Influence of climate change and variability on (mostly U.S. ozone) air quality

Arlene M. Fiore

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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
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
- Model estimates typically based on a few years of present and future (often 2050s) meteorology from 1 realization (ensemble member) of 1 GCM

Wu et al., JGR, 2008: “Climate Penalty”
Projected near-term surface ozone changes due to precursor emissions generally larger than climate change influence

Synthesis from published literature as of mid-2012

Fig 11.22 IPCC AR5 WG1 Ch 11 [Kirtman et al., 2013; see also Fiore et al., Chem Soc. Rev., 2012]
How and why might extreme air pollution events change?

**TEMPERATURE (AIR POLLUTION)**

- **Mean shifts**
- **Variability increases**
- **Symmetry changes**

**Figure SPM.3, IPCC SREX 2012**
http://ipcc-wg2.gov/SREX/

- **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?

**Need to understand how different processes influence the distribution**
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
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

Figure 6a of Fiore, Naik, Leibensperger, JAWMA, 2015

→ 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]

July mean MDA8 ozone (ppb) vs. July mean maximum daily temperature (°C)

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

Figure 6b of Fiore, Naik, Leibensperger, JAWMA, 2015
Cleaner U.S. air is visible from space

Satellite (OMI) tropospheric NO$_2$ columns

2005

2014

\[c/o\] Lok Lamsal & Bryan Duncan, NASA GSFC

New OMI NO$_2$ website: airquality.gsfc.nasa.gov
“The world avoided”? In absence of emission controls, 95th percentile summer EUS MDA8 O3 would have increased

Summer (JJA) 95th percentile MDA8 O3 trends (1988-2014)

Larger circles indicate significant trends (p<0.05)

Model 90th percentile JJA daily max temperature trends

M. Lin et al., ACP, 2017
Coarse-resolution global models can capture spatial patterns of high pollution events (ozone episode in Europe)

Schnell et al., ACP, 2014,
GFDL-AM3 captures interannual variability of O$_3$ anomalies associated with high temperatures

Pennsylvania State Univ [78° W, 41° N, 378 m]

OBS -0.67±0.33 ppb yr$^{-1}$
BASE -0.45±0.32 ppb yr$^{-1}$
FIXEMIS 0.04±0.29 ppb yr$^{-1}$

$\text{r}^2 (\text{O}_3, T_{\text{max}}) = 0.32$
$\text{r}^2 (\text{OBS}, \text{AM3\_BASE}) = 0.67$
$\text{r}^2 (\text{OBS}, \text{AM3\_FIXEMIS}) = 0.30$

1988 with O$_3$ drydep*0.65

M. Lin et al., ACP, 2017
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 simulated trends may be consistent with observed trends (i.e., emission-driven component plus variability)
Wide range (-4 to +4 ppb/decade) in 20-year surface ozone trends solely due to climate variability

Summer (JJA) mean trends in CM3 sampled at Shenandoah NP, VA

Constructed from 181 20-year surface ozone trends in the 200-year GFDL CM3 Control_1990 simulation

see also Barnes et al., JGR, 2016
Influence of climate variability differs by region and season

Standard deviation of 20-year surface ozone trends in GFDL CM3 Control-1990 simulation

Excerpted from Fig. 6 of Barnes, Fiore, Horowitz, JGR, 2016
Climate variability can modulate WUS background ozone: Frequency of deep stratospheric intrusions over WUS tied to known mode of climate variability (La Niña)

- Tropical SST cooling typically peaks in winter

→ May offer a few months lead time to plan for an active stratospheric intrusion season (protect public health, identify exceptional events)

M. Lin et al., Nature Communications, 2015
Ozone relationship with temperature varies with jet latitude

GFDL CM3 RCP4.5*_WMGG (air pollutants at 2005 levels): Decadal averages

Correlation (MDA8, Tmax) in Summer

Arrows indicate change at a given location for 2006-2015 → 2086-2095

OLS Slope (MDA8, Tmax) in summer

→ Observed local O₃:T relationships may not hold if large-scale circulation shifts
→ Differences in simulated jet positions → model discrepancies in O₃ responses?

Barnes & Fiore, GRL, 2013
Projected air quality over the Southeast mainly follows declining precursor emission trajectories

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

**Figure 10 of Fiore, Naik, Leibensperger, JAWMA, 2015**
Doubling of global CH$_4$ abundance (RCP8.5) raises NE USA surface ozone in model (GFDL CM3); largest impact during winter.

- Doubling of methane increases surface O$_3$ background by 6-11 ppb.

Clifton et al., GRL, 2014
Continued NO\textsubscript{x} reductions prevent increases in surface ozone resulting from climate warming (Northeast U.S.A)

Regional mean number of days > 70 ppb in the Northeast U.S.
(GFDL CM3 model, 3 ensemble member average, land cells east of 100°W, north of 36°N)

**RCP8.5:** U.S. NO\textsubscript{x} declines, global methane doubles

**RCP8.5_WMGG:** GHGs rise; ozone precursor emissions (+ methane) held at 2005 levels

“Climate penalty”

Increase in springtime due to rising methane (+ summertime decrease from declining regional O\textsubscript{3} precursors)

H. Rieder et al., in prep.
Multi-model mean surface ozone change at the 87th percentile by 2100 (from 2000) due to climate change (RCP8.5) only

4 ACCMIP global chemistry-climate models with ozone precursor and aerosol emissions held at 2000 levels but climate changes (SSTs, sea ice)

Global mean surface temperature increases by ~4°

Schnell et al., GRL, 2016
PM$_{2.5}$ climate penalty under extreme warming scenario

Change in annual mean PM$_{2.5}$ from 2006-2015 to 2091-2100
Averaged over 3 ensemble members in GFDL CM3 with aerosols held fixed at 2005 levels (RCP8.5_2005Aer)

Westervelt et al., Atmos. Environ., 2016
A climate penalty on fine particulate matter over North America possible, depends on climate scenario

Historical emissions decrease due to controls

Aerosol emissions held constant at 2005 levels

Westervelt et al., Atmos. Environ., 2016
Recommendations from Air Quality and Climate Connections
(2015 AW&MA Critical Review)

• Improve accuracy and trends in past and future emission inventories to underpin accountability analyses

• 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

Fiore, Naik & Leibensperger, JAWMA, 2015
Some final thoughts on AQ response to climate change

- Continued NO\textsubscript{x} reductions guard against ‘climate penalty’ on warm season surface ozone
  → Should continue to be effective as NO\textsubscript{x} emissions further decline
  → PM climate penalty in some regions; less robust than ozone

- Climate variability can confound detection & attribution of air pollutant trends to changes in emissions
  → Evaluate: Does simulated trend range encompass observed trend?
  → Identify low-variability regions/seasons to guide deployment/interpretation of long-term monitoring networks
  → Can alter local pollution-met. relationships; same for climate change

- Need better constraints on regional feedbacks (climate-sensitive sources and sinks)
  → Wildfires, biogenic emissions, anthropogenic emissions
  → Strong sensitivity of surface ozone to dry deposition

- Could incur a ‘penalty’ from rising global methane
  → Amplifies reversal of seasonal cycle induced by NO\textsubscript{x} controls
Greenhouse Gases and Air Pollutant Emissions under “RCPs”

- Methane abundance (ppb)
- CO₂ abundance (ppm)
- Anthrop. SO₂ (Tg yr⁻¹)
- Anthrop. BC (Tg yr⁻¹)
- Anthrop. NO (Tg yr⁻¹)

Figures c/o V. Naik

Overly (?) optimistic 21st century decreases in global air pollutants
Ground-level O₃ is photochemically produced from regional sources (natural + anthrop.) that build on background levels of O₃. CH₄ + CO + NMVOC + NOₓ react in the presence of sunlight to form O₃. This process raises background ozone levels and fuels local-to-regional ozone pollution episodes.
Approach: Targeted sensitivity simulations in a chemistry-climate model to examine chemistry-climate interactions

Tool: GFDL CM3 chemistry-climate model
- ~2° x 2° horizontal resn.; 48 vertical levels
- Over 6000 years of climate simulations that include chemistry (air quality) in coupled atmosphere-ocean-sea ice model
- Options for nudging to re-analysis + global high-res ~50km² [Lin et al., 2012ab; 2014]

\[
\begin{align*}
\text{CH}_4 & + \text{CO} + \text{ NMVOC} + \text{NO}_x \rightarrow \text{O}_3 \\
\end{align*}
\]

Emission (CH$_4$ abundance) pathways prescribed
Biogenic emissions held constant
Lightning NO$_x$ source tied to model meteorology
O$_3$, (aerosols, etc.), affect simulated climate

Donner et al., J. Climate, 2011; Golaz et al., J. Climate, 2011; John et al., ACP, 2012
Turner et al., ACP, 2012
Levy et al., JGR, 2013
Naik et al., JGR, 2013
Barnes & Fiore, GRL, 2013…
Observed declines in EUS summertime surface $O_3$ following regional NO$_x$ reductions

Regional NO$_x$ reductions alleviated the $O_3$ buildup during the recent 2012 heat wave relative to earlier heat waves (e.g., 1988)
Reduced stomatal uptake under drought stress influences the highest ozone events

Model challenges in simulating such land-biosphere couplings (not represented in the Wesley scheme)
“The world avoided”: In absence of emission controls, 95th percentile summer MDA8 O3 would have increased in EUS

1990-2012 trend in the frequency of warm days (above the 90th percentile for 1961-1990 base)

1990-2012 trend in biogenic isoprene emissions

95th percentile MDA8 O3 trend in AM3_FIXEMIS

Larger circles indicate significant trends (p<0.05)