Influence of Changes in Emissions and Climate on Background and Extreme Levels of Air Pollution

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Haze over Boston, MA
http://www.airnow.gov/index.cfm?action=particle_health.page1#3

High-$\text{O}_3$ events typically occur in
-- densely populated areas (local sources)
-- summer (favorable meteorological conditions)

→ Lower threshold would greatly expand non-attainment regions

4th highest maximum daily 8-hr average (MDA8) $\text{O}_3$ in 2010

Tropospheric O$_3$ formation & “Background” contributions

- **NO$_x$** + **NMVOCs**
- **CO**
- **METHANE (CH$_4$)**
- Intercontinental transport

**Stratosphere**

- Lightning
- “Background” ozone

**Natural sources**

**Human activity**

**Fires**

**Land biosphere**

**Ocean**

**Continent**
Historical increase in atmospheric methane and ozone (#2 and #3 greenhouse gases after carbon dioxide [IPCC, 2007])

**CH$_4$ Abundance (ppb) past 1000 years**

[Etheridge et al., 1998]

Preindustrial to present-day radiative forcing [Forster et al., (IPCC) 2007]:

+0.48 Wm$^{-2}$ from CH$_4$

+0.35 Wm$^{-2}$ from O$_3$

**Ozone at European mountain sites 1870-1990** [Marenco et al., 1994]
Benefits of ~25% decrease in global anthrop. CH$_4$ emissions

**OZONE AIR QUALITY**

From -20% global CH$_4$ abundance

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

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

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

**CLIMATE**

Global mean avoided warming in 2050 (°C) [WMO/UNEP, 2011]
Strong correlations between surface temperature and \( \text{O}_3 \) measurements 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

![Graph showing July mean MDA8 \( \text{O}_3 \) (ppb) over years 1990 to 2005 with temperature on the right side.]

What drives the observed \( \text{O}_3 \)-Temperature correlation?

1. Meteorology (e.g., air stagnation)
2. Feedbacks (Emis, Chem, Dep)

\[ \rightarrow \text{Implies that changes in climate will influence air quality} \]
How will surface O$_3$ distributions evolve with future changes in emissions and climate?

**Tool:** GFDL CM3 chemistry-climate model

- ~2°x2°; 48 levels
- Over 6000 years of climate simulations that include chemistry (air quality)
- Options for nudging to re-analysis + global high-res ~50km$^2$ [Lin et al., JGR, 2012ab]

**Climate / Emission Scenarios: Representative Concentration Pathways (RCPs)**

Percentage changes from 2005 to 2100

- RCP8.5
- RCP4.5
- RCP4.5_WMGG

- Global CO$_2$
- Global CH$_4$
- NE USA NO$_x$

- Enables separation of roles of changing climate from changing air pollutants

Global T (°C) (>500 hPa)
GFDL AM3 model captures key features of observed surface O₃ trends (1988-2012): larger decreases in 95% vs. 50% over EUS; increases in WUS.

CASTNet Observations
GFDL AM3 model

Larger circles indicate statistically significant trends ($P<0.05$)

Meiyun Lin, Princeton/GFDL
Regional climate change over the NE USA leads to higher summertime surface O$_3$ (“climate penalty” [Wu et al., JGR, 2008])

GFDL CM3 chemistry-climate model

Moderate climate change increases NE USA surface O$_3$ 1-4 ppb in JJA (agreement in sign for this region across prior modeling studies)

How does NE USA O$_3$ respond to changing regional and global emissions?

O. Clifton/H. Rieder
Large NO$_x$ decreases fully offset any ‘climate penalty’ on surface O$_3$ over NE USA under moderate warming scenario in the GFDL CM3 model.

Seasonal cycle reverses; NE US looks like a remote background site!

Signatures of changing emissions in observed shifts in seasonal cycles

[Parrish et al., GRL, 2013]?

O. Clifton
Surface $\text{O}_3$ seasonal cycle over NE USA reverses – cold season increases under extreme warming scenario (RCP8.5) in the GFDL CM3 model.

Monthly mean surface $\text{O}_3$ (land only) over the NE USA (36-46N, 70-80W) ppb month
Why does surface $O_3$ increase in winter/spring over NE USA under RCP8.5?

Change in monthly mean surface $O_3$ (land only) over the NE USA (36-46N, 70-80W) (2091-2100) – (2006-2015) ppb

$NO_x$ decreases

RCP8.5 (3 ensemble members)
Doubling methane raises surface $O_3$ over NE USA $\sim$5-10 ppb

Change in monthly mean surface $O_3$ (land only) over the NE USA (36-46N, 70-80W) (2091-2100) – (2006-2015)

Doubling $CH_4$ does not fully explain wintertime increase

RCP8.5 (3 ensemble members)
RCP8.5 but chemistry sees 2005 $CH_4$
A contribution from enhanced stratosphere-to-troposphere ozone transport?

Change in monthly mean surface $O_3$ (land only) over the NE USA (36-46N, 70-80W) (2091-2100) – (2006-2015)

ppb

RCP8.5 (3 ensemble members)
RCP8.5 but chemistry sees 2005 $CH_4$

Increase (2091-2100 – 2006-2015) in stratospheric $O_3$ tracer (qualitative indicator; caution: non-linearities!)

Recovery + climate-driven increase in STE? [e.g., Butchart et al., 2006; Hegglin&Shepherd, 2009; Kawase et al., 2011; Li et al., 2008; Shindell et al. 2006; Zeng et al., 2010]

Will the NE USA resemble present-day remote, high-altitude W US sites by 2100?
Extremes: The highest summertime surface $O_3$ events over NE USA decrease strongly under NO$_x$ controls

RCP8.5 vs. RCP4.5: Rising CH$_4$ increases surface $O_3$, at least partially offsetting gains otherwise attained via regional NO$_x$ controls.
Peak latitude of summertime surface $O_3$ variability over Eastern N. America follows the jet as climate warms

Barnes & Fiore, GRL, in press

Could different simulated jet positions explain cross-model disagreement in regional $O_3$ response to climate change?

RCP8.5: most warming, Largest jet shift
Influence of Changes in Emissions and Climate on Baseline and Extreme Levels of Air Pollution: Summary and Next Steps

- Methane controls: ‘win-win’ for climate, air quality; also economic
  - Climate and Clean Air Coalition (http://www.unep.org/ccac/)
  - Observational constraints on CH₄ oxidation (and resulting O₃)?

- Climate change may increase O₃ over NE USA but can be offset by NOₓ reductions which preferentially decrease the highest O₃ events
  - Other regions, seasons, with a focus on extremes
  - Develop robust connections to changes in meteorology

- NOₓ reductions combined with rising CH₄ & strat-to-trop O₃ transport fully reverse O₃ seasonal cycle over NE USA
  - Ongoing evaluation of key processes (recent decades)
  - Long-term measurements crucial [e.g., Parrish et al., 2013]

- Zonal O₃ variability aligns with the 500 hPa jet over NE N. America
- Jet shifts can influence O₃:T [Barnes & Fiore, in press GRL]
  - Decadal shifts in jet; hold on shorter timescales?
  - Explore predictive power and extend beyond O₃
  - Relevant to model differences in O₃ response to climate? [Weaver et al., 2009; Jacob & Winner, 2009; Fiore et al., 2012]