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Major challenges for western U.S. air quality management

MAJOR CHALLENGES:
(1) Deep stratospheric intrusion events in spring
(2) Rising Asian emissions and global CH₄
(3) More frequent wildfires in summer
(4) Warming climate

→ NEED PROCESS-LEVEL UNDERSTANDING ON DAILY TO MULTI-DECADAL TIME SCALES
Today’s presentation

- Stratospheric versus Asian influences on springtime high-$O_3$ events over the WUS

- How does interannual variability of meteorology modulate transport pathways of Asian pollution and stratospheric intrusions?

- Long-term trends of ozone in US surface air and aloft
  - Reconciling observations and models
  - Roles of rising Asian emissions versus US domestic controls

- To what extent wildfire emissions contribute to WUS summertime $O_3$ variability?

- Summary of policy-relevant messages
Asian and stratospheric influences on springtime high-O$_3$ events at IMW sites

Lin et al. (JGR, 2012a, 2012b)
Why does ozone measured at Lassen California show a leveling-off trend in the 2000s?

\[ O_3 = a + bt + ct^2 \]
A poleward shift in transport pathways of Asian pollution in the 2000s plays a role.

NASA AIRS CO (500 hPa, March-April)

Mauna Loa (Lin et al., Nature Geosci., 2014)

Following a La Niña winter, more frequent stratospheric intrusions reaching IMW sites in spring

1999 (La Niña) →

2011 (La Niña) →

→ Potential for developing seasonal prediction [Lin et al., Nature Commun., 2015]
Year-to-year variability in springtime high-O$_3$ events over WUS tied to stratospheric influence

- Large IAV due to STT can confound attribution of observed O$_3$ trends calculated over short record length

Lin et al., Nature Communications, 2015
Figure 1 of Lin et al. (ACP, 2017): Emission data from Lamarque et al. (2010, 2012); Satellite (GOME/SCIAMACHY) data from KNMI (www.temis.nl)
Baseline $O_3$ trends derived from observations and free-running chemistry-climate models differ by a factor of 2 (Parrish et al., 2014)

These discrepancies reflect a combination of factors:
1. Internal climate variability (Lin et al., 2014; 2015a; Barnes et al., 2016)
2. Measurement sampling biases (Lin et al., 2015b)
3. Model difficulty resolving observed remote baseline conditions (Lin et al., 2017)
Influence of measurement sampling biases

Western N. American FT (3-8 km altitude)

$\text{Ozone Anomaly (ppb)}$

<table>
<thead>
<tr>
<th>Year (April-May)</th>
<th>1995-2008 (ppb yr$^{-1}$)</th>
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<tbody>
<tr>
<td>BASE co-sampled</td>
<td>0.64 ± 0.31 (p&lt;0.01)</td>
</tr>
<tr>
<td>BASE true average</td>
<td>0.75 ± 0.38 (p&lt;0.01)</td>
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<tr>
<td>OBS [Cooper2010, Nature]</td>
<td>0.25 ± 0.32 (p=0.12)</td>
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$\text{O}^2(\text{OBS, AM3}) = 0.74$

$\text{O}^2(\text{OBS, AM3}) = 0.45$

Nudged to “real” winds

→ 15-year trends driven by internal climate variability can be as large as emission-driven trends.
→ Even with co-sampling, free-running CCMs are not expected to reproduce the trends.

Lin, M.; Horowitz, LW; Cooper, OR et al. [GRL, 2015]
Model baseline sampling approach for evaluating O₃ trends at IMW sites

Within a ~200x200 km² model grid cell

Baseline (Lassen)

Pollution

Observed spring MDA8 O₃ trend 1988-2014

Larger circles indicate significant trends (p<0.05)

AM3_BASE surface

AM3_BASE 700 hPa, filtered

Lin, M., Horowitz L.W., Payton, R., Fiore, A.M., Tonnesen, T. [ACP, 2017]
Median springtime MDA8 O$_3$ trends at Great Basin NP

Most of the observed variability reflect changes in the background

The effects of US NO$_x$ controls (BASE minus NAB) are $< 0.1$ ppb yr$^{-1}$

See Figure 13 of Lin et al. (ACP, 2017) for additional analysis for other sites
SPRING US surface MDA8 O₃ trends over 1988-2014

Figure 7 from Lin et al. [ACP, 2017]
SPRING US surface MDA8 O₃ trends over 1988-2014

Background

FIXEMIS

Small circles indicate insignificant trends (p>0.05)

Decreasing  ppb yr⁻¹  Increasing

-0.8  -0.6  -0.4  -0.2  0.0  0.2  0.4  0.6  0.8

Figure 10 from Lin et al. [ACP, 2017]
SUMMER US surface MDA8 O$_3$ trends over 1988-2014

Figures 8 and 11 from Lin et al. [ACP, 2017]
Summarizing drivers of decadal mean O$_3$ changes from 1981-1990 to 2003-2012 over WUS

Delta O$_3$ [ppb]


- BASE
- Background
- Meteorology
- Asian (~50%)
- CH$_4$ (~15%)
- Wildfires
  (6% in spring; 12% in summer)

Figure 20 from Lin et al. [ACP, 2017]
Wildfires: NOT the primary driver of summer O$_3$ IAV over WUS?

**Yellowstone NP (AUG)**

- **FIXEMIS**: $0.04 \pm 0.13$ ppb yr$^{-1}$, $r(OBS, FIXEMIS) = 0.67$
- **IAVFIRE**: $0.15 \pm 0.15$ ppb yr$^{-1}$, $r(OBS, IAVFIRE) = 0.75$

**Interannual correlations (YEL O$_3$, $T_{\text{max}}$)**

- Hot and dry summers:
  - deeper PBLH allowing more O$_3$ to mix down to the surface (see also Zhang et al., 2014)
  - The buildup of O$_3$ produced from regional anthropogenic emissions (e.g., Denver / Rocky Mountain NP)

**Figs 15 and 16 from Lin et al. [ACP, 2017]**
Summertime $O_3$ in Denver correlates with temperature

**Fig. 17c from Lin et al. [ACP, 2017]**

- Role of VOCs from fires + urban $NO_x$ (Jaffe & Wigder, 2012; Baker et al., 2016)?
- The 2017 Fires, Asian and Stratospheric Transport – Las Vegas Ozone Study → Funded by Clark County (Zheng Li)
  → NOAA ESRL measurement team (A.O. Langford) + NASA AJAX?
  → GFDL-AM4 and GEOS-Chem modeling (PI: Meiyun Lin; now hiring post-doc)
### Some final policy-relevant messages

| Stratospheric intrusions | - can episodically increase surface MDA8 $O_3$ by 20-40 ppb above the baseline level (~20 ppb)  
  - The key driver of observed year-to-year variability in springtime high-$O_3$ events >70 ppb |
|-------------------------|-------------------------------------------------------------------------------------------------|
| Asian pollution         | - contributes ~5 ppb to mean WUS $O_3$ background in spring  
  - The key driver of multi-decadal WUS background $O_3$ increases (~65%; 0.2 ppb/yr) |
| Rising global methane   | - contributes 15% of the WUS background $O_3$ increase |
| Wildfires               | - can enhance monthly mean MDA8 $O_3$ at individual sites by 2-8 ppb in some summers  
  - but not the primary driver of observed $O_3$ year-to-year variability at rural sites |
| More frequent hot extremes & rising BVOC emissions | - contribute to raising background $O_3$ over EUS  
  - would have worsened the highest $O_3$ events over EUS if NO$_x$ emissions had not declined |
Additional Slides for Q & A Discussions
Springtime ozone observed in Denver has increased at a rate similar to remote rural sites.
Projections of near-term changes in WUS lower trop. ozone in spring (March-April-May)

Figure 14 from Lin et al. [ACP, 2017]
SUMMER US surface $O_3$ trends over 1988-2014

Figures 4 and 8 from Lin et al. [ACP, 2017]
Why does AM3 in Lin et al. (2012, 2015) show smaller biases than in Fiore et al. (2014)?

- Lin et al. focus on late spring (April to early June) when the model has better skills in representing deep mixed layers.
- Higher resolution (Lin et al. 2012a,b), greater skills in representing observations at high end.
- FIXEMIS simulation in Lin et al. (2015a) applies the 1970-2010 climatological mean emissions.
- Differences in wildfire emissions may also contribute.
Simulations of deep SI events in GFDL-AM3
(May 28, 2010 example)

- 0.5° model better captures vertical structure
- 2° model reproduces the large-scale view

Lin MY et al (JGR, 2012b): Springtime high surface ozone events over the WUS …
GFDL-AM3 model captures observed deep stratospheric intrusions over WUS

S. California (May 23, 2010)

Lidar (Langford)

Altitude (km)

O\textsubscript{3} Strat

GFDL-AM3

Flight track

[ppb]

30
60
90
120
150

Surface O\textsubscript{3} (ppb), MDA8

New Standard OBS, AM3

Background (zero out US anthrop. emissions)

May 24

May/24/2010

May 24

O\textsubscript{3} Strat

O\textsubscript{3} Strat

May/13/2010

Jun/1/2010

Lin M.Y. et al (JGR, 2012b), Springtime high surface ozone events over the WUS: Quantifying the role of stratospheric intrusions
Observed changes in surface $O_3$ distribution, particularly in the upper tail

Neutral: $\mu = 56.5, \sigma = 7.5$
El Niño (1998, 2010): $\mu = 56.9, \sigma = 7.3$
La Niña (1999, 2008, 2011): $\mu = 58.5, \sigma = 7.9$
Pinatubo (1992, 1993): $\mu = 54.3, \sigma = 6.5$

Observed daily max 8-h average $O_3$ [ppbv], Apr-May

- Little change in WUS surface air during El Niño despite increased UTLS $O_3$ burdens reported previously [e.g. Langford1998; Bronnimann2004; Neu2014].

Statistical testing

Inset: KS tests, $P<0.05$
Surface O$_3$ distribution in high vs low background springs

Meiyun Lin et al. (Nature Communications, 2015)
GFDL-AM3 captures interannual variability of O$_3$ anomalies associated with high temperatures.

Penn State University

\[ \text{R}^2 (\text{OBS, AM3_BASE}) = 0.67 \]
\[ \text{R}^2 (\text{OBS, AM3_FIXEMIS}) = 0.30 \]

\( \Delta O_3 \) (ppb)

\( \Delta T_{\text{max}} \) (K)

- But O$_3$ deposition sink to vegetation must be reduced by 35% to match the observed anomaly during the severe drought of 1988.

Meiyun Lin et al. [ACP, 2017]
Influence of droughts on ozone removal

- Reduced stomatal uptake under drought stress
- Influence the highest ozone events
- Model challenges in simulating such land-biosphere couplings (not represented in the Wesley scheme)

Meiyun Lin et al. [ACP, 2017]
If NOx emissions had not declined, more frequent hot extremes since 1990 would have worsened the highest O₃ events over 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)

Meiyun Lin et al. [ACP, 2017]