Seattle, Aug. 21, 2018.

PM$_{2.5}$ = 110 ug/m$^3$, highest PM$_{2.5}$ ever measured in Seattle
Wildfire and prescribed burning impacts on air quality in the United States

Daniel A. Jaffe\textsuperscript{a}, Susan M. O’Neill\textsuperscript{b}, Narasimhan K. Larkin\textsuperscript{b}, Amara L. Holder\textsuperscript{c}, David L. Peterson\textsuperscript{d}, Jessica E. Halofsky\textsuperscript{d}, and Ana G. Rappold\textsuperscript{e}

• Dan Jaffe: UW Bothell, School of STEM and UW Seattle, Dept of Atmospheric Sciences. (air quality impacts and atmospheric chemistry of smoke)
• Susan O’Neill and Sim Larkin, U.S. Forest Service, Pacific North West Research Station (monitoring and modeling of smoke, use of satellite data)
• Amara Holder, U.S. Environmental Protection Agency, Office of Research and Development (smoke emissions and emission inventories).
• Dave Peterson and Jessica Halofsky: UW Seattle, School of Environmental and Forest Sciences (forest health, patterns and trends in fires)
• Ana Rappold: U.S. Environmental Protection Agency, National Health and Environmental Effects Research Lab (health effects of smoke).

Thanks to all coauthors and AWMA Critical Review committee!
Outline of presentation

Part I: Dan Jaffe
• Patterns and trends in fires in the US.
• Causes of wildland fires. (lightning, humans, arson, prescribed and agricultural).
• Role of climate change.
• Emissions (fuels, combustion conditions, variability, prescribed vs wildfires).
• Atmospheric chemistry of smoke.
• Air quality impacts in urban areas (PM, O₃, etc).
  • *******

Part II: Susan O’Neill
• Monitoring smoke from ground networks and satellites.
• Modeling smoke transport and impacts.
• Health impacts from smoke.
• Smoke-ready communities.
• Regulatory impacts
  **********************

• Dan: Recommendations
Trend is driven by a small number of fires that grow to very large size (Dennison et al 2014).
Causes of wildland fires (NIFC data)

Ignition source:
• Humans (~80% by number, 45% by area)
  – Vehicles or industrial machinery
  – Campfires, fireworks
  – Electrical transmission lines
  – Arson
• Lightning (~20% by number, 55% by area)

Contributing factors:
• Past fire suppression causing fuel accumulation
• Climate change
  – Warmer temps
  – Droughts
  – Increased lightning
Humans responsible for 84% of wildland fires (by number) or 44% (by area)
Role of Climate change

Annual area burned (y-axis) for Western U.S. vs normalized fuel aridity. (Abatzoglou and Williams 2016).

Annual area burned (y-axis, log scale) for California vs average daily max temp. (Williams et al 2019).
Emissions

Pole Creek Fire, Sept 2012 from Mt. Bachelor
Photo by Honglian Gao, UW Bothell
Emissions (Wolverine Ridge fire, my photo)

- CO₂
- Primary aerosols (largely Organic compounds)
- Volatile Organic Compounds (VOCs = gas phase)
- Oxygenated-VOCs (e.g., CH₂OH; CH₃COCH₃, CH₃CHO, etc)
- CO, NOₓ (NO + NO₂), NH₃, HONO, etc
Emissions depend on combustion conditions

<table>
<thead>
<tr>
<th>Smoldering</th>
<th>Flaming</th>
</tr>
</thead>
<tbody>
<tr>
<td>More VOCs</td>
<td>Lower VOCs</td>
</tr>
<tr>
<td>Less Black carbon</td>
<td>More Black Carbon</td>
</tr>
<tr>
<td>Less NOx</td>
<td>More NOx</td>
</tr>
<tr>
<td>More NH(_3)</td>
<td>Less NH(_3)</td>
</tr>
<tr>
<td>More primary PM</td>
<td>Less primary PM</td>
</tr>
</tbody>
</table>
### 100s of Different VOCs are Emitted by Wildfires

<table>
<thead>
<tr>
<th>Acetylene (C2H2)</th>
<th>i-Pentane (C5H12)</th>
<th>trans-2-Butene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzene (C6H6)</td>
<td>Isoprene (C5H8)</td>
<td>trans-2-Pentene</td>
</tr>
<tr>
<td>cis-2-Butene (C4H8)</td>
<td>Methane (CH4)</td>
<td>Xylenes (C8H10)</td>
</tr>
<tr>
<td>cis-2-Pentene (C5H10)</td>
<td>n-Butane (C4H10)</td>
<td>Ethanol</td>
</tr>
<tr>
<td>Cyclopentane (C5H10)</td>
<td>n-Hexane (C6H14)</td>
<td>Methanol</td>
</tr>
<tr>
<td>Ethane (C2H6)</td>
<td>n-Pentane (C5H12)</td>
<td>Phenol</td>
</tr>
<tr>
<td>Ethylbenzene (C8H10)</td>
<td>n-Propylbenzene (C9H12)</td>
<td>Formaldehyde</td>
</tr>
<tr>
<td>Ethylene (C2H4)</td>
<td>Propadiene (C3H4)</td>
<td>Acetaldehyde</td>
</tr>
<tr>
<td>Heptane (C7H16)</td>
<td>Propane (C3H8)</td>
<td>Methy vinyl ethere</td>
</tr>
<tr>
<td>i-Butane (C4H10)</td>
<td>Propylene (C3H6)</td>
<td>n-Propyl Nitrate</td>
</tr>
<tr>
<td>i-Butene (C4H8)</td>
<td>Propyne (C3H4)</td>
<td>i-Propyl Nitrate</td>
</tr>
<tr>
<td></td>
<td>Toluene (C6H5CH3)</td>
<td>2-Butyl Nitrate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>And many more!</td>
</tr>
</tbody>
</table>

**These have a range in volatility and reactivity.**

Akagi et al 2011
Emission factors (EF)

\[ \text{EF}_X = F_c \times \frac{\Delta X}{\Delta CO_2} \times C \]

**EF** = Emission factor in grams/kg fuel burned.

**F_c** = Fraction of carbon in fuel.

\( \frac{\Delta X}{\Delta CO_2} \) = Normalized enhancement ratio observations near fire.

**C** = Conversion factor to get units right.
Emission factors in SERA database

https://depts.washington.edu/nwfire/sera/

• Prichard et al 2020
Example EFs in SERA database (grams/kg biomass consumed)

<table>
<thead>
<tr>
<th>Compound</th>
<th>Avg</th>
<th>Max</th>
<th>Min</th>
<th>SD</th>
<th>RSD %</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>99.0</td>
<td>302.</td>
<td>2.8</td>
<td>49.5</td>
<td>50.0</td>
<td>493</td>
</tr>
<tr>
<td>PM$_{2.5}$</td>
<td>22.5</td>
<td>90.</td>
<td>2.1</td>
<td>17.0</td>
<td>75.6</td>
<td>252</td>
</tr>
<tr>
<td>Partic. Organic Carbon</td>
<td>18.3</td>
<td>137.</td>
<td>0.2</td>
<td>28.4</td>
<td>155.</td>
<td>54</td>
</tr>
<tr>
<td>NOx</td>
<td>3.0</td>
<td>11.3</td>
<td>0.0</td>
<td>2.1</td>
<td>70.2</td>
<td>97</td>
</tr>
<tr>
<td>H$_2$CO (Formaldehyde)</td>
<td>1.6</td>
<td>4.8</td>
<td>0.1</td>
<td>0.9</td>
<td>58.6</td>
<td>194</td>
</tr>
<tr>
<td>CH$_3$COOH (Acetic acid)</td>
<td>2.1</td>
<td>9.3</td>
<td>0.2</td>
<td>1.8</td>
<td>86.7</td>
<td>139</td>
</tr>
<tr>
<td>C$_3$H$_7$NO$_3$ (Isopropyl nitrate)</td>
<td>4.6</td>
<td>5.8</td>
<td>3.3</td>
<td>1.8</td>
<td>39.1</td>
<td>2</td>
</tr>
</tbody>
</table>

- Large range in EFs due to fuels, burning conditions, meteorology, etc.
- While some compounds have many EF observations others very few.
- Large fraction of PM$_{2.5}$ is organic.
Largest area burned is in the South and Southeast US, but relatively few ER observations. Most of this is prescribed or agricultural burning.
Prescribed fires

• Reduce fuel load.
• Improve ecosystem health.
• Remove crop residue or other agricultural fires.
• Most states require smoke management plan.

Photo courtesy of Texas A+M University
## 2017 Largest state emissions from Prescribed and Wild fires

<table>
<thead>
<tr>
<th>State</th>
<th>Annual Area Burned (ha)</th>
<th>Peak Month</th>
<th>Peak month-Area Burned (ha)</th>
<th>Peak month-PM$_{2.5}$ Emitted (tons)</th>
<th>Peak Month – Largest observed Daily PM$_{2.5}$ (µg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wildfires:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CA</td>
<td>641,440</td>
<td>Oct.</td>
<td>151,492</td>
<td>106,657</td>
<td>215</td>
</tr>
<tr>
<td>Prescribed fires:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TX</td>
<td>632,470</td>
<td>Feb.</td>
<td>143,468</td>
<td>12,807</td>
<td>29</td>
</tr>
</tbody>
</table>

Data from EPA National Emission Inventory for 2017.
“Seeley Lake residents urged to leave due to wildfire smoke”

“Probably the worse smoke event in U.S. history” Sarah Coefield

“ER visits more than doubled in Missoula”

Seattle Is Choking on a Cloak of Wildfire Smoke
DAVID KROMAN AUG 21, 2018

For the third summer in a row, the Pacific Northwest city is blanketed in air pollution from massive wildfires nearby. This is the worst year yet.

Montana residents are desperate for clean air, and they're calling me

“STAY INSIDE, CALIFORNIANS: WILDFIRE SMOKE IS A BIG HEALTH RISK

Wildfire Smoke Makes Seattle and Portland World’s Dirtiest Cities

Seattle, WA

Seattle, WA

Fallout from Camp Fire: Air quality in Bay Area at dangerous levels

Smoke-Filled Snapshot: California Wildfire Generates Dangerous Air Quality For Millions
Wildfires are causing extreme PM$_{2.5}$ and O$_3$ in the W. US

<table>
<thead>
<tr>
<th>Location</th>
<th>Extreme PM$_{2.5}$ events (selected cases)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seeley Lake, MT</td>
<td>Highest daily PM$<em>{2.5}$ on record in the US (642 µg/m$^3$ on 9/6/2017). In August and September 2017, there were 35 days with PM$</em>{2.5}$ &gt; 150 µg/m$^3$ and 18 days with PM$_{2.5}$ &gt; 250 µg/m$^3$.</td>
</tr>
<tr>
<td>Ventura, CA</td>
<td>Extremely high PM$_{2.5}$ (557 µg/m$^3$) measured on 12/6/2017, with a two-week average concentration of 165 µg/m$^3$.</td>
</tr>
<tr>
<td>San Francisco, CA</td>
<td>Highest daily PM$_{2.5}$ ever recorded in San Francisco (177 µg/m$^3$ on 11/16/2018).</td>
</tr>
<tr>
<td>Seattle, WA</td>
<td>Highest daily PM$_{2.5}$ ever recorded in Seattle (110 µg/m$^3$ on 8/21/2018).</td>
</tr>
<tr>
<td>Medford, OR</td>
<td>Eight days over 100 µg/m$^3$ in 2017, with highest daily PM$_{2.5}$ of 268 µg/m$^3$ on 9/6/2017.</td>
</tr>
<tr>
<td>Enumclaw, Issaquah and North Bend, WA</td>
<td>Highest O$_3$ in the last 10 years during August 2017 smoke events with 8-hour max of 90-103 ppb (MDA8) over multiple days.</td>
</tr>
<tr>
<td>Portland, OR</td>
<td>Highest O$_3$ in the last 20 years during August 2017 smoke events with MDA8 values of 90-116 ppb over multiple days.</td>
</tr>
<tr>
<td>Sacramento, CA</td>
<td>Highest O$_3$ in the last 10 years during August 2018 smokes events with MDA8 values of 90-115 ppb over multiple days.</td>
</tr>
</tbody>
</table>

This is a selection of extremely high days, there are many more examples.

Laing and Jaffe, EM, June 2019.

No smoke days:
- Average MDA8 = 36 ppb
- Fraction of days that have MDA8 > 70 ppb = 0.4%

Smoke days:
- Average MDA8 = 51 ppb.
- Fraction of days that have MDA8 > 70 ppb = 10.1%.
- Smoke days are 40% of all days with MDA8>70
- Using a machine learning algorithm, we find that smoke contributes about 8 ppb, on average, to the MDA8, but with lots of variability (Gao et al 2020).
Complications of $O_3$ production in smoke

- Role of transport time and PM levels (McClure et al. 2018; Buysse et al. 2019);
- Role of UV Photolysis (Baylon et al. 2018; Alvarado et al. 2015).
- Role of Temperature (Gao et al. 2020).
- Use of machine learning to predict $O_3$ MDA8 in smoke (Gong et al. 2017; Gao et al. 2020)

Chemical evolution of smoke: Camp Fire, Nov. 10, 2018

24-hour HYSPLIT trajectories initialized at three heights over fire location.
Smoke transported to Bay area in 12-24 hours.

Smoke transport from Camp Fire shown with MODIS true color imagery.
Increasing aerosol O/C ratio in smoke plumes with aging

Observations during BBOP campaign from DOE-ARM G-1 aircraft and at Mt. Bachelor (Collier et al 2016)
**Chemical evolution of smoke**

<table>
<thead>
<tr>
<th>Particulate phase:</th>
<th>Gas phase:</th>
</tr>
</thead>
<tbody>
<tr>
<td>➢ Oxidation of VOCs to yield secondary organic aerosols (SOA).</td>
<td>➢ Gas-particle exchange (e.g. NH$_3$↔NH$_4^+$)</td>
</tr>
<tr>
<td>➢ Evaporation of semi-volatiles in more dilute environments.</td>
<td>➢ NOx ↔ Peroxyacetyl nitrate.</td>
</tr>
<tr>
<td>➢ Oxidation of primary organic aerosol to yield more oxidized and more toxic particulate matter.</td>
<td>➢ Oxidation of hundreds of VOCs.</td>
</tr>
<tr>
<td>➢ Organic coatings on elemental carbon (soot).</td>
<td>➢ In some cases, rapid oxidation due to emissions of HONO.</td>
</tr>
<tr>
<td>➢ Little change in total PM mass during downwind transport, but significant change in composition.</td>
<td>➢ Production of O$_3$ (depending on NOx).</td>
</tr>
<tr>
<td></td>
<td>➢ Nighttime chemistry (e.g. NO$_3$ oxidation).</td>
</tr>
</tbody>
</table>

*Chemistry of smoke plumes is extremely complex!*
Presentation continues with Susan O’Neill
Summary and Recommendations

Smoke is here to stay and will likely increase in the future. Fire is an ever-present part of the landscape. We need to learn to live with it and better manage our natural resources.

Recommendations:
1. Need for better understanding of the factors that cause fires, both immediate and indirect causes such as climate change, so as to improve predictions of future fire scenarios across all ecosystems.
2. Better understanding of emissions from prescribed burning and strategies that can be used to minimize emissions.
3. Need for improved approaches to use the multitude of satellite observations, especially new satellite data.
4. Improved smoke modeling including ensemble forecasts to generate smoke probability for an area, similar to precip forecasts.
Summary and Recommendations

5. Better understanding of atmospheric chemistry, especially as it relates to secondary organic aerosols and O$_3$ formation.
6. Better understanding of health effects, especially impact of long-term and repeated smoke exposure on birth outcomes, neurological and cognitive effects, and progression and incidence of chronic disease.
7. Need for more integrated (large-scale) experiments to examine fires, emissions, chemistry and impacts from the ground up.
8. Better community planning (Smoke-ready communities) to improve communication and actionable steps for individuals to protect their health.
9. COVID-19 and smoke. Communities and individuals need to do even more advance preparations for fires and smoke, as options will be more limited in 2020.