Characterizing and interpreting changes in U.S. climate and air pollution means and extremes

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Acknowledgments
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Air pollutants and their precursors contribute to climate forcing from preindustrial to present.

- Regulated in U.S.A. as precursors to ground-level O\textsubscript{3}.

**Anthropogenic greenhouse gases** methane + tropospheric ozone together contribute

~1/2 (abundance) to 2/3 (emissions) of CO\textsubscript{2} radiative forcing.

(Lifetimes must also be considered: CO\textsubscript{2} dominates long-term.)

Adapted by E. Leibensperger (SUNY Plattsburgh) from IPCC, 2013 for Fiore, Naik, Leibensperger, in press.
Ground-level $O_3$ is photochemically produced from regional sources (natural + anthrop.) that build on background levels.

Raise background ozone levels

$CH_4$  $CO$  $NMVOC$

Fuel local-to-regional ozone pollution episodes

$+ NO_x$  $O_3$
The U.S. ozone smog problem is spatially widespread

4th highest maximum daily 8-hr average (MDA8) $O_3$ in 2010


High-$O_3$ events typically occur in
-- densely populated areas (sources)
-- summer (favorable meteorology)

→ Lower threshold (65-70 ppb, Oct 2015) would expand non-attainment regions

Estimated benefits from a ~1 ppb decrease in surface $O_3$:
~ $1.4$ billion (agriculture, forestry, non-mortality health) within U.S. [West and Fiore, 2005]
~ 500-1000 avoided annual premature mortalities within N. America [Anenberg et al., 2009]
Implies that changes in climate (via regional air pollution meteorology) will influence air quality.

Models estimate a ‘climate change penalty’ (+2 to 8 ppb) on surface $O_3$ over U.S.; disagree in sign regionally (Wu et al. 2008; Weaver et al., 2009; Jacob and Winner, 2009; Fiore et al., 2012, in prep) but often use only a few years of meteorology from 1 realization of 1 GCM.
**NOx emissions affect the O3-temperature relationship**
[e.g., Bloomer et al., 2009; Rasmussen et al., 2012; Brown-Steiner et al., 2015]

Decline in O3 increase per degree temperature rise after implementing EUS NOx emission controls → Historical relationships may not hold in future (Meteorology may also change [Barnes & Fiore, 2013])

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

Fiore, Naik, Leibensperger, in press.
In polluted (high-NO$_x$) regions, surface O$_3$ typically peaks during summer (monthly averages at 3 NE USA measurement sites).

[Reidmiller et al., ACP, 2009]
Shifting surface ozone seasonal cycle evident in observations over NE USA

[Reidmiller et al., ACP, 2009]

→ Summer ozone decreases; shift towards broad spring-summer maximum following EUS NO_x controls (“NO_x SIP Call”)

O. Clifton
Characterizing observed ‘extreme’ ozone pollution events

Gaussian: Poor fit for extremes

EVT Approach: (Peak-over-threshold) for MDA8 $O_3 > 75$ ppb

→ Extreme Value Theory (EVT) methods describe the high tail of the observed ozone distribution (not true for Gaussian)

Rieder et al., ERL 2013
EVT methods enable derivation of probabilistic “return levels” for JJA MDA8 O$_3$ within a given “return period”

→ Sharp decline in return levels from 1988-1998 to 1999-2009; longer return periods for a given event (attributed to NO$_x$ emission controls)

→ Consistent with prior work [e.g., Frost et al., 2006; Bloomer et al., 2009, 2010]

→ New approach to translate air pollution changes into probabilistic language

Apply methods to 23 EUS CASTNet sites to derive 1-year return levels
→ Decreased by 2-16 ppb
→ Remain above 75 ppb
How and why might extreme climate and/or air pollution events change?

Need to understand how different processes influence the distribution

- Meteorology (e.g., stagnation vs. ventilation)
- Responses to meteorology (Emis, Chem, Dep)
- Changing global emissions (baseline)
  → Shift in mean?
- Changing regional emissions (episodes)
  → Change in symmetry?
Approach: Targeted sensitivity simulations in a chemistry-climate model to examine chemistry-climate interactions

Tool: GFDL CM3 chemistry-climate model
- ~2°x2° horizontal resn.; 48 vertical levels
- Over 6000 years of climate simulations that include chemistry (air quality)
- Options for nudging to re-analysis + global high-res ~50km² [Lin et al., 2012ab; 2014]


Emission (CH₄ abundance) pathways prescribed
Biogenic emissions held constant
Lightning NOₓ source tied to model meteorology
O₃, (aerosols, etc.), affect simulated climate
Approach: Historical + Future global change scenarios & targeted sensitivity simulations in GFDL CM3 CCM

**Scenarios** developed by CMIP5 [Taylor et al., BAMS, 2012] in support of IPCC AR5 [e.g., Cubasch et al., 2013; Ch 1 WG 1 IPCC (see Box 1.1)]

1. **Preindustrial control** (perpetual 1860 conditions >800 years)
2. **Historical** (1860-2005) [Lamarque et al., 2010]
   - All forcings (5 ensemble members) → evaluate with observations
   - Greenhouse gas only (3)
   - Aerosol only (3)

![Percentage change: 2005 to 2100](chart)

- **RCP8.5 (3)**
- **RCP4.5 (3)**
- **RCP8.5_WMGG (3)**
- **RCP4.5_WMGG (3)**
- **RCP8.5_2005CH4**

→ CMIP5/AR5 [van Vuuren, 2011; Lamarque et al., 2011; Meinshausen et al., 2011]

→ Isolate role of warming climate
→ Quantify role of rising CH$_4$ (vs. RCP8.5)
Structure of observed changes in monthly mean ozone captured by GFDL CM3 CCM (despite mean state bias)

Monthly averages across 3 NE USA sites

CM3 NE US shows summer O$_3$ decrease, small winter increase from ~25% decrease in NO$_x$ emissions (applied year-round)

[Reidmiller et al., ACP, 2009]

[see also EPA, 2014; Parrish et al., GRL, 2013 find shifts at remote sites]
“Climate penalty” on monthly mean NE USA surface O₃ as simulated with the GFDL CM3 model

- “Penalty” limited to increases during warmest months
- Extends into May and September in high warming scenario
- Fully offset by regional precursor emission reductions under RCPs

Clifton et al., GRL, 2014
Reversal of surface $O_3$ seasonal cycle occurs in model under scenarios with dramatic regional $NO_x$ reductions.

NE US 36-46N 80-70E

2005 to 2100 % change

2006-2015
2006-2015
2091-2100
2091-2100

RCP4.5
RCP8.5

Decreasing $NO_x$ emissions $\rightarrow$ lower summer $O_3$

3 ensemble members for each scenario

NE USA evolves from “polluted” to “background” over the 21st C

Reversal occurs after 2020s (not shown)

Clifton et al., GRL, 2014
Doubling of global CH$_4$ abundance (RCP8.5) raises NE USA surface ozone in model; largest impact during winter

Clifton et al., GRL, 2014
Under RCPs, NE USA high-O$_3$ summertime events decrease; beware ‘penalty’ from rising methane (via background O$_3$) "2006-2015 2016-2025 2026-2035 2036-2045 2046-2055 2056-2065 2066-2075 2076-2085 2086-2095"

- RCP8.5: Extreme warming
- RCP4.5: Moderate warming

H. Rieder

→ Rising CH$_4$ in RCP8.5 partially offsets O$_3$ decreases otherwise attained with regional NO$_x$ controls (RCP4.5)
GFDL CM3 generally captures NE US JJA surface $\text{O}_3$ decrease following $\text{NO}_x$ emission controls (-25% early 1990s to mid-2000s) following 

\> Implies bias correction based on present-day observations can be applied to scenarios with $\text{NO}_x$ changes (RCPs for 21st C) 
\> Focus on upper half of distribution

Rieder et al., JGR, 2015
Projected changes in high-ozone events: 1-year return levels (probability of MDA8 O₃ occurrence on 1/92 summer days, as estimated by CM3 chemistry-climate model (bias-corrected))

2006-2015 1-year return levels

1-year return levels over entire region fall during 21st C:
- below 70 ppb by 2030s
- below 60 ppb by 2060s

Rieder et al., JGR, 2015
Simple relationship between changes in regional NO\textsubscript{x} emissions and in regional average summer 1-year return levels

Rieder et al., JGR, 2015

GFDL CM3 Chemistry-Climate Model, RCP4.5

$R=0.99$

Change in 1-yr return level [ppb]

Change in NO\textsubscript{x} emissions [%]
Site-level Projections: Apply changes from chem-climate model at each percentile of the regional O$_3$ distribution to each site’s distribution

Average number of summer (JJA) days with MDA8 O$_3$ > 75 ppb at CASTNET sites

2001-2005

2046-2055, RCP8.5 from GFDL CM3

By mid-century under RCP8.5 scenario:
→ regional NO$_x$ emissions decrease by ~70%
→ 3 or fewer JJA days with MDA8 O$_3$ > 75 ppb

... but global methane doubles

Rieder et al., in prep
Summertime decreases at least partially offset by winter-spring increases (from methane [Clifton et al., GRL, 2014])

Change in 90th percentile MDA8 O₃ over Eastern U.S.A. in RCP8.5

Rieder et al., in prep
Climate forcing from air pollutants (aerosols) alters incidence of regional climate extremes, opposing GHG influence

Changes in summer (JJA) days above the 90th percentile daily maximum temperature from 1860-1890 to 1976-2006

Aerosol Only

Greenhouse Gas Only

\[ r = -0.72 \]

X = outside range of variability (95%) of differences between 30-year intervals in preind. control simulation Tx90p, see e.g., Sillman et al., JGR 2013ab; reference period 1961-1990

→ Aerosols mask GHG influence on extreme temperatures

→ Strongest response to forcing in the Western U.S.

→ Southeast U.S. warming/cooling hole collocated with observed warming hole (e.g. Meehl et al, 2012, Weaver et al, 2012, Leibensperger et al, 2012)

Mascioli et al., in prep
Changes in hydroclimate in the Southeast US contribute to warming/cooling hole

Changes in total summertime precipitation (mm) from 1860-1890 to 1976-2006

**Aerosol Only**

**Greenhouse Gas Only**

$X =$ outside range of variability (95%) of differences between 30-year intervals in preind. control simulation

$\rightarrow$ Aerosols decrease EUS summertime precipitation, most significantly in SE (‘cooling hole’)

$\rightarrow$ Greenhouse gases significantly increase SE summer precipitation, collocated with the ‘warming hole’

Mascioli et al., in prep
Aerosols and GHGs induce offsetting changes in winter precipitation extremes over the historical period

Changes in winter (DJF) 99th percentile precipitation, 1860-1890 to 1976-2006

Aerosol Only

Greenhouse Gas Only

X = outside range of variability (95%) of differences between 30-year intervals in preind. control simulation

→ Strongest wintertime responses in EUS

→ Spatial correlation does not persist in spring where GHGs dominate (no significant aerosol response)

Mascioli et al., in prep
Extreme temperatures become the new normal!
(high warming scenario, RCP8.5, GFDL CM3)

Change in summer days above the 90th percentile daily maximum temperature
1976-2006 to 2071-2100

→ 90th percentile temperature threshold exceeded over much of U.S.A.
  for half the summer
→ Amplified warming from aerosol removal leads to +8 to 12 days above
  the 90th percentile threshold

X = outside range of variability (95%) of differences between 30-year intervals in preind. control simulation

Mascioli et al., in prep
Co-occurrence of extremes:
Heat wave event with high $O_3$ and PM pollution

Health implications?

Fiore, Naik, Leibensperger, in press
Atmospheric Chemistry Group at LDEO/CU

On the roof of our building following mid-Dec 2013 snowfall
(missing from photo: Jean Guo; George Milly)
Characterizing and Interpreting changes in U.S. climate and air pollution means and extremes

- Rising CH$_4$ + decreasing NO$_x$ shift balance of regionally produced vs. transported O$_3$
  - Double ‘penalty’ on NE US O$_3$ from climate change + rising CH$_4$?
  - Simple relationship between emissions (NO$_x$) and extreme EUS O$_3$ events (1-year return levels)

- NO$_x$ reductions reverse the O$_3$ seasonal cycle over NE USA
  - Will NE US evolve to ‘background’ air quality over the 21$^{st}$ C?
  - CH$_4$ offsets some of gains attained via regional emission controls

- Application of extreme value theory methods to characterize pollution extremes
  - Translation to probabilistic language, ”1-year event”, useful for decadal planning?

- Detecting chemistry-climate interactions
  - Will (global) aerosol removal amplify the response of U.S. climate extremes to rising GHGs?
  - Extreme temperatures become the new normal?