Global dimensions to ground-level ozone: Transboundary transport and climate change

Maximum Daily Average 8-hour (MDA8) Ozone
Jun 15, 2012

Concentration (ppb)

10 20 30 40 50 60 70 80 90

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Ground-level $O_3$ is photochemically produced from regional sources (natural + anthropogenic) that build on “baseline” levels.

- Raise baseline ozone levels
- Fuel local-to-regional ozone pollution episodes

Chemical reactions:

$$CH_4 + CO + NMVOC + NO_x \rightarrow O_3$$
Definition: Maximum Daily Average 8-hour (MDA8) Ozone

- The metric used to assess compliance with the ozone National Ambient Air Quality Standard (NAAQS)

- (Current formulation is a 3-year average of the 4th highest value in each of the 3 individual years)
In polluted regions, $O_3$ correlates with surface temperature on daily to inter-annual time scales [e.g., Bloomer et al., 2009; Camalier et al., 2007; Cardelino and Chameides, 1990; Clark and Karl, 1982; Korsog and Wolff, 1991]

Observations at a monitoring site in Pennsylvania

July mean MDA8 $O_3$ and July mean daily maximum temperature

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

JAWMA = Journal of the Air and Waste Management Association
What drives ozone-temperature correlations? (& Why would climate change influence ozone?)

- Meteorology (e.g., stagnation vs. ventilation)
  - Degree of mixing
  - Pollutant sources

- Feedbacks (Emissions, Chemistry, Deposition)

VOCs, NO\textsubscript{x}

\begin{center}
\includegraphics[width=\textwidth]{diagram.png}
\end{center}

Lowers O\textsubscript{3} over remote regions
Ozone is trending downward over this time period as NO\textsubscript{x} emission controls are implemented.

Observations at a monitoring site in Pennsylvania

July mean MDA8 O\textsubscript{3} and July mean daily maximum temperature

Figure 6a of Fiore, Naik, Leibensperger, JAWMA, 2015
Decreasing NO\textsubscript{x} emissions reduces sensitivity of O\textsubscript{3} to temperature
[e.g., Bloomer et al., 2009; Rasmussen et al., 2012; Brown-Steiner et al., 2015]

Observations at a monitoring site in Pennsylvania

![Graph showing the relationship between July mean MDA8 ozone (ppb) and July mean maximum daily temperature (°C) with two trend lines for different time periods: 1988-2001: 4.1 ppb/C and 2002-2014: 2.4 ppb/C.](image)

Figure 6b of Fiore, Naik, Leibensperger, JAWMA, 2015
Cleaner U.S. air is visible from space: Major changes over the last decade

Satellite (OMI) tropospheric NO$_2$ columns

2005

2014

$c/o$ Lok Lamsal & Bryan Duncan, NASA GSFC

Much more available at: airquality.gsfc.nasa.gov
“The world avoided”? In absence of emission controls, 95th percentile summer Eastern US MDA8 O₃ would have increased.

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

Trends in the GFDL AM3 model; Larger circles indicate significant trends (p<0.05)

MODEL WITH ALL EMISSIONS ON

MODEL WITH EMISSIONS HELD FIXED

Model trends in 90th percentile summertime daily max temperature

M. Lin et al., Atmospheric Chemistry & Physics, 2017
Models estimate a ‘climate change penalty’ on surface \( O_3 \) over U.S.A. but often disagree at regional scales (e.g. -2 to +9 ppb in summer over Midwest [Fiore et al., JAWMA, 2015, Table S3]).

“Climate Penalty” [Wu et al., JGR, 2008]:
Change in MDA8 by \( O_3 \) solely because of climate change

\[ (+1.6 \, ^\circ C \text{ global mean surface temp. 2000 } \rightarrow 2050) \]

\( \rightarrow \) Uncertain regional climate responses to global warming
\( \rightarrow \) Model estimates (until recently) based on a few years of present and future meteorology from 1 realization of 1 climate model

JGR = Journal of Geographic Research
Uncertainty in surface ozone projections from climate (internal) variability

Summertime U.S. temperature trends in the warmest and coolest of 40 ensemble members (only atmosphere initial conditions differ) in a single model

→ Ozone projections are tied to temperature projections
→ Using a few years from 1 simulation with 1 climate model is not sufficient to remove this "climate noise"; need to average over an ensemble to reveal "forced" climate signal

Deser et al., NCC, 2012 (excerpts from their Figure 2)
NCAR CCSM3 model, A1B scenario

NCC = Nature Climate Change
• Continued NO\textsubscript{x} reductions guard against ‘climate penalty’ on warm season surface ozone

• Climate change tends to increase ozone in polluted regions
Definitions

Baseline Ozone
A measureable quantity. Ozone observed at remote sites with little influence from recent U.S. anthropogenic emissions

Background Ozone
A model construct. Ozone originating from any natural sources or during methane oxidation, plus ozone produced by anthropogenic sources outside of the nation or continent*

*See next slides for more specific definitions
“U.S. Background Ozone” = USB

NO_x + NMVOCs + CO → global methane

U.S. Background ozone

International transport

Stratosphere lightning

Natural NO_x, NMVOC

Human activity

Biosphere, Fires

Foreign Nations

Ocean

Biosphere, Fires

U.S.A.
“North American Background Ozone” = NAB

- **Foreign Continents**
  - NMVOCs
  - CONOx + O3
  - Lightning
  - Intercontinental transport

- **Biosphere, Fires**
  - Natural NOx, NMVOC
  - Fires
  - Biosphere

- **Human activity**
  - CO
  - Global methane

- **Ocean**

-Fiore et al., EM, 2014
Total O$_3$ in surface air over North America = "NAB (N. Amer. Background)" + Anthropogenic regional O$_3$

- **Human activity**
- **Foreign Continents**
- **Biosphere, Fires**
- **Ocean**
- **North America**
We need to be able to describe the sources that contribute to each exceedance day.

adapted from T. Keating, U.S. EPA
Estimates for seasonal mean USB ozone:

- 20-40 ppb at low elevation sites
- > 50 ppb at high altitude WUS sites
- ± 10 ppb uncertainty

Jaffe et al., *Elementa*, 2018
Model estimated NAB annual 4th highest MDA8 ozone usually lower than observed (total) ozone (2010-2014 averages)

4th highest USB ozone > 60 ppb at some high altitude sites (large uncertainty)

Figure 3 of Jaffe et al., 2018
North American Background estimates differ across models
(4th highest MDA8 ozone; Mar 1 to Aug 31, 2006)

MODEL 1 (GFDL AM3; ~2° x 2° )

MODEL 2 (GEOS-Chem; ½° x ⅔° )

Surface ozone in simulations with N. American anthrop. emissions set to zero

Fiore et al., Atmospheric Environment, 2014
Wide range in model estimates of individual background sources, in part because these sources vary strongly in space and time

Lin et al., JGR, 2012; Fiore et al., EM, 2014

Ozone (ppb)

FIRES

STRATOSPHERE

ASIA

Poor understanding of ozone produced from fires

Stratospheric influence is highest in spring, early summer at high-altitude (Western US)

Asian pollution may “push” a region over the NAAQS level (but not by itself!)

Lin et al., JGR, 2012; Fiore et al., EM, 2014
Upwind international emissions are changing rapidly: 2005 → 2014 changes in satellite NO₂ columns over China

- Beijing: -10%
- Dalian: +40%
- Guangzhou: -40%

Duncan et al., JGR, Fig. 9, 2016
• Continued NO\textsubscript{x} reductions guard against ‘climate penalty’ on warm season surface ozone

• Climate change tends to increase ozone in polluted regions

• U.S. background ozone varies in space and time
  ➔ Highest at high-altitude Western US where stratospheric and transboundary transport are usually max (spring-early summer); see also Atmos. Chem. Phys. HTAP/MICS/AQMEII special issue
Background drives much of day-to-day variability in total surface ozone over high-altitude Western US in two models.

MODEL 1 (GFDL AM3; ~2° × 2°)

MODEL 2 (GEOS-Chem; ½° × ¾°)

Correlation coefficient (r) of simulated TOTAL & NAB MDA8 ozone in surface air; models are sampled at CASTNet sites.

Fiore et al., Atm. Env., 2014
Top 10 observed MDA8 days in summer are enhanced by regional production, not transboundary transport

2004-2012 average on top 10 observed MDA8 ozone days in summer (JJA)

2004-2012 average of all summer (JJA) days

Estimated with a series of 2004-2012 sensitivity simulations in the GEOS-Chem model (2°x2.5°), regional averages sampled at AQS monitors

Guo et al., ACPD, 2018
The GEOS-Chem model captures much of the year-to-year variability in the top 10 observed MDA8 days in summer.

2004-2012 simulations in the GEOS-Chem model (2°x2.5°); regional averages sampled at AQS monitors.

Despite bias, model captures “wiggles”.
Not much of a trend (only 9 years; yet NOx declined).
Correlated with temperature.

Model vs. observed: $r = 0.88$
Model vs. observed: $r = 0.96$

Guo et al., ACPD, 2018
In the model, ozone produced from U.S. anthropogenic emissions declines from 2004 → 2012 but USB rises

Regionally averaged on the highest 10 observed MDA8 days during summer (JJA)

Estimated with a series of 2004-2012 sensitivity simulations in the GEOS-Chem model (2°×2.5°), regional averages sampled at AQS monitors

Guo et al., ACPD, 2018
Warmer regional climate may raise USB ozone by enhancing temperature-sensitive biogenic VOC and NO$_x$ emissions

Regionally averaged on the highest 10 observed MDA8 days during summer (JJA)

Estimated with a series of 2004-2012 sensitivity simulations in the GEOS-Chem model (2°x2.5°), regional averages sampled at AQS monitors

Guo et al., ACPD, 2018
Summary #3

• Continued NO\textsubscript{x} reductions guard against ‘climate penalty’ on warm season surface ozone

• Climate change tends to increase ozone in polluted regions
  → May raise “natural” background

• U.S. background ozone varies in space and time
  → Highest at high-altitude WUS where stratospheric and transboundary transport are usually max (spring-early summer); ACP special issue (HTAP/MICS/AQMEII)

• “Top 10” events enhanced by regional ozone production, not transboundary transport
  → Meteorology + weather-sensitive emissions, chemistry, deposition
What might the future hold? Up first: Model Evaluation

OVER THE INTERMOUNTAIN WEST:
Model vs. observed decadal mean seasonal cycle

Mean bias: +4.1 ppb; r = 0.72

Clifton et al., Geophysical Research Letters, 2014
A chemistry-climate model projects 21\textsuperscript{st} Century WUS ozone increase in cooler months despite U.S. NO\textsubscript{x} decreases.

**EMISSION PROJECTIONS (RCP8.5)**

2005 to 2100 (% change)

- CO\textsubscript{2}
- CH\textsubscript{4}
- Global NO\textsubscript{x}
- USA NO\textsubscript{x}
- WUS NO\textsubscript{x}

**MONTHLY MEAN OZONE (ppb)**

GFDL CM3 chemistry-climate model over the high-altitude WUS

2006-2015
2091-2100

GRL = Geophysical Research Letters

Clifton et al., GRL, 2014
Over the high-altitude WUS, cool season ozone increases as global methane rises

EMISSION PROJECTIONS (RCP8.5)

2005 to 2100 (% change)

MONTHLY MEAN OZONE (ppb)

In the warm season, more-than-doubling of global methane offsets NO\textsubscript{x}-driven decreases

Clifton et al., GRL, 2014
Climate change (rising global mean surface temperature) tends to increase ozone pollution but decrease background.

Change in summer (JJA) MDA8 surface ozone from 2010s → 2050s

+1.5 °C Global mean surface temperature (RCP8.5 scenario)

Estimated with the GFDL AM3 model

Dan Westervelt, LDEO
Summary: Global dimensions to ground-level ozone: Transboundary transport and climate change

- Continued NO\textsubscript{x} reductions guard against ‘climate penalty’ on warm season surface ozone
  → May incur additional “penalty” from rising global methane

- Climate change tends to increase ozone in polluted regions
  → May raise “natural” background, lowers transported background
  → How will the biosphere respond? (source, but also a key sink!)

- U.S. background ozone varies in space and time
  → Highest at high-altitude WUS where stratospheric and transboundary transport are usually max (spring-early summer); ACP special issue (HTAP/MICS/AQMEII)

- “Top 10” events enhanced by regional ozone production, not transboundary transport
  → Meteorology + weather-sensitive emissions, chemistry, deposition

→ Advance process-level understanding (daily to multi-decadal time scales)
→ Systematic uncertainty assessments (error-vs-variability; see Jaffe et al., 2018)