Relevance of climate change to air quality policy

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Global temperatures

Arctic sea ice

The reality of climate change

http://nsidc.org/arcticseaicenews/

http://data.giss.nasa.gov/gistemp/
1. Global radiative equilibrium: $F_{in} = F_{out}$

2. Perturbation to greenhouse gases or aerosols disrupts equilibrium: $F_{in} \neq F_{out}$
   - $\Delta F = F_{in} - F_{out}$ defines the radiative forcing
   - Global response of surface temperature is proportional to radiative forcing: $\Delta T_{surface} \sim \Delta F$
• CO₂ forcing is $1.6 \pm 0.2$ W m$^{-2}$

• Tropospheric ozone forcing is $+0.3$-$0.7$ W m$^{-2}$; range reflects uncertainty in natural levels

• Aerosol forcing could be as large as $-2$ W m$^{-2}$; range reflects uncertainty in aerosol sources, optical properties, cloud interactions
• Beneficial impact of methane, BC, CO, NMVOC controls

• Detrimental impact of SO₂, OC controls

• NOₓ is climate-neutral within uncertainty
Methane is “win-win” – but only as part of a global strategy

Effect on surface ozone air quality is through decrease in ozone background and does not depend on where methane emission is reduced

Reduction in annual MDA8 ozone from 20% global decrease in anthropogenic methane emissions

[West et al., 2006]

Global 2005 anthropogenic methane emissions (EDGAR inventory): US accounts for ~10%

<table>
<thead>
<tr>
<th>Source (Tg a⁻¹)</th>
<th>US [EPA, 2009]</th>
<th>Global</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil fuel</td>
<td>9.5</td>
<td>80-120</td>
</tr>
<tr>
<td>Agriculture</td>
<td>8.2</td>
<td>110-200</td>
</tr>
<tr>
<td>Landfills</td>
<td>7.0</td>
<td>40-70</td>
</tr>
</tbody>
</table>
SCIAMACHY satellite data indicate underestimate of EPA methane emissions from oil/gas and agriculture.

SCIAMACHY column methane, 1 July - 15 August 2004

GEOS-Chem model column methane, 1 July – 15 August 2004, using EPA emission estimates

ICARTT aircraft data (summer 2004) show the same pattern of discrepancy; national emissions may be too low by ~ factor of 2

Kevin Wecht (Harvard)
Radiative forcing by aerosols is very inhomogeneous

...in contrast to the long-lived greenhouse gases

Present-day annual direct radiative forcing from anthropogenic aerosols (GEOS-Chem model)

Aerosol radiative forcing more than offsets greenhouse gases over polluted continents; what is the implication for regional climate response?

Leibensperger et al. [submitted]
US aerosol sources have decreased over past decades
providing a test of regional climate response

GEOS-Chem global aerosol simulation of 1950-2050 period:

- **SO\textsubscript{2}**
- **NO\textsubscript{x}**
- **Black Carbon**
- **Primary Organic**
Sulfate and black carbon trends, 1980-2010

1990

Circles = observed
Background = model

Sulfate

Black Carbon

2010

\( r^2 = 0.95 \)
\( NMB = +10.0\% \)
\( y = 1.20x - 0.32 \)

\( r^2 = 0.41 \)
\( NMB = -43.1\% \)
\( y = 0.36x + 0.06 \)

\( r^2 = 0.79 \)
\( NMB = +4.8\% \)
\( y = 1.28x + 0.11 \)

\( r^2 = 0.19 \)
\( NMB = -20.4\% \)
\( y = 0.60x - 0.04 \)

\( \mu g \text{ m}^{-3} \)

Leibensperger et al. [submitted]
Radiative forcing from US anthropogenic aerosol

Forcing is mostly from sulfate, peaked in 1970-1990
Little leverage to be had from BC control
Indirect (cloud) forcing is of similar magnitude to direct forcing

Spatial pattern

1950-2050 trend over eastern US

- Forcing is mostly from sulfate, peaked in 1970-1990
- Little leverage to be had from BC control
- Indirect (cloud) forcing is of similar magnitude to direct forcing

Leibensperger et al., [submitted]
Cooling due to US anthropogenic aerosols in 1970-1990

From difference of GISS general circulation model (GCM) simulations with vs. without US aerosol sources (GEOS-Chem), including direct and indirect effects

- Surface cooling (up to 1°C) is strongly localized over eastern US
- Cooling at 500 hPa (5 km) is more diffuse because of heat transport
Observed US surface temperature trend

- US has warmed faster than global mean, as expected in general for mid-latitudes land
- But there has been no warming between 1930 and 1980, followed by sharp warming after 1980

"Warming hole" observed in eastern US from 1930 to 1990; US aerosol signature?
1950-2050 surface temperature trend in eastern US

- US anthropogenic aerosol sources can explain the “warming hole”
- Rapid warming has taken place since 1990s that we attribute to source reduction
- Most of the warming from aerosol source reduction has already been realized
#### Effect of climate change on air quality

Air quality is sensitive to weather and so will be affected by climate change.

<table>
<thead>
<tr>
<th>Expected effect of 21st-century climate change</th>
<th>Observed dependences on meteorological variables (polluted air)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stagnation</td>
<td>Ozone</td>
</tr>
<tr>
<td>Temperature</td>
<td>PM</td>
</tr>
<tr>
<td>Mixing depth</td>
<td></td>
</tr>
<tr>
<td>Precipitation</td>
<td></td>
</tr>
<tr>
<td>Cloud cover</td>
<td></td>
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<tr>
<td>Relative humidity</td>
<td></td>
</tr>
</tbody>
</table>

Climate change is expected to degrade ozone air quality; effect on PM uncertain.

*Jacob and Winner [2009]*
IPCC projections of 2000-2100 climate change in N. America

2080-2099 vs. 1980-1999 changes for ensemble of 20 models in A1B scenario

- Increasing temperature everywhere, largest at high latitudes
- Frequency of heat waves expected to increase
- Increasing precipitation at high latitudes, decrease in subtropics but with large uncertainty
- Decrease in meridional temperature gradient expected to weaken winds, decrease frequency of mid-latitude cyclones
Importance of mid-latitudes cyclones for ventilation

- Cold fronts associated with cyclones tracking across southern Canada are the principal ventilation mechanism for the eastern US
- The frequency of these cyclones has decreased in past 50 years, likely due to greenhouse warming

Leibensperger et al. [2008]
Observed trends of ozone pollution and cyclones in Northeast US

# ozone episode days ($O_3 > 80$ ppb) and # cyclones tracking across SE Canada in summer 1980-2006 observations

- Cyclone frequency is predictor of interannual pollution variability
- Observed 1980-2006 decrease in cyclone frequency would imply a corresponding degradation of air quality if emissions had remained constant
- Expected # of 80 ppb exceedance days in Northeast dropped from 30 in 1980 to 10 in 2006, but would have dropped to $\approx$ zero in absence of cyclone trend

Leibensperger et al. [2008]
General GCM-CTM approach to quantify the effects of climate change on air quality

- Socioeconomic emission scenario
  - Greenhouse gas emissions
  - Global climate model (GCM)
  - Input meteorology
  - Global chemical transport model (CTM)
    - Boundary conditions
    - Input meteorology
    - Regional climate model (RCM)
      - Boundary conditions
      - Regional CTM for ozone-PM AQ

Socioeconomic emission scenario

Jacob and Winner [2009]
Ensemble model analysis of the effect of 2000-2050 climate change on ozone air quality in the US

Results from six coupled GCM-CTM simulations

- Models show consistent projection of ozone increase over most of US
- Typical mean increase is 1-4 ppb, up to 10 ppb for ozone pollution episodes
- No such consistency is found in model projections for PM, including in sign of effect (± 0.1-1 µg m⁻³)

Weaver et al. [2010]
Association of PM$_{2.5}$ components with temperature from multivariate regression of deseasonalized PM with meteorological data

- Correlations with $T$ reflect direct dependences for nitrate (volatilization) and OC (vegetation, fires) but also covariations with other factors
- Correlations with meteorological modes of variability point to cyclone frequency as major factor for PM$_{2.5}$ variability in Midwest/Northeast

Tai et al. [submitted]
Increasing wildfires could be the major effect of climate change on PM.

- Temperature and drought index can explain 50-60% of interannual variability in fires.

- Climate change is projected to increase biomass burned in US by 50% in 2050, resulting in 0.5-1 \( \mu g m^{-3} \) increase in PM in West.[Spracklen et al., 2009]
Air Quality Applied Sciences Team (AQAST)

EARTH SCIENCE SERVING AIR QUALITY MANAGEMENT NEEDS

Team leader: Daniel J. Jacob

Earth science resources

- satellites
- suborbital platforms
- models

Air Quality Management Needs

- Pollution monitoring
- Exposure assessment
- AQ forecasting
- Source attribution of events
- Quantifying emissions
- Assessment of natural and international influences
- Understanding of transport, chemistry, aerosol processes
- Understanding of climate-AQ interactions

For more information on how AQAST can help you please ask me!
Effect of climate change on mercury cycling

Hg has a large soil reservoir due to binding with organic carbon; as global warming causes increased soil respiration, will this Hg stockpile be released?

Present-day global biogeochemical cycle of mercury [Selin et al., 2008]
Effect of climate change on mercury in the Arctic Ocean

Atmospheric Hg depletion events (AMDEs) associated with ice leads

- Summer rebound in atmospheric observations cannot be explained by snow re-emission; we hypothesize a major source from Arctic rivers runoff
- Increasing river runoff in future climate could greatly affect Hg levels in Arctic Ocean

Fisher et al. [2011]
Effect of 2000-2050 climate change on annual mean PM$_{2.5}$

Different models show ± 0.1-1 μg m$^{-3}$ effects of climate change on PM$_{2.5}$ but there is no consistency across models including in the sign of the effect.

Decrease of SO$_2$ emissions ameliorates effect of climate change by changing PM speciation from sulfate to nitrate.

Pye et al. [2009]; Lam et al. [2010]
Correlating PM$_{2.5}$ observations to meteorological variables

Multilinear regression model fit to 1998-2008 deseasonalized EPA/AQS data for PM2.5 (total and speciated)

$$y_i = \beta_{0,i} + \sum_{k=1}^{9} \beta_{k,i} x_{k,i} + \text{interaction terms}$$

mostly precipitation
mostly temperature and stagnation

Tai et al., 2010
Climate-driven mobilization of anthropogenic Hg from soils

GEOS-Chem model simulation of soil mercury

- Mercury accumulates in soil by binding to organic carbon; part is volatilized when organic carbon is respired

- Mercury has a mean lifetime in soil of 600 years, but deposited anthropogenic mercury has a lifetime of only 80 years

- Increased soil respiration in future climate could lead to large soil mercury release

Smith-Downey et al. [2010]
Importance of AQ-related emissions for short-term climate change

Integrated radiative forcing over 20-year time horizon from 2000 emissions

Methane and aerosol sources are as important as CO₂

IPCC [2007]
Better understanding of methane sources is needed to support emission control strategies.

Leveling off in past decade, uptick in past two years are not understood.
Hydrological cycle perturbations due to US anthropogenic aerosols from difference of GCM simulations with vs. without US aerosol sources for 1970-1990, including aerosol direct and indirect radiative effects

- Cooling decreases evaporation over eastern US and hence precipitation over eastern seaboard;
- Increasing flow from Gulf of Mexico moistens south-central US

Leibensperger et al., in prep.
Global Temperature (meteorological stations)

THE REALITY OF CLIMATE CHANGE

http://data.giss.nasa.gov/gistemp/
http://nsidc.org/arcticseaicenews/
Aerosol effects on climate
Projections of global AQ-relevant emissions in IPCC scenarios

- Large differences in projections between SRES and RCP scenarios
- The RCP scenarios project large decreases for all emissions except NH$_3$
- Even China and India are projected to decrease emissions in next 2 decades except for RP8.5 (peak in 2040)