Air Quality and Climate Connections

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Ozone and Particulate Matter (PM) are the top two U.S. air pollutants

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>One or more NAAQS</td>
<td>142.2</td>
</tr>
<tr>
<td>Ozone (8-hour)</td>
<td>133.2</td>
</tr>
<tr>
<td>PM$_{2.5}$ (annual/24-hr)</td>
<td>28.2</td>
</tr>
<tr>
<td>PM$_{10}$ (24hr)</td>
<td>16.1</td>
</tr>
<tr>
<td>SO$_2$ (1-hr)</td>
<td>15.1</td>
</tr>
<tr>
<td>Lead (3-month)</td>
<td>8.1</td>
</tr>
<tr>
<td>NO$_2$ (annual/1-hr)</td>
<td>0</td>
</tr>
<tr>
<td>CO (8-hr)</td>
<td>0</td>
</tr>
</tbody>
</table>

 Millions of people living in counties with air quality concentrations above the level of the U.S. National Ambient Air Quality Standards

EPA, 2014: [http://www.epa.gov/airtrends/aqtrends.html#comparison](http://www.epa.gov/airtrends/aqtrends.html#comparison)
Summary schematic of air quality-climate connections

Figure 2, Fiore, Naik, Leibensperger, JAWMA, 2015
Summary schematic of air quality-climate connections

Figure 2, Fiore, Naik, Leibensperger, JAWMA, 2015

#1 Air pollutants → Climate

Chemical reactions
- CH$_4$ + O
- NMVOCs + NO$_x$

Long-range Transport
- LRT
- wind speed

Chemical & physical processes
- NMVOCs, NO$_x$, NH$_3$
- OC, BC, SO$_2$, DMS, dust & sea salt
- SOA, SO$_4^{2-}$, NO$_3^-$

Anthropogenic and Natural Emissions

- regional stagnation
- CH$_4$ from wetlands
- regional emissions
- soil NO$_x$
- wildfire emissions
- BVOCs from trees
Summary schematic of air quality-climate connections

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#1 Air pollutants → Climate

#2 Climate → Air Pollution
Summary schematic of air quality-climate connections

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#1 Air pollutants → Climate

#2 Climate → Air Pollution

#3 Holistic approaches to meet both air quality and climate goals?
Summary schematic of air quality-climate connections

Figure 2, Fiore, Naik, Leibensperger, JAWMA, 2015

#1 Air pollutants → Climate
Air pollutants affect climate

Greenhouse gases absorb infrared radiation

NMVOCs, CO, CH₄

O₃, H₂O, OH + NOₓ

Aerosols interact with sunlight (radiation and cloud interactions)

Smaller droplet size → clouds last longer
→ increase albedo
→ less precipitation

Black carbon

Sulfate

organic carbon

Surface of the Earth

pollutant sources
Tropospheric ozone and precursors contribute to climate forcing from pre-industrial to present-day

Adapted by E. Leibensperger (SUNY Plattsburgh) from IPCC, 2013 for Fiore, Naik, Leibensperger, in press

Radiative Forcing components: 
- CO₂, CH₄, Strat. H₂O, Trop. O₃

Emitted Species:
- CO₂
- CH₄
- CO
- NMVOC
- NOₓ

Radiative Forcing Since 1750 (W/m²)
PM and precursors also contribute to climate forcing from pre-industrial to present-day

Radiative Forcing components:
- CO₂, CH₄, Strat. H₂O, Trop. O₃
- sulfate, nitrate, dust
- BC (BF+FF; BB; snow albedo)
- OC (BF+FF; BB)

Net impact of aerosols (-0.9 W m⁻²) opposes warming from GHGs

Adapted by E. Leibensperger (SUNY Plattsburgh) from IPCC, 2013 for Fiore, Naik, Leibensperger, in press
Air pollutants are Near-Term Climate Forcers (NTCFs); CO$_2$ dominates long-term climate (peak warming)

**Radiative Forcing components**
- CO$_2$, CH$_4$, Strat. H$_2$O, Trop. O$_3$
- sulfate, nitrate, dust
- BC (BF+FF; BB; snow Albedo)
- OC (BF+FF; BB)

**Short-Lived Climate Pollutants (SLCPs) = warming NTCF**s

Adapted by E. Leibensperger (SUNY Plattsburgh) from IPCC, 2013 for Fiore, Naik, Leibensperger, in press
Climate responses attributed to anthropogenic black carbon (and brown carbon)

The impact of BC on snow and ice causes additional warming in the Arctic region and contributes to snow/ice melting. Very likely but magnitude uncertain.

BC in northern hemisphere mid-latitude snow leads to earlier springtime melt and reduces snow cover in some regions. Likely but magnitude uncertain.

The warming caused by BC is concentrated in the northern hemisphere. Very likely.

Absorbing aerosols may have caused changes in precipitation patterns with largest effects likely to be in South Asia.

The hemispheric nature of the BC forcing causes a northward shift in the ITCZ. Likely.

Absorbing aerosols may cause circulation changes over the Tibetan Plateau and darkening of the snow. The importance of this for glacier melting is unknown.

Bond et al, JGR, 2013
Most sources emit more than one pollutant

Example estimate of near-term climate impacts from individual sectors

Sector (Net radiative forcing)

- On-road (199)
- Household biofuel (132)
- Animal Husbandry (98)
- Household fossil fuel (84)
- Waste/landfill (84)
- Power (79)
- Agriculture (29)
- Off-road land (20)
- Aviation (-6)
- Agr. waste burning (-14)
- Shipping (-43)
- Biomass burning (-106)
- Industry (-158)

Near-term (2020)

- Ozone
- Sulfate
- Nitrate
- Black carbon
- Organic carbon
- Aerosol-cloud
- Methane
- Nitrous Oxide
- Carbon Dioxide

Neglects brown carbon and other factors that may reverse biomass burning sign to net warming [Jacobson, 2014]

CR Figure 5a, from Unger et al., PNAS 2010
Choice of time scale crucial when assessing climate impacts: carbon dioxide dominates long-term (2100)

CR Figure 5b, from Unger et al., 2010
Summary schematic of air quality-climate connections

Figure 2, Fiore, Naik, Leibensperger, JAWMA, 2015

#1 Air pollutants → Climate

#2 Climate → Air Pollution
Models estimate a ‘climate change penalty’ (+2 to 8 ppb) on surface O$_3$ over U.S. but often disagree in sign regionally.

- Uncertain regional climate responses (meteorology, emissions and chemistry) to global warming
- Model estimates typically based on a few years of present and future (often 2050s) meteorology from 1 realization of 1 GCM

Wu et al., JGR, 2008: “Climate Penalty”
Climate variability can confound detection of anthropogenic climate change and limits predictability.

Summer (JJA) U.S. temperature trends in the warmest and coolest of 40 NCAR CCSM3 ensemble members (A1B; only atmospheric initial conditions differ).

→ Uncertain air quality (surface ozone) projections
→ A range of trends may be consistent with observed trends (i.e., emission-driven component plus variability)

Deser et al., NCC, 2012 (excerpts from their Figure 2)
O$_3$ correlates with surface temperature on daily to inter-annual time scales in polluted regions [e.g., Bloomer et al., 2009; Camalier et al., 2007; Cardelino and Chameides, 1990; Clark and Karl, 1982; Korsog and Wolff, 1991]

Observations at U.S. EPA CASTNet site Penn State, PA 41N, 78W, 378m

→ Implies that changes in climate (via regional air pollution meteorology) will influence air quality

→ Downward trend in O$_3$ as EUS NO$_x$ emission controls are implemented
Decreasing NO$_x$ emissions reduces sensitivity of O$_3$ to temperature; helps to guard against any “climate penalty” [e.g., Bloomer et al., 2009; Rasmussen et al., 2012; Brown-Steiner et al., 2015]

**Graph:**
- 1988-2001: 4.1 ppb/C
- 2002-2014: 2.4 ppb/C

→ Historically observed relationships may not hold as emissions change
→ Meteorology may also change [e.g., Barnes & Fiore, 2013; Shen et al., 2015]

Figure 6b of Fiore, Naik, Leibensperger, JAWMA, 2015
What might the future hold? Emissions of NO$_x$ and SO$_2$ over the Southeast (and nationwide) are projected to decline.
Projected air quality over the Southeast mainly follows precursor emission trajectories.

Coupled Model Intercomparison Project 5 (CMIP5) and Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP) models

SUMMER (JJA) $O_3$ (ppb)

WINTER (DJF) $O_3$

Annual mean PM$_{2.5}$ ($\mu$g m$^{-3}$)

Figure 10 of Fiore, Naik, Leibensperger, JAWMA, 2015
Greenhouse Gases and Emissions of Near-Term Climate Forcers (NTCFs) under “RCPs”

Overly (?) optimistic 21st century decreases in global air pollutants
Doubling of global CH$_4$ abundance (RCP8.5) raises NE USA surface ozone in model (GFDL CM3); largest impact during winter.

Clifton et al., GRL, 2014
How and why might extreme air pollution events change?

- Need to understand how different processes influence the distribution
  - Meteorology (e.g., stagnation vs. ventilation)
  - Degree of mixing
  - Pollutant sources
  - Feedbacks (Emis, Chem, Dep)
  - Changing global emissions (baseline)
    - Shift in mean?
  - Changing regional emissions (episodes)
    - Change in symmetry?

Figure SPM.3, IPCC SREX 2012
http://ipcc-wg2.gov/SREX/
Ozone and particulate matter build up during heat wave; cold fronts ventilate the polluted boundary layer

Warmer climate $\rightarrow$ more heat waves $\rightarrow$ more pollution?

Figure 7 of Fiore, Naik, Leibensperger, JAWMA, 2015
Summary schematic of air quality-climate connections

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#1 Air pollutants \(\rightarrow\) Climate

#2 Climate \(\rightarrow\) Air Pollution

#3 Holistic approaches to meet both air quality and climate goals?
20th century increase in global aerosols exerted a cooling; their projected removal implies a 21st century warming.

All effective aerosol radiative forcing relative to 1850:
- 1850
- 1900
- 1950
- 2000
- 2050
- 2100

2100 (RCP8.5) vs. 2000
(5 ACCMIP models)

+1.01 W m^-2

2000 vs. 1850
(8 ACCMIP models)

-1.17 W m^-2
Removing anthropogenic aerosol induces warming and changes precipitation patterns.

Determined by differencing two GFDL CM3 simulations: (2090s RCP4.5) - (2090s RCP4.5 but aerosols remain at 2005 levels)

Change in annual mean sulfate column

Climate response patterns do not necessarily mirror spatial pattern of changes in aerosol abundances

CR Figure 4b; Levy et al., JGR, 2013
Aerosol (PM) has already declined across much of the U.S.A.

Obs. PM [Murphy et al., 2011]

Did U.S. regulations impact recent climate change?
→ Are the impacts regional, hemispheric, global?

c/o E. Leibensperger
Globally, BC emissions may still be growing; \( \text{SO}_2 \) is declining.

Climate policy (RCP4.5) leads to lower global BC and \( \text{SO}_2 \) emissions.

Smith and Bond, 2014, ACP
Radiative Forcing over the eastern U.S.A. from U.S. anthropogenic Aerosols

U.S. BC is weak!

Forcing largest 70s-90s

Estimated with GEOS-Chem aerosols in GISS GCM

Leibensperger et al., ACP, 2012a
U.S. PM cooled eastern U.S.A. and North Atlantic (and hemisphere, but not significant relative to inter-annual variability)

Determined from simulations with and without 1970-1990 U.S. aerosols (GISS GCM)

Leibensperger et al., ACP, 2012b
Cleaner U.S. air visible from space

Satellite (OMI) tropospheric NO$_2$ columns

2005

2011

Check out the new OMI NO$_2$ website:

[airquality.gsfc.nasa.gov](http://airquality.gsfc.nasa.gov)

c/o Bryan Duncan, NASA GSFC
Trends in summer daytime (11am-4pm) average ozone at rural U.S. monitoring sites (CASTNet): 1990 to 2010

Cooper et al., JGR, 2012

Success in decreasing highest levels, but baseline rising (W. USA)

Decreases in EUS attributed in observations and models to NO\textsubscript{x} emission controls in late 1990s, early 2000s [e.g., Frost et al., 2006; Hudman et al., 2007; van der A. et al., 2008; Stavrakou et al., 2008; Bloomer et al., 2009, 2010; Fang et al., 2010]
Lower $O_3$ NAAQS level likely expands non-attainment regions

EPA-approved ozone monitoring sites

Percentage of sites in the western and eastern domains exceeding the current ozone standard of 75 ppbv

Cooper et al., Science, 2015
The “tightening vise” of ozone management

Future may require concerted efforts to lower background

Air pollution-climate connection via methane

Benefits of ~25% decrease in global anthrop. methane emissions

Possible at cost-savings / low-cost [West & Fiore 2005; West et al.,2012]

$1.4 billion (agriculture, forestry, non-mortality health) within U.S. alone [West and Fiore, 2005]

7700-400,000 annual avoided cardiopulmonary premature mortalities in the N. Hemisphere uncertainty in concentration-response relationship only [Anenberg et al., ES&T, 2009]

OZONE AIR QUALITY

Range over 18 models

- N. America
- Europe
- East Asia
- South Asia

[Fiore et al., JGR, 2009; TF HTAP, 2007, 2010; Wild et al., ACP, 2012]

CLIMATE

Global mean avoided warming in 2050 (°C) [WMO/UNEP, 2011]
Reducing air pollutant SLCPs lessens near-term climate warming (and improves air quality by decreasing background $O_3$; $PM_{2.5}$)

$\textbf{CH}_4$ measures: for oil and gas production, long distance gas transmission, coal mines, municipal waste/landfills, wastewater, livestock manure, rice paddies.

$\textbf{BC}$ measures: (tech) for diesel vehicles, clean biomass stoves, brick kilns, coke ovens; (regulatory) bans on agricultural burning, eliminate high emitting vehicles, modern cooking and heating.

→ Target $CH_4$ and some BC-rich sources to offset near-term warming from health-motivated controls on $SO_2$ emissions

Adapted from Fig 12 Fiore et al. 2015
Mitigate BOTH near-term AND long-term climate change by reducing SLCPs AND CO$_2$

CO$_2$ and SLCPs can induce other climate responses that affect pollution levels:
- Hydrologic cycle
- Circulation patterns (including “air pollution meteorology”)
Implications from Air Quality and Climate Connections

- Methane reductions are a ‘win-win’ for climate and air quality.
- Black carbon controls may reduce near-term warming and are urgently needed for lessening global health burden.
- Sulfate controls motivated by health outcomes unmask near-term warming (removal of cooling that offsets warming from CO2 and other warming agents), BUT will also lessen disruption of hydrologic cycle and other climatic responses to sulfate aerosols.

→ Controls on methane, black carbon could be used to lessen near-term warming rate from sulfate reductions.
Recommendations from Air Quality and Climate Connections

- Improve accuracy and trends in past and future emission inventories to underpin accountability analyses
  - Impacts of climate-motivated changes in emissions on air quality
  - Impacts of health-motivated changes in emissions on climate

- Continue attempting to bound the influence of near-term climate forcers (NTCFs) on the climate system

- Develop process-level knowledge of biosphere-atmosphere interactions and their sensitivity to changes in air pollution and climate (+ land-use, agricultural practices)

- Establish tools for rapid translation of research findings for decision-making that connects air pollution and climate responses to health and environmental outcomes