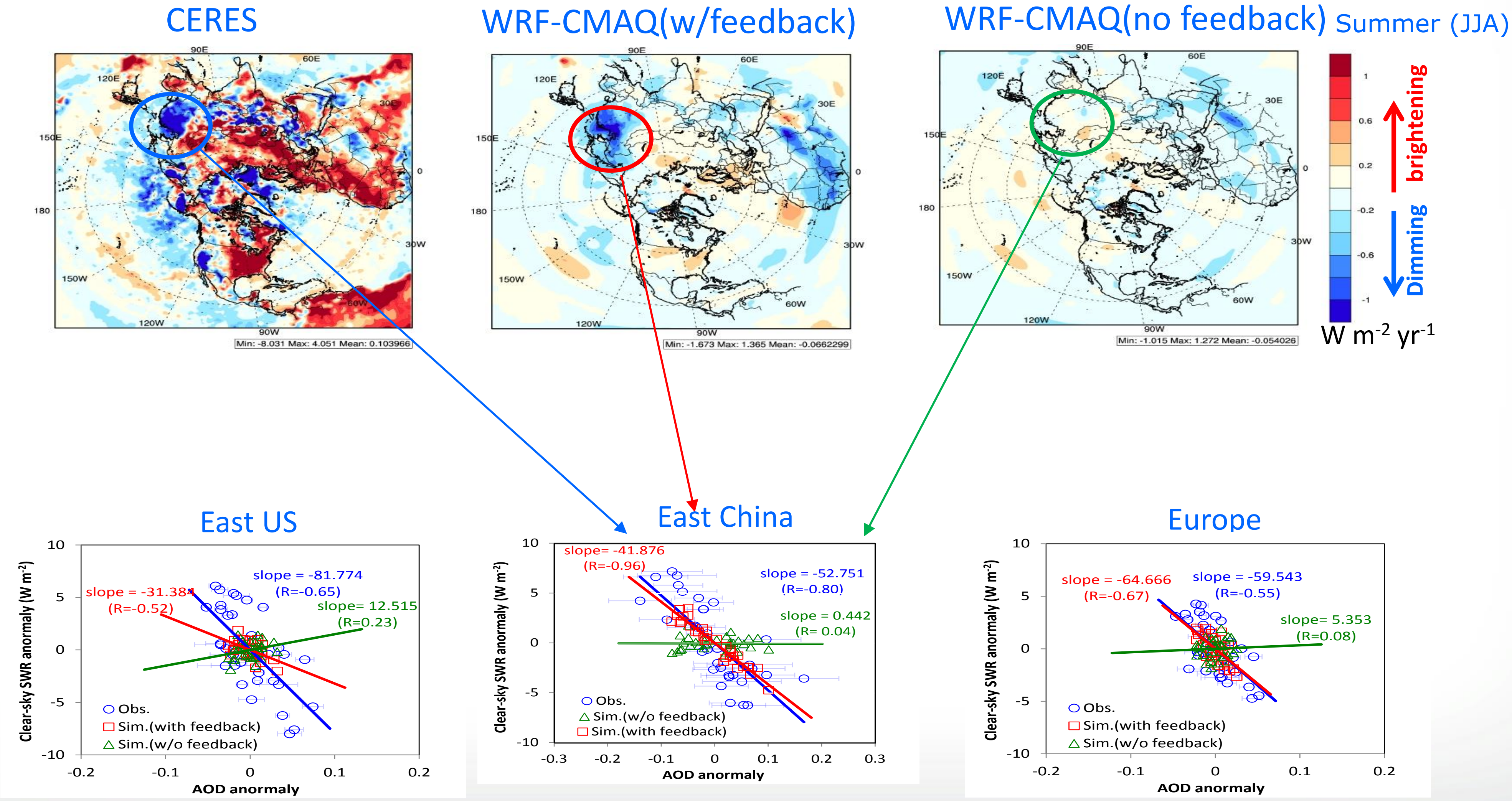
Xing et al., Observations and modeling of air quality trends over 1990–2010 across the Northern Hemisphere: China, the United States and Europe. ACP, 2015

Trends in Aerosol Optical Depth (2000-2010)



Xing et al., Can a coupled meteorology–chemistry model reproduce the historical trend in aerosol direct radiative effects over the Northern Hemisphere? ACP, 2015

Trends in Clear-sky SWR at the Surface (2000-2010)



aerosol direct radiative efficiency

EPA

Estimating Trends in $PM_{2.5}$ Related Mortality

Calculation of $PM_{2.5}$ Related Mortality:

$$Mortality_{PM2.5} = \sum_{i=IHD,stroke,COPD,LC,ALRI} incidence_{0,i} \times PAF_i \times Population \quad [1]$$

$$PAF_i = (RR_i - 1)/RR_i \quad [2]$$

$$\begin{cases} \text{for } C < C_0, \ RR_i(C) = 1 \\ \text{for } C \geq C_0, \ RR_i(C) = 1 + \alpha \times \{1 - exp[-\gamma \times (C - C_0)^{\delta}]\} \end{cases} \quad [3]$$

- Method based on BenMap – CE and GBD (Lim et al., 2012; Burnett et al., 2014)
- Incidence rates from Naghavi et al. (2015)
- RR estimates from Apte et al. (2015)

Calculation of Species-Specific Mortality and Emission Mitigation Efficiency (EME):

$$Mortality_{p,y} = \frac{Mortality_y}{Concentration_{PM_{2.5},y}} \times Concentration_{PM_p,y} \qquad (y = 1990 \ldots 2010) \quad [4]$$

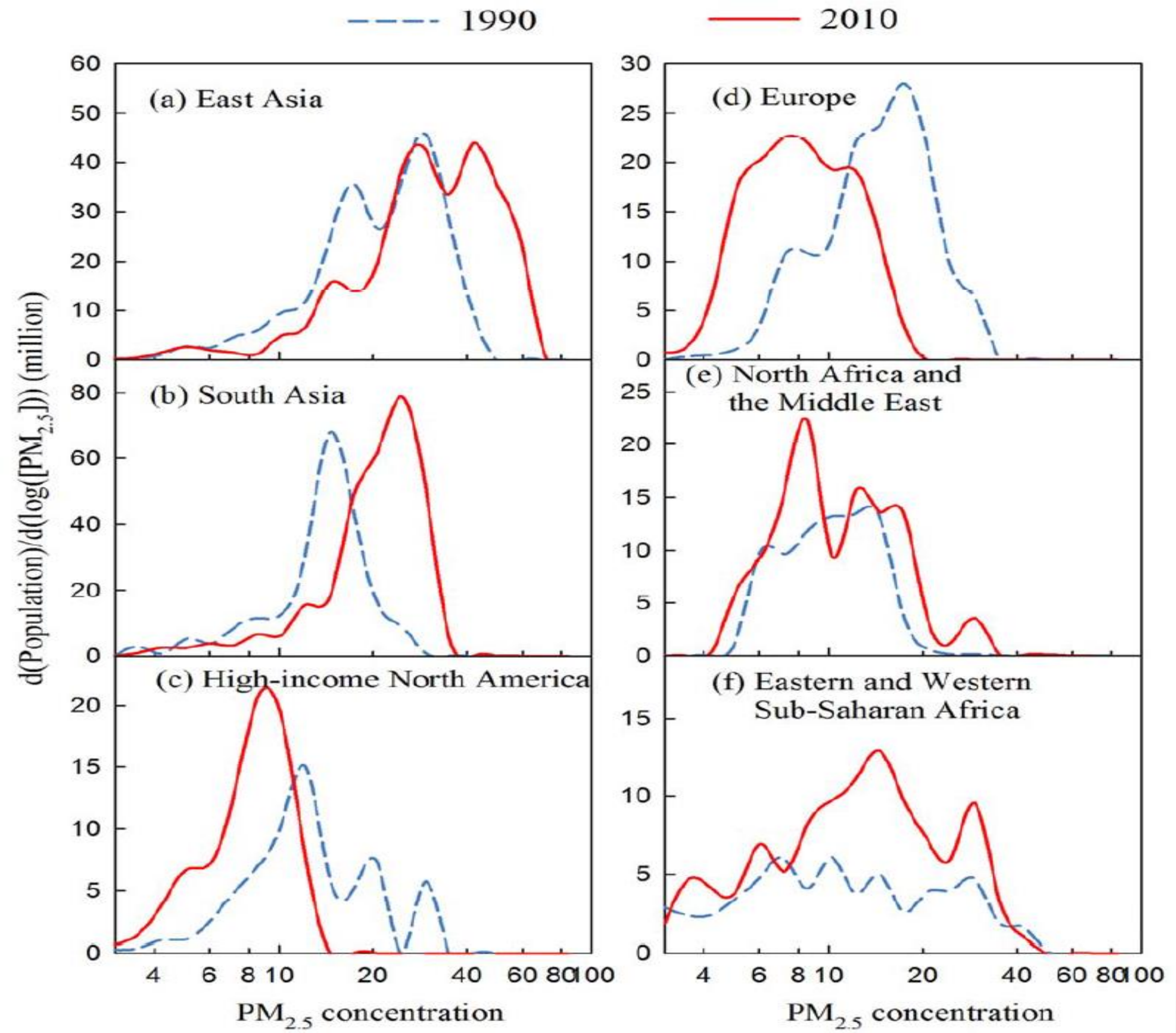
$$EME_{p,y'} = \frac{Mortality_{p,y'} - Mortality_{p,1990}}{Emission_{p,y'} - Emission_{p,1990}} \qquad (y' = 1991 \ldots 2010) \quad [5]$$

$$p = \{SO_2, \ NO_x, NH_3, primary \ PM\}$$

$$PM_p = \{SO_4^{2-}, NO_3^-, NH_4^+, other \ inorganic \ particles \ and \ primary \ organic \ aerosols\}$$

Population Scale Factor (PSF): Population-Weighted $PM_{2.5}$ / Regional-Average $PM_{2.5}$

Changes in $PM_{2.5}$ and Population 1990 - 2010

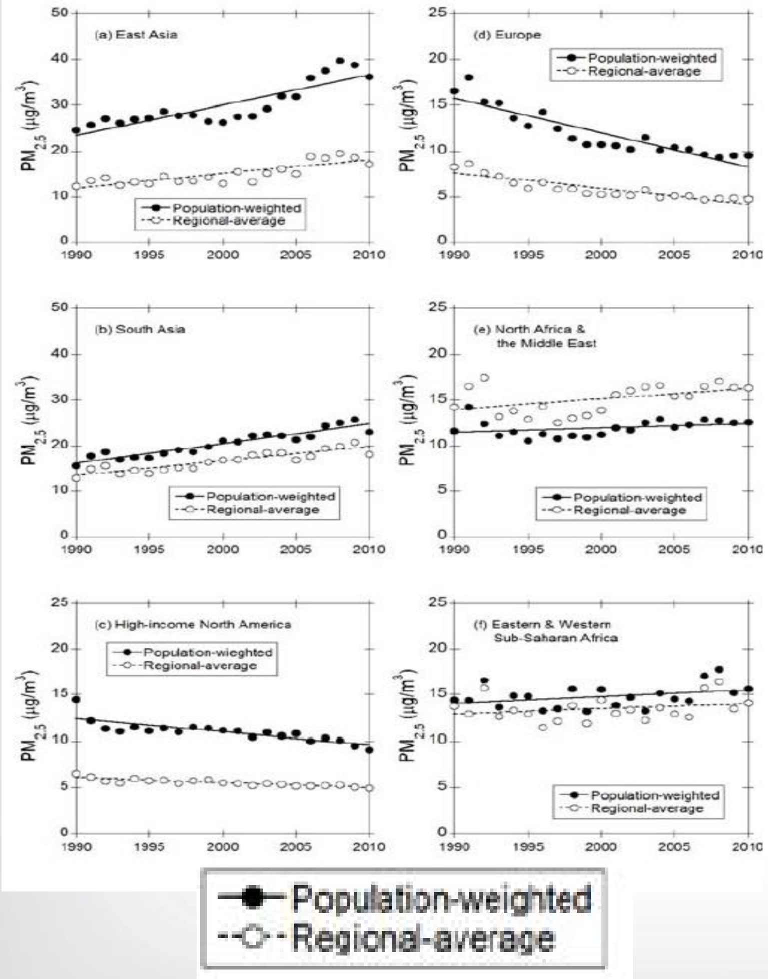


- Changing population exposure to ambient PM2.5 levels across six sub-regions of the northern hemisphere
- WRF-CMAQ estimated surface $PM_{2.5}$ concentrations across grid cells in a region are grouped by population distribution
- d(Population)/d(log([PM2.5])) represents the population per unit $PM_{2.5}$ section in log scale. The area below a curve represents the total population for that region for that year.
- East and South Asia: Population growth and shift towards higher $PM_{2.5}$
- Europe and North America: Shift of population distribution towards lower $PM_{2.5}$

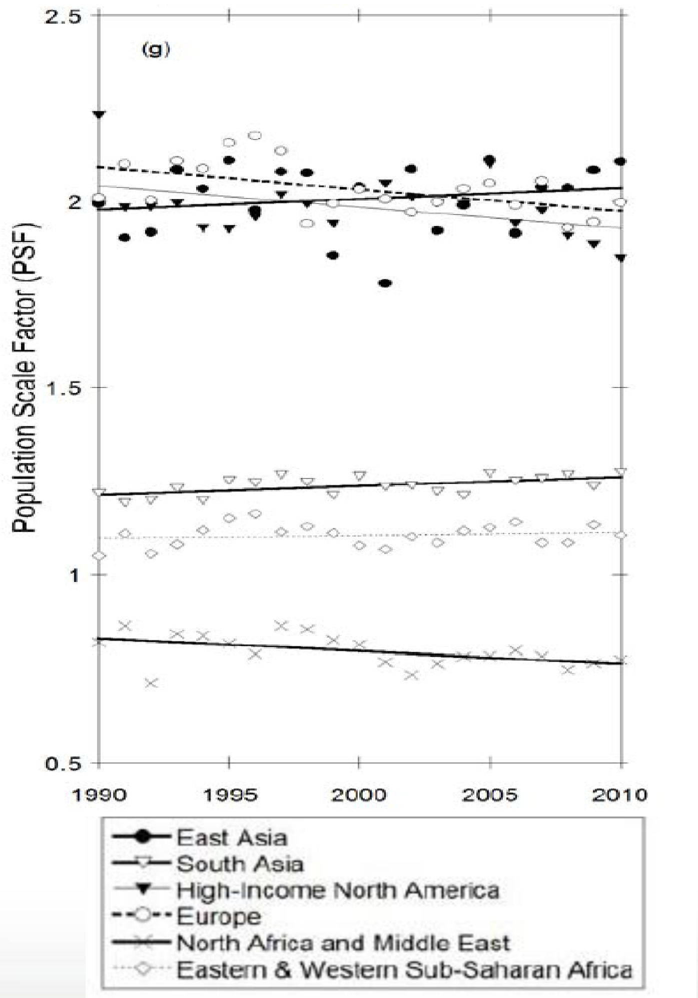
Wang et al., Historical Trends in PM2.5-Related Premature Mortality during 1990-2010 across the Northern Hemisphere. EHP, 2016

Trends in $PM_{2.5}$ and Population Scale Factor (PSF) 1990 - 2010

Trends in Population-Weighted and Regional Average $PM_{2.5}$



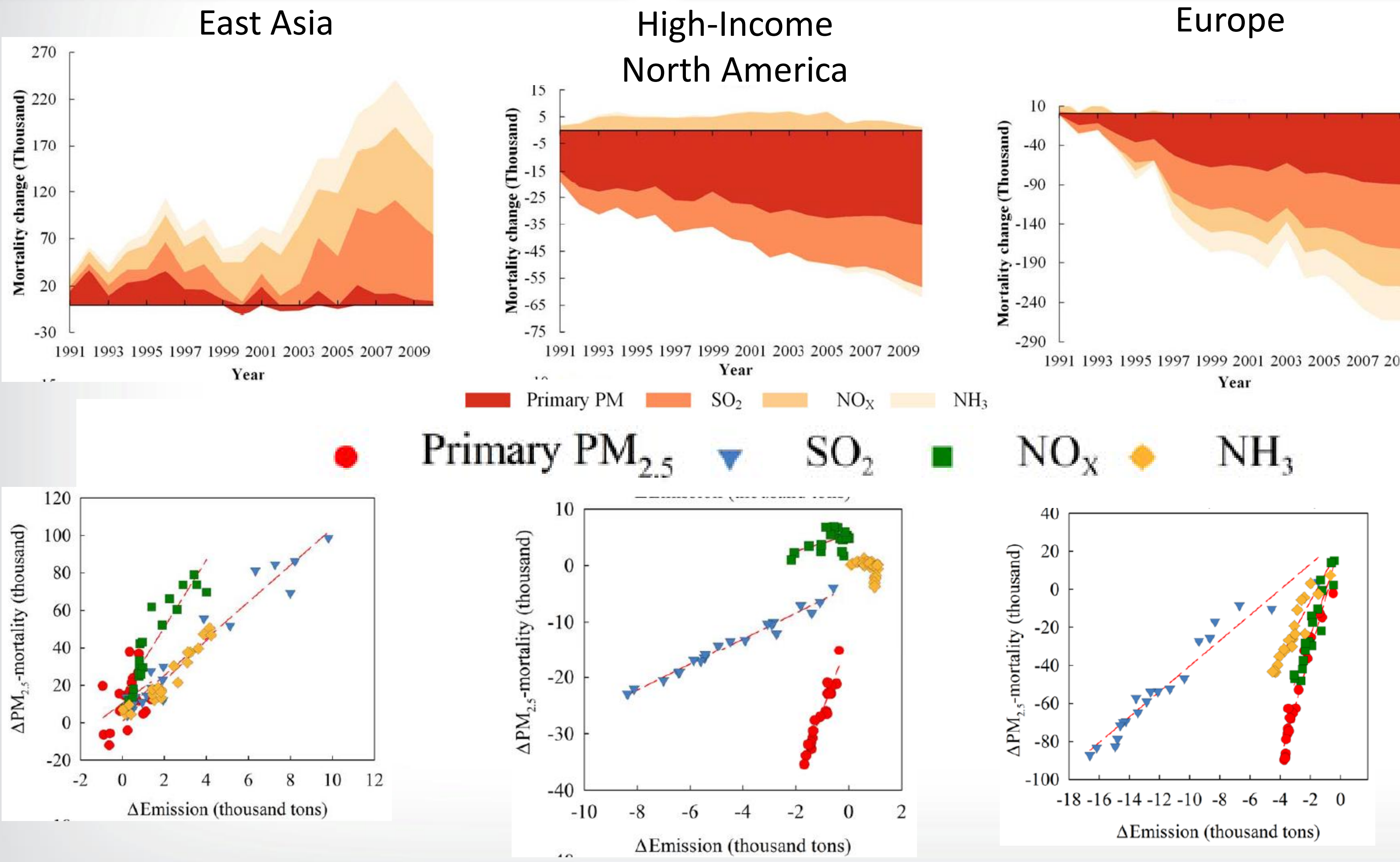
Trends in PSF



- South and East Asia: increases in PSF
- Europe and High-Income North America: decreases in PSF

Wang et al., Historical Trends in PM2.5-Related Premature Mortality during 1990-2010 across the Northern Hemisphere. EHP, 2016

Precursor-Attributed Mortality and Emission Mitigation Efficiency (EME)



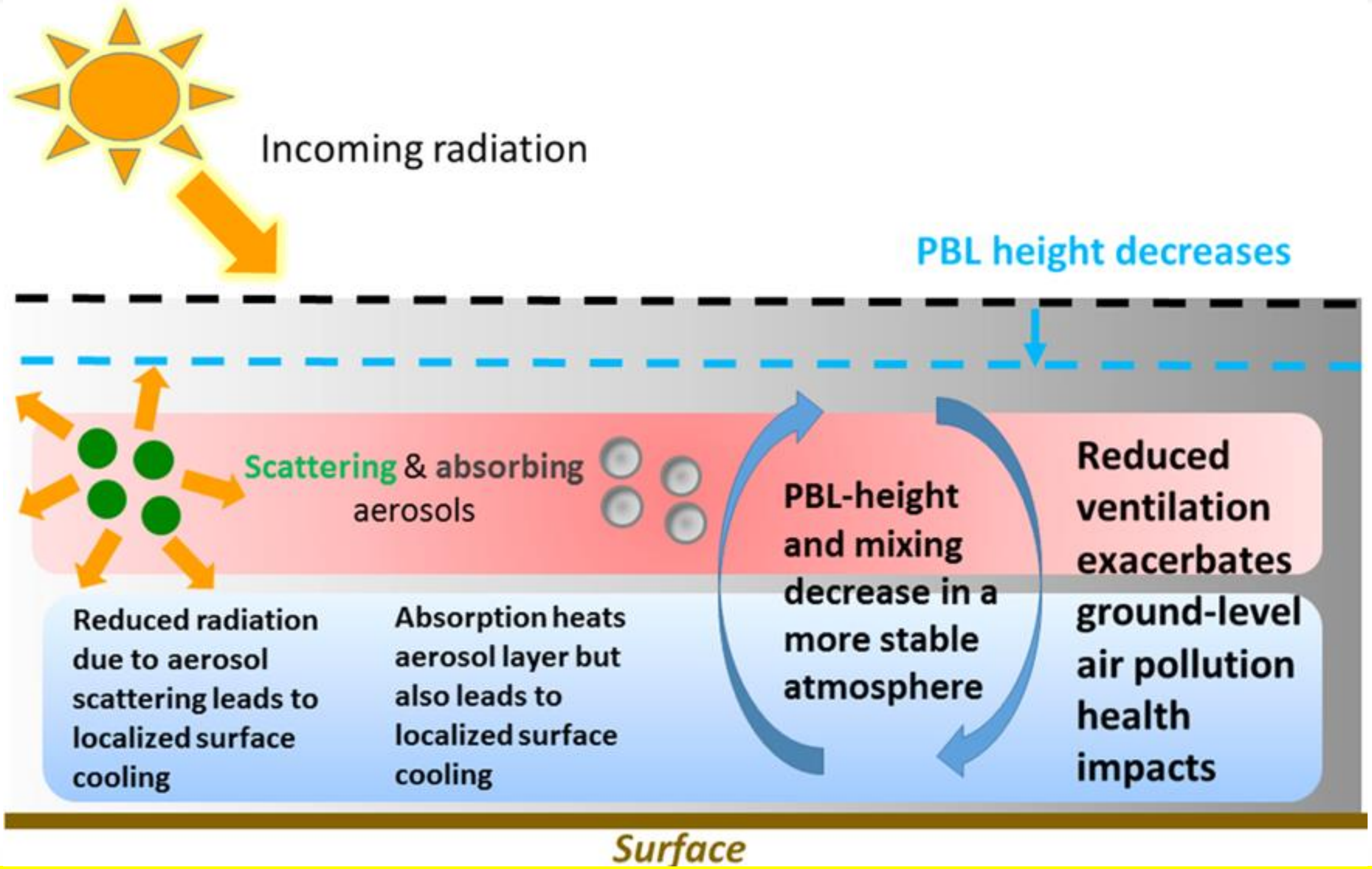
Top: Estimated changes in $PM_{2.5}$-mortality associated with changes in precursor emissions during 1991 to 2010 with respect to the 1990 values

Bottom: Relationship between changes in $PM_{2.5}$-mortality and changes in emissions. The slope of the linear regression between the variables represents the emission mitigation efficiency, i.e., EME.

Results show highest EME for primary $PM_{2.5}$ in all regions and benefit of controlling NH_3 in Europe

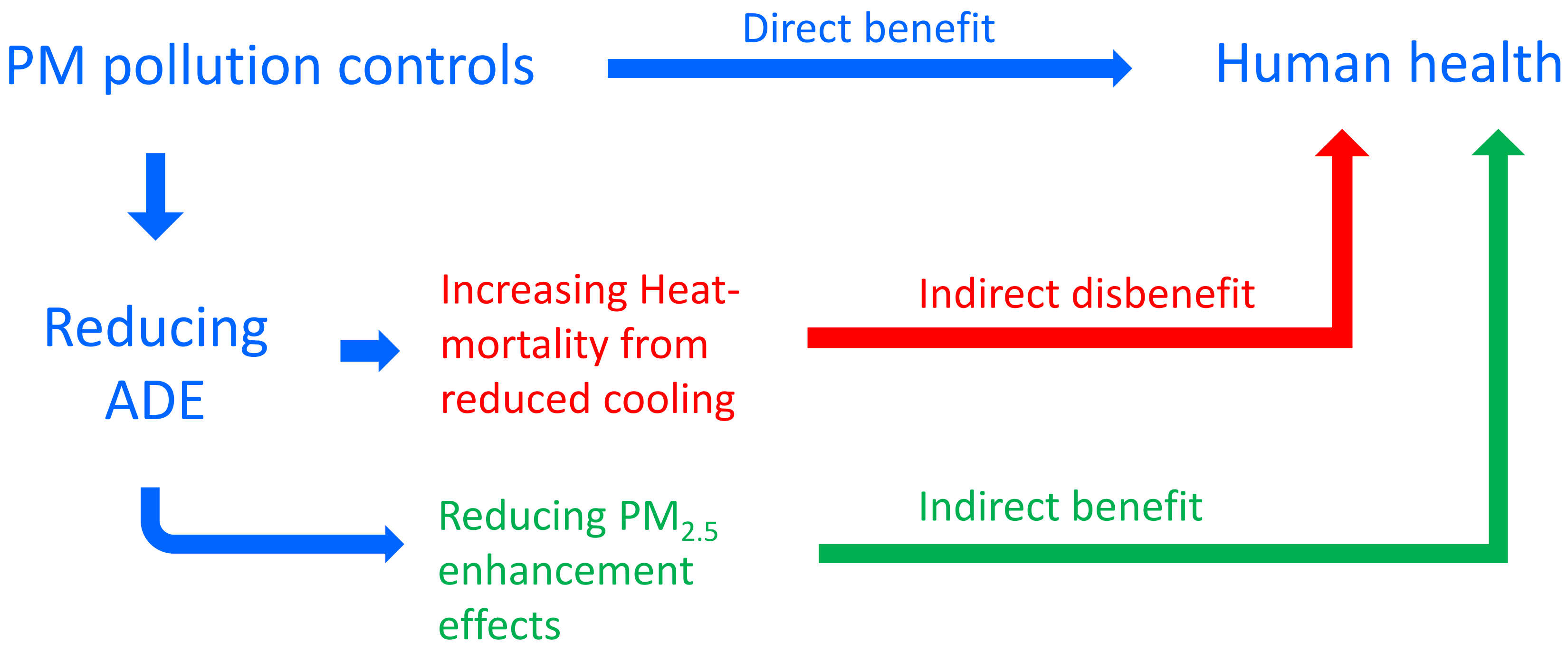
Wang et al., Historical Trends in PM2.5-Related Premature Mortality during 1990-2010 across the Northern Hemisphere. EHP, 2016

Impact of Aerosol Direct Effects (ADE) on Atmospheric Dynamics



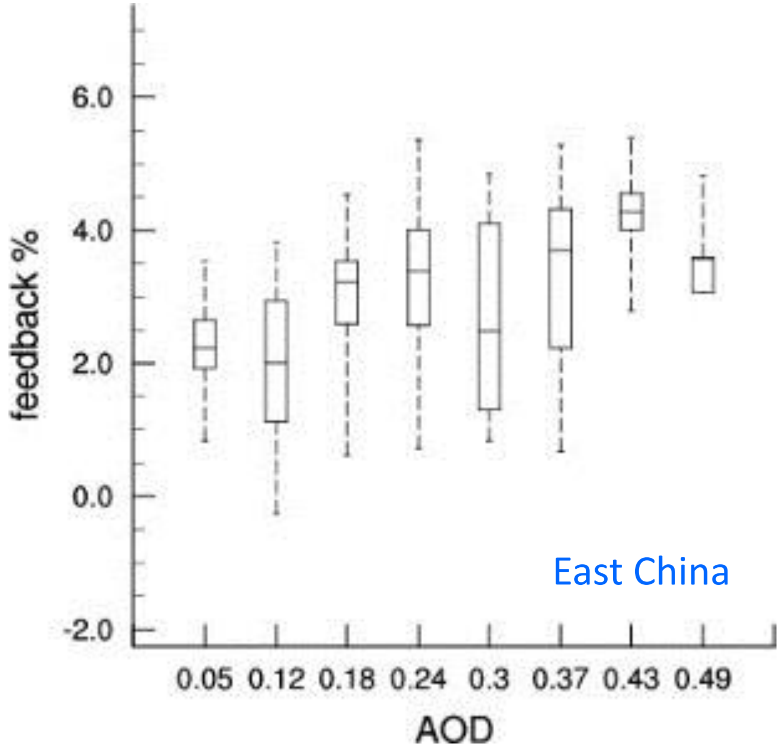
We need a comprehensive assessment with consideration of multiple manifestations of aerosol direct effects

Health Impacts Associated with ADE



$PM_{2.5}$ Response to ADE

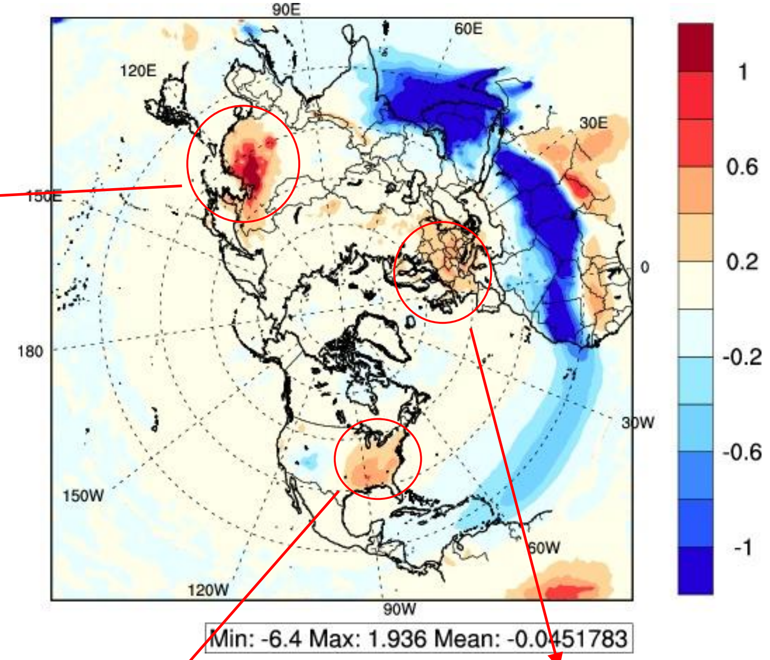
Correlations between $PM_{2.5}$ response (%) and AOD

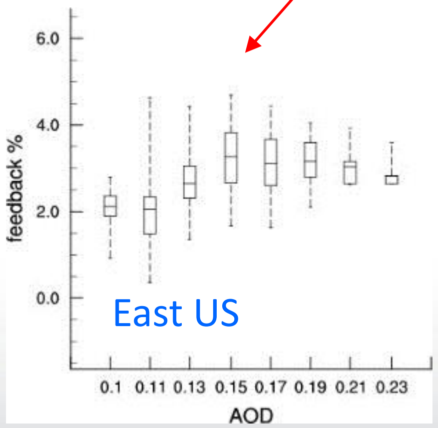


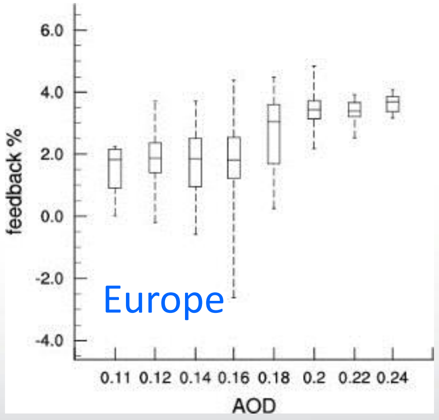
Clean area ➡ Polluted area

feedback% =
(feedback – no_feedback)/no_feedback*100%

21-year averaged $PM_{2.5}$ response due to ADE



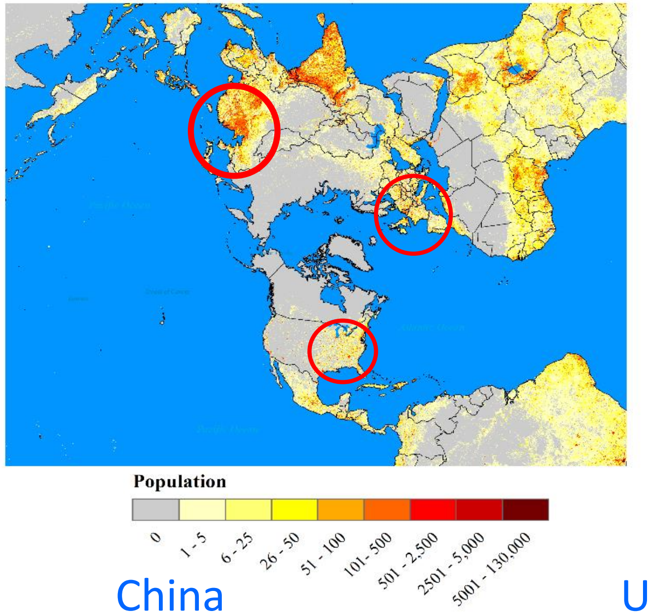




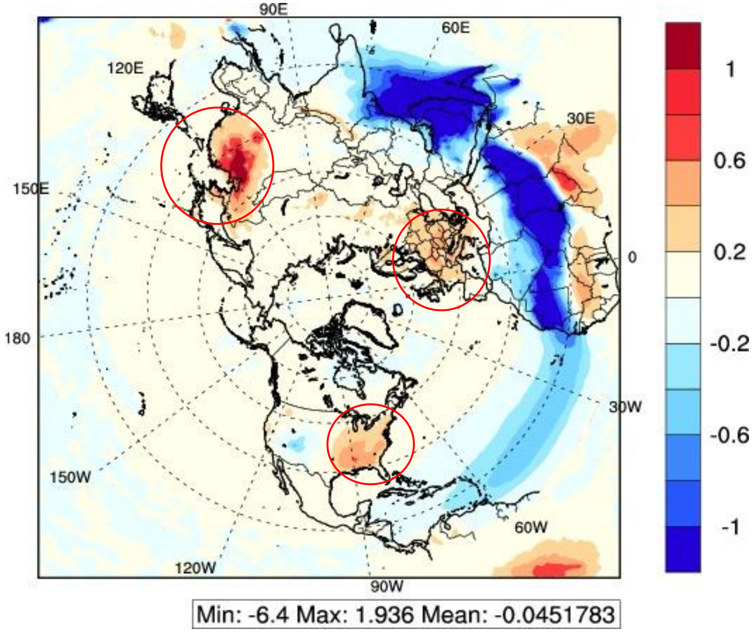
Xing et al., Unexpected benefits of reducing aerosol cooling effects. Environmental Science & Technology, 2016

$PM_{2.5}$ Response vs Population

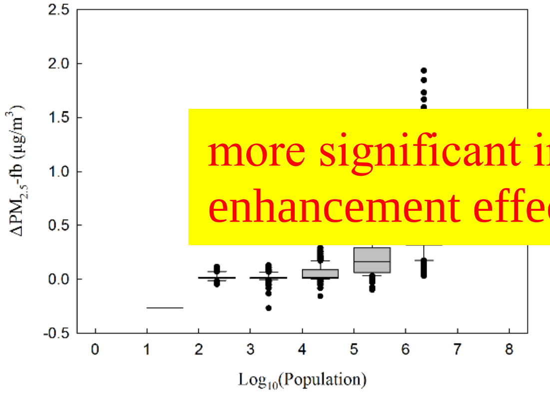
Landscan Population Data
(from Oak Ridge National Laboratory)



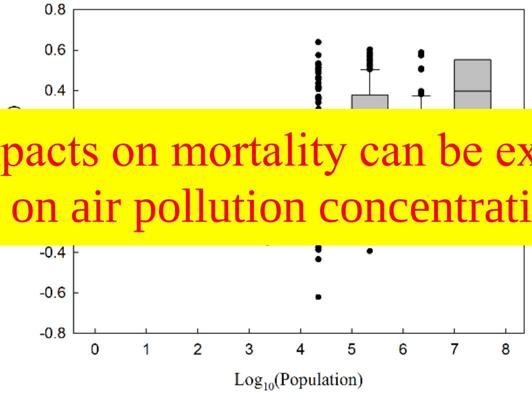
21-year Averaged $PM_{2.5}$ Response Due to ADE



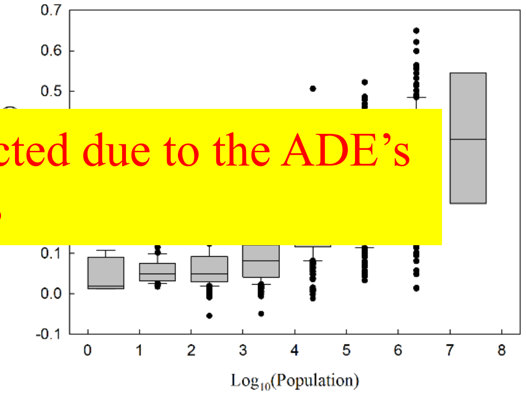
China



United States



Europe



more significant impacts on mortality can be expected due to the ADE's enhancement effect on air pollution concentrations

Xing et al., Unexpected benefits of reducing aerosol cooling effects. Environmental Science & Technology, 2016

Estimation of $PM_{2.5}$ Related Premature Mortality

Based on the GBD (Global Burden of Disease) Integrated Exposure–Response Model

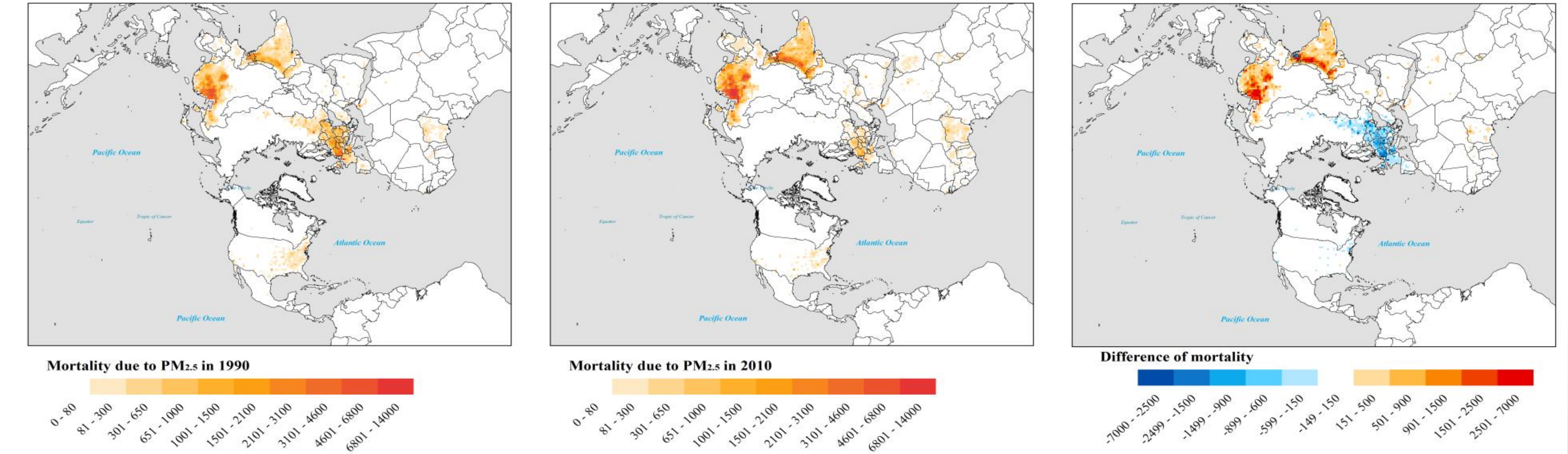
population attributable fraction

$$Mortality_{PM2.5} = \sum_{i=IHD,stroke,COPD,LC,ALRI} incidence_{0,i} \times PAF_i \times Population$$

cause-specific premature mortality

baseline incidence rate

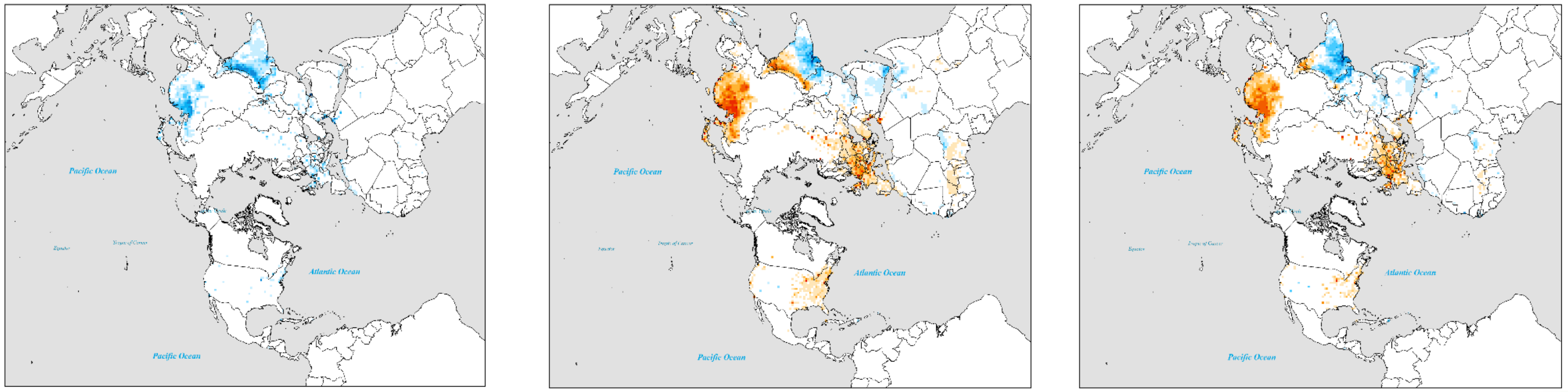
1990 | 2010 | Diff. between 2010 to 1990

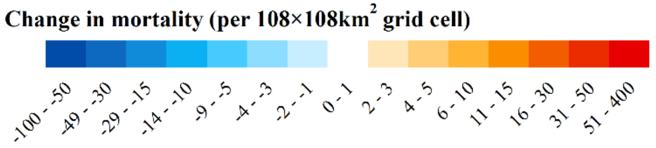


Xing et al., Unexpected benefits of reducing aerosol cooling effects. Environmental Science & Technology, 2016

Health Impacts Associated with ADE

Cooling effects	Enhancement effects	Total effects
Due to ΔT-fb	Due to $\Delta PM_{2.5}$-fb	Due to ($\Delta PM_{2.5}$-fb + ΔT-fb)



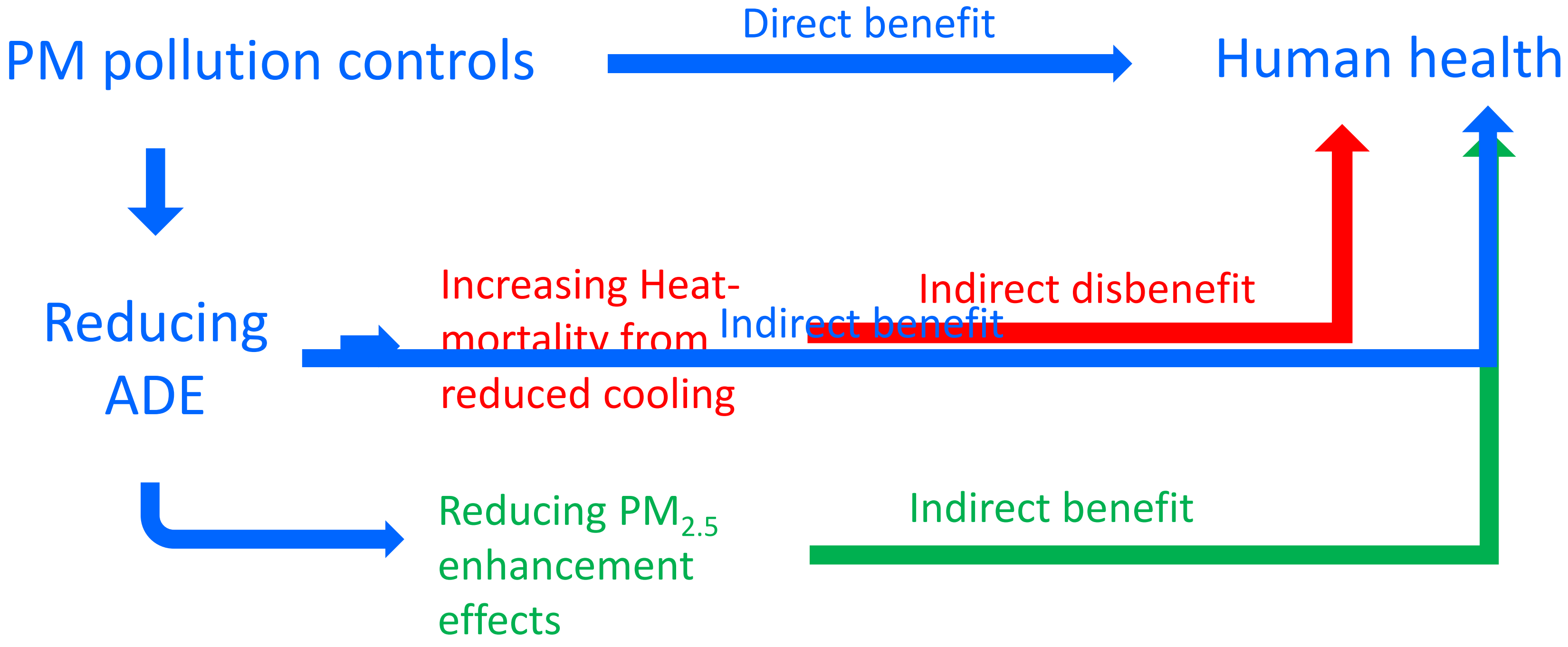


Heat-related mortality calculations were based on Basu et al. (2005; 2008) and Voorhees et al. (2009)

$$\text{mortality}_{\text{temperature}} = \text{incidence}_0 \times (\exp(\beta \times \Delta\text{temperature}) - 1) \times \text{population}$$

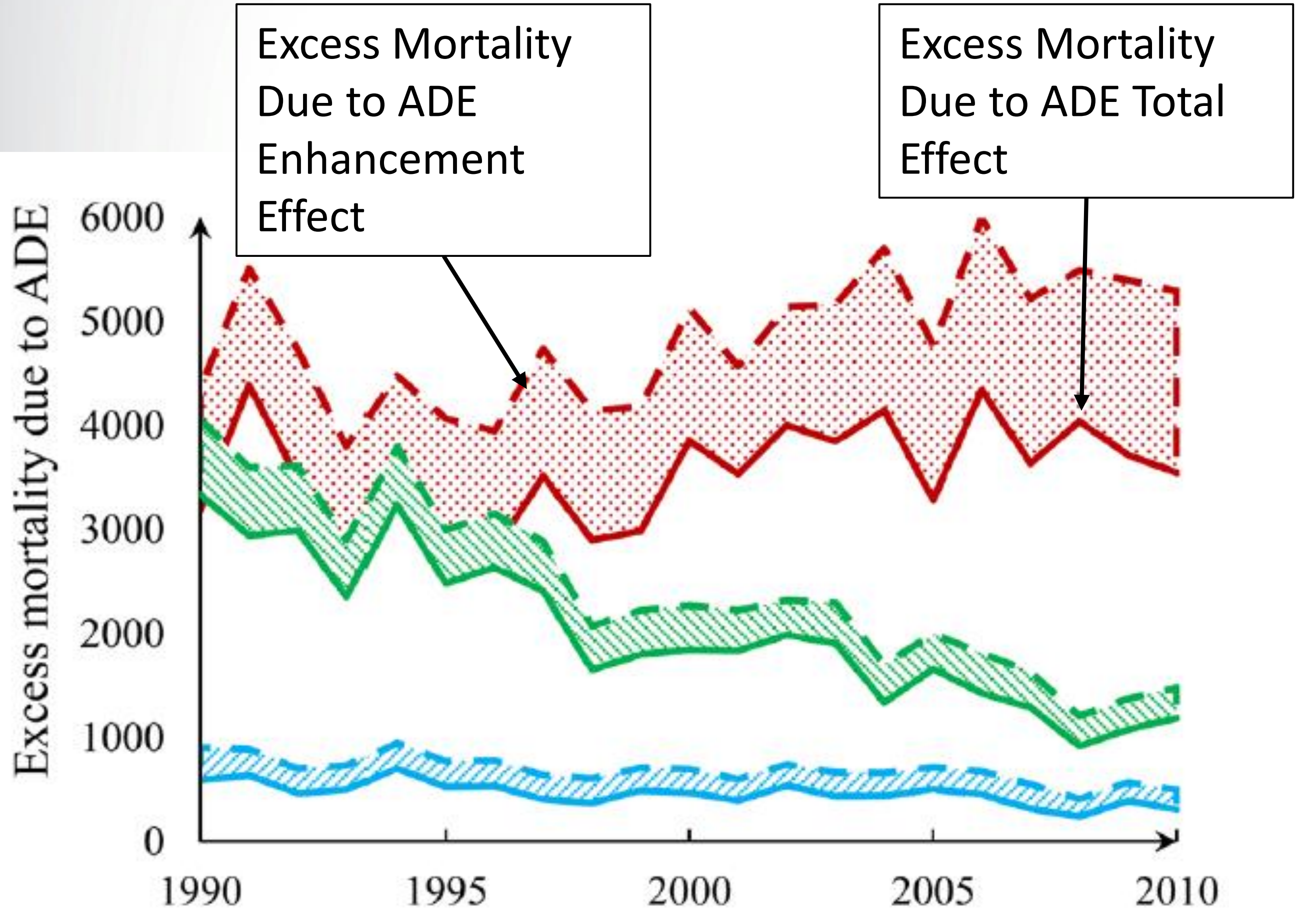
Xing et al., Unexpected benefits of reducing aerosol cooling effects. Environmental Science & Technology, 2016

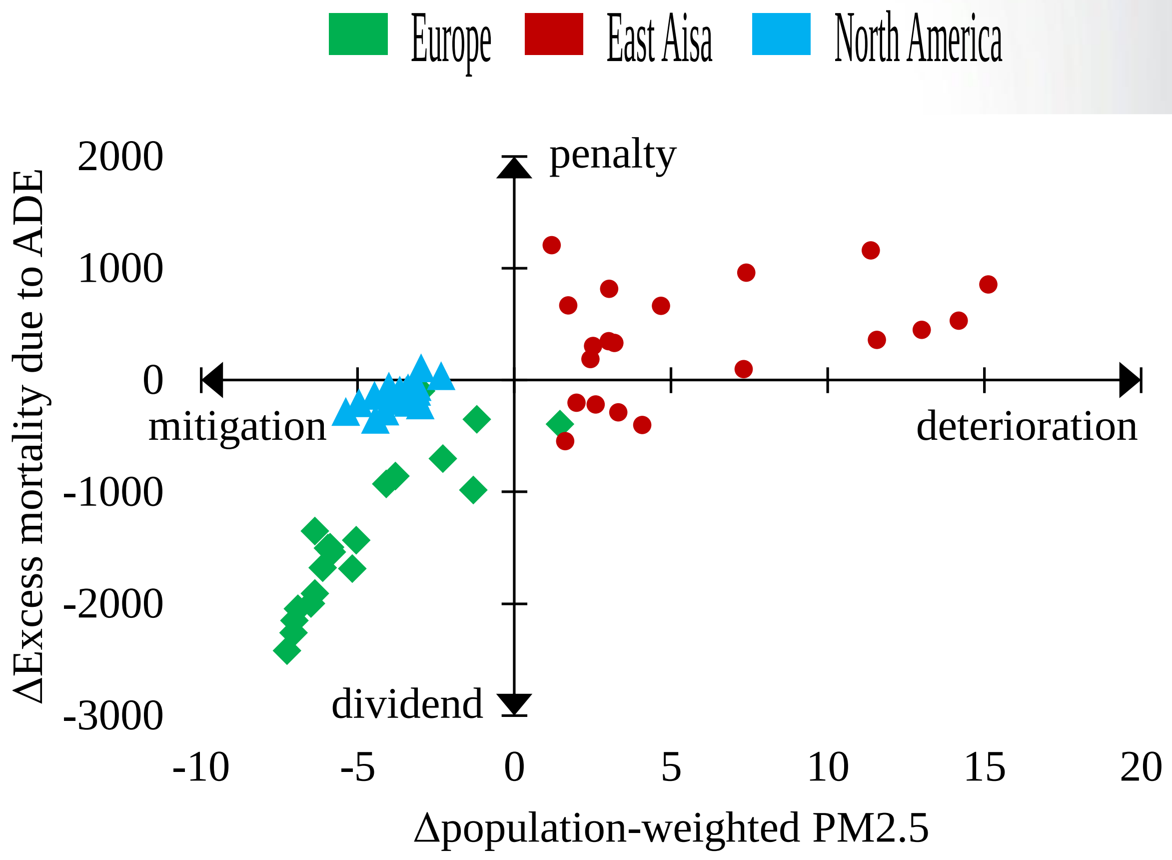
Health Impacts Associated with ADE



Mitigating aerosol pollution provides direct benefits on health, and indirect benefits on health through changes in local climate and not offsetting changes as traditionally thought.

Excess Mortality Due to ADE





Xing et al., Unexpected benefits of reducing aerosol cooling effects. Environmental Science & Technology, 2016

Summary

- Changes in emissions over the past decades led to substantial changes in air quality, aerosol/radiation feedback effects, and $PM_{2.5}$-related mortality in the U.S. as well as the entire hemisphere
- The coupled WRF-CMAQ system was used to quantify the changes in air quality and aerosol/radiation feedback effects
- Output from these WRF-CMAQ simulations was used to estimate changes in mortality due to changes in $PM_{2.5}$ concentrations as well as changes in aerosol/radiation feedback effects

Disclaimer and Acknowledgments

Although this presentation has been reviewed and approved for presentation by the U.S. Environmental Protection Agency (EPA), it does not necessarily reflect the views and policies of the agency.

This work was supported in part by an interagency agreement between the Department of energy project (IA number is DE-SC000378) and EPA (IA number is RW-89-9233260 1), also the MEP's Special Funds for Research on Public Welfare (201409002) and Strategic Priority Research Program of the Chinese Academy of Sciences (XDB05020300). This research was performed while Jia Xing Chuen-Meei Gan, and Chao Wei held a National Research Council Research Associateship Award at U.S. EPA, and Jiandong Wang held a China Scholar Council Award at U.S. EPA. The authors gratefully acknowledge the availability of population data from GPW and cause of death data from HEI.