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

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Motivation

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 heterogeneous 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.

van Donkelaar et al, Environmental Health Perspectives, 2015
**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)

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.

Observed and Simulated Trends in Air Quality 1995 - 2010

- 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

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

- 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

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\times108~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
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.

Striking contrast in emission trends between developed and developing countries
**Trends in Annual Maximum of Daily Maximum 8-hr Ozone (1990-2010)**

**JP-WDCGG**
- Obs: (-1.07µg m$^{-3}$ yr$^{-1}$, -0.74% yr$^{-1}$)
- Sim: (-1.31µg m$^{-3}$ yr$^{-1}$, -0.87% yr$^{-1}$)

**EU-EMEP**
- Obs: (-1.86µg m$^{-3}$ yr$^{-1}$, -1.10% yr$^{-1}$)
- Sim: (-0.95µg 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)

MODIS-terra

WRF-CMAQ

Summer (JJA)

East China

Europe

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)

- **CERES**
- **WRF-CMAQ**(w/feedback)
- **WRF-CMAQ**(no feedback) Summer (JJA)

**East US**
- Obs.
- Sim.(w/o feedback)
- Sim.(w/feedback)

**East China**
- Obs.
- Sim.(w/o feedback)
- Sim.(w/feedback)

**Europe**
- Obs.
- Sim.(w/o feedback)
- Sim.(w/feedback)

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

**aerosol direct radiative efficiency**
Estimating Trends in PM$_{2.5}$ Related Mortality

Calculation of PM$_{2.5}$ Related Mortality:

$$\text{Mortality}_{PM_{2.5}} = \sum_{i=IHD, stroke, COPD, LC, ALRI} \text{incidence}_{0,i} \times PAF_i \times \text{Population} \quad [1]$$

$$PAF_i = \frac{(RR_i - 1)}{RR_i} \quad [2]$$

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

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

$$\text{Mortality}_{p,y} = \frac{\text{Mortality}}{\text{Concentration}_{PM_{2.5},y}} \times \text{Concentration}_{PM_{p,y}} \quad (y = 1990 \ldots 2010) \quad [4]$$

$$\text{EME}_{p,y} = \frac{\text{Mortality}_{p,y} - \text{Mortality}_{p,1990}}{\text{Emission}_{p,y} - \text{Emission}_{p,1990}} \quad (y' = 1991 \ldots 2010) \quad [5]$$

\[ p = \{SO_2, NO_x, NH_3, \text{primary PM}\} \]

\[ PM_p = \{SO_2^-, NO_3^-, NH_4^+, \text{other inorganic particles and primary organic aerosols}\} \]

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

- 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)
Changes in PM$_{2.5}$ and Population 1990 - 2010

- Changing population exposure to ambient PM$_{2.5}$ 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
- $d(\text{Population})/d(\log([\text{PM2.5}]))$ 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

- 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)

East Asia
High-Income North America
Europe

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
We need a comprehensive assessment with consideration of multiple manifestations of aerosol direct effects.
Health Impacts Associated with ADE

PM pollution controls $\rightarrow$ Direct benefit $\rightarrow$ Human health

Reducing ADE $\rightarrow$ Increasing Heat-mortality from reduced cooling $\rightarrow$ Indirect disbenefit

Reducing PM$_{2.5}$ enhancement effects $\rightarrow$ Indirect benefit
PM$_{2.5}$ Response to ADE

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

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

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

East China
Clean area ➔ Polluted area

East US
Europe

Xing et al., Unexpected benefits of reducing aerosol cooling effects. Environmental Science & Technology, 2016
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
Based on the GBD (Global Burden of Disease) Integrated Exposure–Response Model

\[ \text{Mortality}_{PM_{2.5}} = \sum_{i=1}^{\text{IHD, stroke, COPD, LC, ALRI}} \text{incidence}_{0,i} \times \text{PAF}_i \times \text{Population} \]

cause-specific premature mortality

baseline incidence rate

population attributable fraction

Xing et al., Unexpected benefits of reducing aerosol cooling effects. Environmental Science & Technology, 2016
Heat-related mortality calculations were based on Basu et al. (2005; 2008) and Voorhees et al. (2009).

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

Xing et al., Unexpected benefits of reducing aerosol cooling effects. Environmental Science & Technology, 2016
Reducing ADE pollution controls results in direct benefits on human health.

- **Direct benefit:** Reducing PM$_{2.5}$ enhancement effects provides direct benefits on health.
- **Indirect benefit:** Increasing heat-mortality from reduced cooling enhances indirect benefits on health.
- **Indirect disbenefit:** Not offsetting changes as traditionally thought.

**Mitigating aerosol pollution** provides direct benefits on health and indirect benefits on health through changes in local climate.
Excess Mortality Due to ADE

Excess Mortality Due to ADE
Enhancement Effect

Excess Mortality Due to ADE Total Effect

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