Geophysical Research Letters

RESEARCH LETTER

10.1029/2024GL111481

Key Points:

- During summer 2023 Canada experienced its most intense wildfire season on record
- Smoke from these fires impacted the United States (U.S.) Upper Midwest during May–June, leading to regional scale surface enhancements of $PM_{2.5}$ and ozone
- These unusual early season fires produced the highest regional-scale surface ozone levels ever recorded across the northern United States

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

O. R. Cooper and K.-L. Chang,
owen.r.cooper@noaa.gov;
kai-lan.chang@noaa.gov

Citation:

Cooper, O. R., Chang, K.-L., Bates, K., Brown, S. S., Chace, W. S., Coggon, M. M., et al. (2024). Early season 2023 wildfires generated record-breaking surface ozone anomalies across the U.S. Upper Midwest. *Geophysical Research Letters*, *51*, e2024GL111481. https://doi.org/10.1029/2024GL111481

Received 29 JUL 2024
Accepted 27 OCT 2024

Early Season 2023 Wildfires Generated Record-Breaking Surface Ozone Anomalies Across the U.S. Upper Midwest

Owen R. Cooper[1], Kai-Lan Chang[1,2], Kelvin Bates[1,2,3], Steven S. Brown[1], Wyndom S. Chace[1,2,4], Matthew M. Coggon[1], Alan M. Gorchov Negron[1,5], Ann M. Middlebrook[1], Jeff Peischl[2,6], Alison Piasecki[7], Nell Schafer[1,2], Chelsea E. Stockwell[1], Siyuan Wang[1,2], Carsten Warneke[1], Kristen Zuraski[1,2], Kazuyuki Miyazaki[8], Vivienne H. Payne[8], Elyse A. Pennington[8], John R. Worden[8], Kevin W. Bowman[8], and Brian C. McDonald[1]

[1]NOAA Chemical Sciences Laboratory, Boulder, CO, USA, [2]Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, CO, USA, [3]Now at: Department of Mechanical Engineering, University of Colorado Boulder, Boulder, CO, USA, [4]Department of Chemistry, University of Colorado Boulder, Boulder, CO, USA, [5]Renewable & Sustainable Energy Institute, University of Colorado Boulder, Boulder, CO, USA, [6]NOAA Global Monitoring Laboratory, Boulder, CO, USA, [7]US Geological Survey, Denver, CO, USA, [8]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

Abstract During summer 2023 Canada experienced its most intense wildfire season on record. Smoke plumes from these fires advected across the United States (U.S.) Upper Midwest, producing regional scale surface enhancements of $PM_{2.5}$ and ozone, as recorded by the U.S. surface monitoring network. These events are notable because they occurred early in the fire season (May 15-June 30), and they produced the highest regional-scale surface ozone levels ever recorded across the northern tier of the U.S. during early (May–June) or late (July-August) summer. Specifically, the Upper Midwest 50th ozone percentile was greater than in any other year since 1995, when the ozone monitoring network had sufficient coverage to assess regional-scale ozone levels; the 90th percentile was the highest since 2002. Satellite and aircraft measurements demonstrate the availability of ozone precursors and ozone production within the smoke plumes.

Plain Language Summary Ozone is a trace gas in the atmosphere that acts as an important greenhouse gas, and high concentrations near Earth's surface are a form of air pollution, detrimental to human health and vegetation productivity. Ozone is formed by sunlight reacting with precursor gases, such as those emitted by fossil fuel combustion. Wildfires are also an important source of ozone precursor gases. During summer 2023 Canada experienced its most intense wildfire season on record. Smoke from these fires impacted the U.S. Upper Midwest during May–June 2023, leading to regional scale surface enhancements of fine particulate matter and ozone. These unusual early season fires produced the highest regional-scale surface ozone levels ever recorded across the northern U.S. Mid-latitude wildfires have increased as the planet warms, and their frequency is expected to increase further with continued climate change. This analysis suggests that extreme ozone pollution episodes associated with wildfires could also increase in the future.

1. Introduction

Ozone production from biomass burning emissions was first documented in the late 1950s and early 1960s, related to land clearing and removal of agricultural waste in California (Darley et al., 1966; Feldstein et al., 1963). The first airborne observations of ozone production from smoke occurred in prescribed burning plumes in Australia during the early 1970s, with greater production at the top of the plume where solar radiation was strongest (Evans et al., 1974, 1977). The processes revealed by these observations, and from subsequent measurements in the Colorado Rocky Mountains, suggested that biomass burning could contribute to ozone production on the global scale (Crutzen et al., 1979). Studies in the 1980s, enabled by new satellite observations of total and tropospheric column ozone, discovered widespread tropospheric ozone enhancements above the tropical regions of South America and the South Atlantic Ocean, largely attributed to biomass burning (Crutzen et al., 1985; Fishman et al., 1986, 1991; Moxim & Levy, 2000; Sauvage et al., 2007; Thompson et al., 1996). Similarly, analysis of exploratory aircraft measurements in the 1990s attributed a significant portion of the ozone above the tropical South Pacific Ocean to biomass burning (Schultz et al., 1999). Model studies have also demonstrated that singular events, such as the 1997–1998 Indonesian peat fires can impact ozone on the global scale (Bowman et al., 2009; Duncan et al., 2003; Fiore et al., 2022; Rowlinson et al., 2019). A recent assessment of airborne observations above the world's oceans concluded that biomass burning emissions contribute to ozone production on a scale greater than or equal to urban emissions (Bourgeois et al., 2021).

Focusing on the U.S., many studies have demonstrated surface and free tropospheric ozone production from wildfire smoke (Jaffe et al., 2013, 2020; Johnson et al., 2021; Lu et al., 2016; McKeen et al., 2002; Wotawa & Trainer, 2000). Most observations of direct ozone production have occurred in the western states where smoke levels are most intense, and where instrumented aircraft experiments have targeted wildfire plumes (O'Dell et al., 2020; Robinson et al., 2021; Warneke et al., 2023). Sharp ozone increases at western rural monitoring sites were associated with widespread wildfires during summer 2020 (Putero et al., 2023), despite ozone decreases in the free troposphere caused by the COVID-19 economic downturn (Chang et al., 2023; Miyazaki et al., 2021). Enhanced ozone production in urban and suburban areas has also been attributed to wildfire smoke (Langford et al., 2023; Lee & Jaffe, 2024; Lill et al., 2022; Peischl et al., 2023; Pollack et al., 2021; Rickly et al., 2023).

This analysis reports extreme surface ozone enhancements across the Upper Midwest during the early summer of 2023, caused by frequent smoke plumes from Canadian wildfires. These events are notable because they occurred early in the fire season (May–June), and they produced the highest regional-scale surface ozone levels ever recorded across the northern tier of the U.S. during early summer (based upon observations since the mid-1990s, when widespread ozone data became available for assessing regional-scale ozone enhancements). Furthermore, these events were associated with the most intense Canadian wildfire season on record. The fires burned 15.0 Mha, more than seven times the annual average, produced continental scale anomalies of aerosol optical depth and carbon monoxide, and emitted four times as much carbon as Canada's annual fossil fuel emissions (Byrne et al., 2024; Dunn et al., 2024). In contrast, the U.S. experienced its smallest area burned (1.1 Mha) since 1998, far less than the record year of 2015 (4.1 Mha) (https://www.nifc.gov/fire-information/statistics/wildfires).

2. Methods

This study relies upon nationwide observations of maximum daily 8-hr average surface ozone (MDA8) and 24-hr average surface $PM_{2.5}$ archived by the U.S. Environmental Protection Agency (EPA). These metrics were chosen because they are relevant for protecting human health with regards to short-term exposure to ozone and $PM_{2.5}$, and they align with the U.S. National Ambient Air Quality Standards (NAAQS) as follows: (a) the 24-hr average primary and secondary NAAQS for $PM_{2.5}$ are 35 μg m^{-3}; attaining the NAAQS requires the 3-year average of the 98th percentile remain at or below 35 μg m^{-3}; (b) the primary and secondary NAAQS for ozone are 70 ppb; attaining the NAAQS requires the 3-year average of the annual fourth highest MDA8 ozone value remain at or below 70 ppb.

We downloaded MDA8 ozone (1990–2023) and 24-hr average $PM_{2.5}$ (2009–2023) observations at all available EPA-approved monitoring sites. In 2023 there were 1173 sites monitoring ozone and 773 sites monitoring $PM_{2.5}$; 453 sites monitored both pollutants. The observations were filtered to remove 24-hr average $PM_{2.5}$ values with fewer than 22 hourly observations. If a particular monitoring site reported $PM_{2.5}$ from more than one instrument, the data were averaged across all instruments. As this study focuses on regional scale enhancements, our analysis is limited to years with adequate data coverage for estimating regional ozone levels. Ozone data availability is sufficient for regional-scale assessments for 1995–2023, and $PM_{2.5}$ data availability is sufficient for 2011–2023.

The surface observations were spatially interpolated to produce daily gridded exposure maps of ozone and $PM_{2.5}$. The synthesis of observations from hundreds of individual monitoring sites is challenging because the method must account for irregularly distributed measurement locations (see Chang et al. (2021) for detailed discussions). Geographically weighted modeling requires certain flexible spatial correlation structures, which must be fit through the observations, in order to build a regular grid with interpolated values at unsampled locations. Our spatial modeling is implemented via the framework of the generalized additive models (GAM) (Wood, 2017), and spatial interpolations based on Gaussian processes are applied to the daily ozone and $PM_{2.5}$ concentrations, which is appropriate for daily scale data (Berrocal et al., 2012). Further details of this method are described by Chang et al. (2021). Our analysis compares ozone observations at a particular monitoring site to nearby $PM_{2.5}$ observations based on the interpolated $PM_{2.5}$ daily exposure maps. Oftentimes $PM_{2.5}$ monitors are not located at the same sites as the ozone monitors, and therefore the inferred $PM_{2.5}$ levels are subject to interpolation errors.

We focus on the Upper Midwest, which can be broadly defined as the states of North Dakota, South Dakota, Nebraska, Minnesota, Iowa, Wisconsin, Illinois and Michigan. Most of the high ozone episodes occurred in a region we refer to as North Central (38.95°N–49°N, 87°W–104°W), which includes all of the Upper Midwest states except for Michigan. For comparison we also define two other regions, Northwest (38.95°N–49°N, 104°W–125°W) and Northeast (38.95°N–49°N, 66°W–87°W). Together, these three regions span the entire northern half of the conterminous U.S. The southern bound of the three study regions was selected so that it includes most of the ozone enhancements above the central U.S., while omitting the regions of California with the highest anthropogenic emissions (and associated ozone levels), such as Sacramento, San Francisco and southern California. This demarcation allows the analysis to focus on regions of the Northwest where wildfires are expected to have the greatest relative impact. However, this southern boundary omits the 2023 ozone enhancements that occurred from St. Louis, Missouri, down to southern Illinois.

Additional data sets are described in the Supporting Information S1: (a) aircraft observations of ozone production within a Canadian smoke plume; (b) satellite detected ozone precursors within the smoke plumes; (c) GOES-West satellite images showing the smoke plumes; and (d) satellite detected fire radiative power.

3. Results

Beginning in early May 2023, NOAA polar orbiting satellites revealed wildfire temperature hotspots in western Canada (Figure 1), and NOAA geostationary satellite imagery showed the associated smoke plumes advecting southwards across the northern U.S. We monitored the Canadian wildfires all season to gauge their potential impacts on U.S. surface air quality. The plume locations were reported daily by the NOAA Hazard Mapping System Fire and Smoke Product, and their projected paths were forecast by the NOAA National Air Quality Forecast Capability (https://airquality.weather.gov). The average location of the smoke plumes during early summer is indicated by satellite observations of the ozone precursors carbon monoxide (CO) and peroxy acyl nitrates (PANs) (Figure 1). These precursors were detected by the CrIS satellite instrument, which is primarily sensitive to thermal infrared emissions in the free troposphere, and is capable of measuring trace gases within smoke plumes (Juncosa Calahorrano et al., 2021). On May 16th the first surface observations of $PM_{2.5}$ above 35 μg m^{-3} occurred in Montana, and the smoke plume quickly spread across the Upper Midwest on May 17–18, as shown in the daily maps of interpolated ozone and $PM_{2.5}$ observations (Figure S1 in Supporting Information S1). The first widespread surface ozone enhancements (>70 ppbv) associated with surface-level smoke plumes appeared across the Upper Midwest on May 22 (Figure 2). This pattern repeated several times until June 30 (Figure S1 in Supporting Information S1), with two notable events occurring on June 6 and 28 (Figure 2). The presence of PANs within these individual plumes was detected by the CrIS satellite instrument (Figure S2 in Supporting Information S1). As previously observed in urban areas (Buysse et al., 2019), the ozone response to smoke levels can be non-linear, with the highest ozone levels not always associated with the highest $PM_{2.5}$ concentrations.

Figure 3 summarizes the number of days during May 15-June 30 that exceeded the ozone and $PM_{2.5}$ NAAQS. Several dozen sites across the Upper Midwest experienced 3–8 $PM_{2.5}$ exceedances during the 47-day period, while on average there were no exceedances during May 15–June 30 over the previous 10 years. Similarly, a typical early summer period across the Upper Midwest has very few ozone exceedances, with most occurrences ringing Lake Michigan (Cleary et al., 2022). However, early summer 2023 saw frequent ozone exceedances across the Upper Midwest, distinct from the typical Great Lakes distribution of exceedances. Most sites recorded at least four exceedances, and some surpassed twenty.

Examples of the unusual number of ozone exceedances are illustrated with long-term observations at 12 monitoring sites (3 urban and 9 rural) across the Upper Midwest (Figures S3 and S4 in Supporting Information S1). The rural ozone monitor at Devil's Lake in southern Wisconsin was close to the epicenter of the most frequent ozone and $PM_{2.5}$ exceedances shown in Figures 3c and 3d. From 1995 through 2022, warm season (April-September) MDA8 ozone values decreased at the rate of -3.2 ± 0.4 ppbv decade^{-1} (p-value = 0.00), consistent with previous trend analysis across this region (Fleming et al., 2018; Simon et al., 2015). Exceedances of the current ozone standard were once common at this site from 1995 through 2005, but became rare from 2006 to 2022, making the 15 exceedances in 2023 highly unusual. Similar behavior occurred at the other 11 sites, regardless of an urban or rural setting, although not all sites show decreasing ozone trends.

To place the early summer Upper Midwest ozone levels in the context of the historical record we divided the northern half of the conterminous U.S. into 3 regions, Northwest, North Central and Northeast. The domains of these regions are shown in Figure 3a, with the North Central region encompassing much of the Upper Midwest.

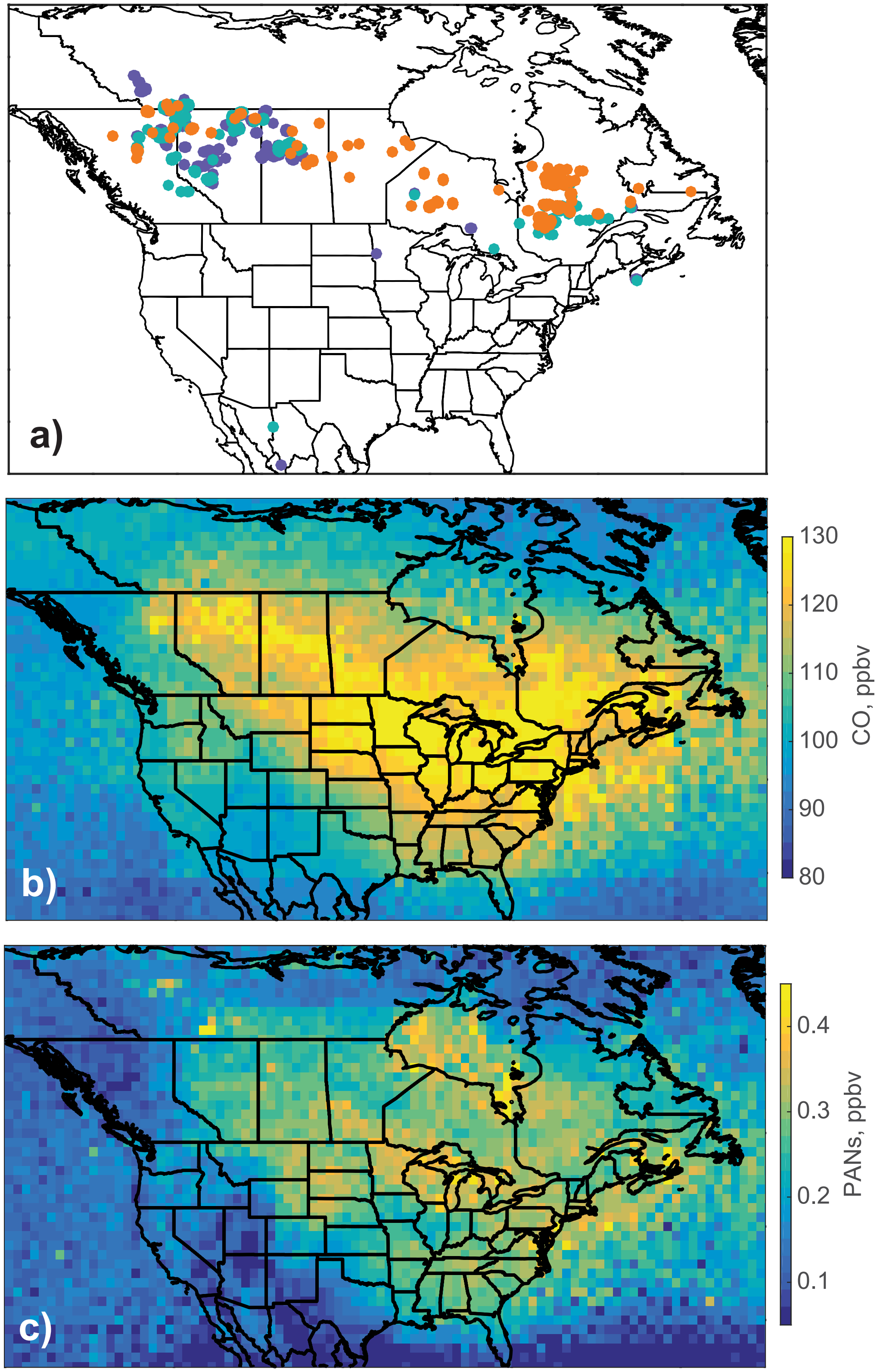

Figure 1. (a) NOAA-20 VIIRS fire detections with fire radiative power (FRP) greater than 290 MW, which is the 90th percentile of all detections above North America during May 15–30 June 2023. Detections are shown for three time periods: May 15–31 (purple), June 1–15 (teal), and June 16–30 (orange), 2023. Also shown are CrIS observations of CO (b) and PANs (c), averaged over May 15–30 June 2023.

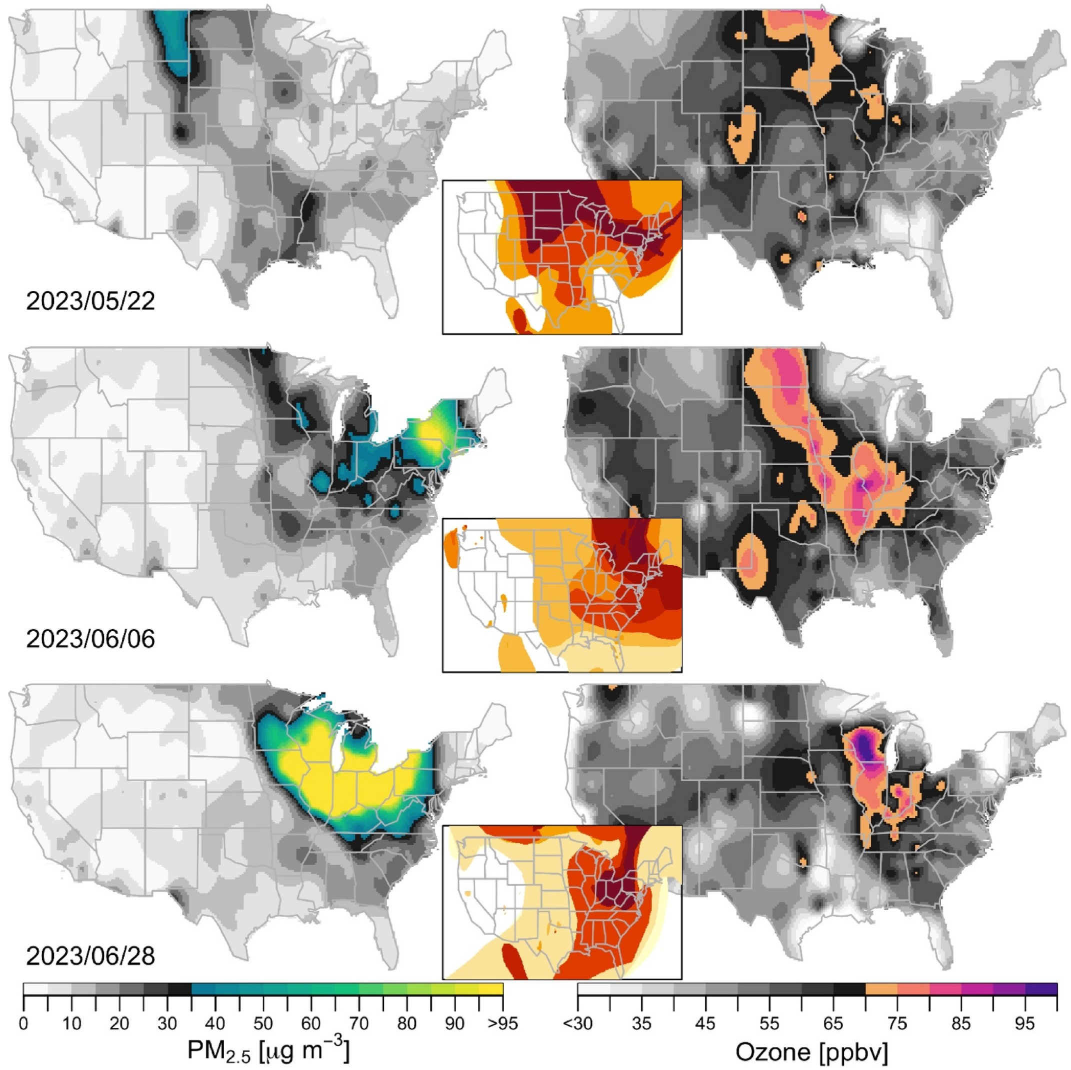

Figure 2. Interpolated observations of 24-hr average $PM_{2.5}$ (left) and MDA8 ozone (right) on May 22 (top), June 6 (middle), and June 28 (bottom), 2023. Inset panels show the NOAA smoke product on the same days; shading indicates light smoke (yellow) to heavy smoke (dark red).

Figures 4a–4c compare the 90th, 50th and 10th ozone percentiles in the North Central region to the Northwest and Northeast for the years 2009–2023, and for the early (May 15– June 30) and late (July and August) summer periods. Figures S5 and S6 in Supporting Information S1 show the same data, but in more detail and for the full record for which regional-scale ozone can be assessed across the northern U.S. (1995–2023). Figures 4b–4d (and Figures S7 and S8 in Supporting Information S1) show similar results for $PM_{2.5}$, but regional-scale $PM_{2.5}$ can only be assessed back to 2011. The 50th ozone percentile in the North Central region in May–June 2023 was 58 ppbv, which was 8 ppbv greater than the Northwest and 10 ppbv greater than the Northeast. The North Central May–June 50th percentile was also 8–14 ppbv greater than these same three regions during late summer. Going back to 1995, none of these regions has ever experienced a 50th percentile so high, in either early or late summer, although the Northwest came close in July–August 2021 (56 ppbv) when wildfires were associated with high ozone across this region (Putero et al., 2023). The 90th percentile across the North Central region was 73 ppbv during May–June 2023, the highest since 1995. The Northwest has never reached this level, while the Northeast frequently exceeded 73 ppbv long ago (1995–2002), but hasn't reached this level since 2002. In terms of $PM_{2.5}$, the North Central and Northeast regions experienced 90th percentiles in early summer (May–June) 2023 that were greater than any other year (going back to 2011), in either early or late summer, with the exception of the Northwest in July-August of 2018 and 2021 when wildfires were widespread across the region (Buchholz

10.1029/2024GL111481

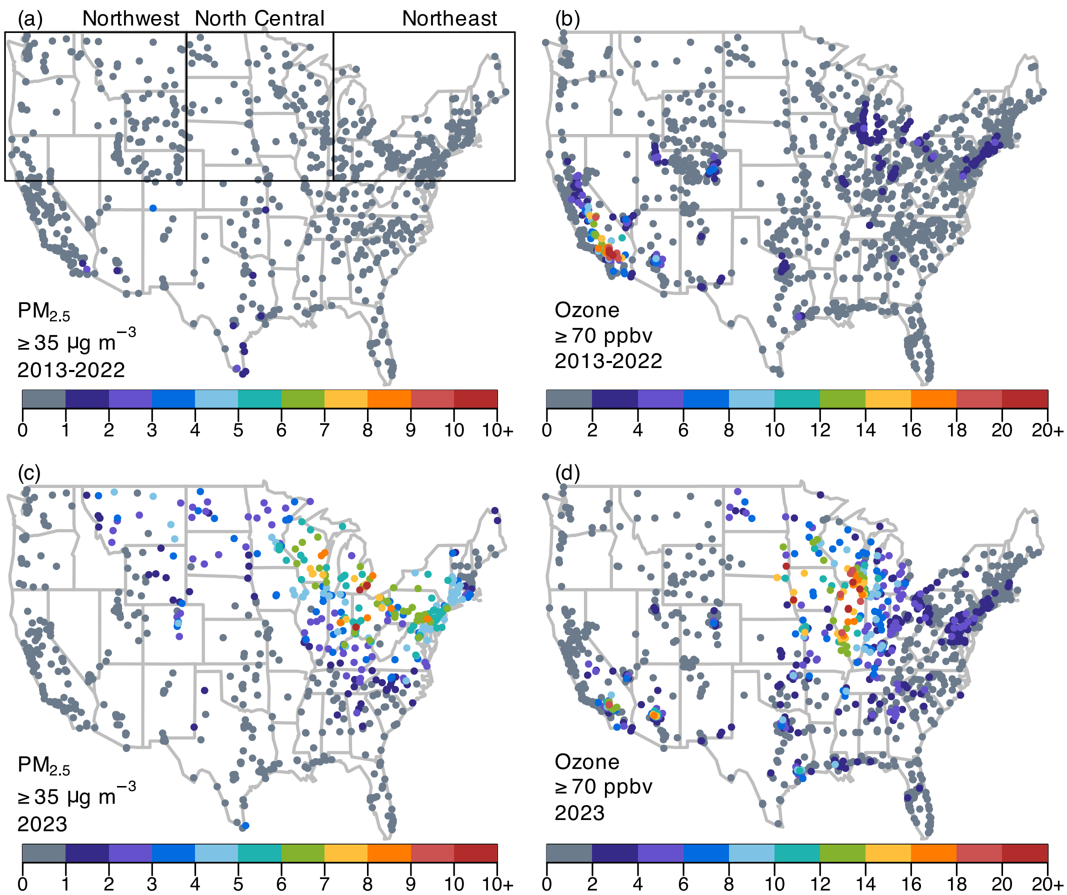

Figure 3. Comparison of observed MDA8 ozone (right) and 24-hr average $PM_{2.5}$ (left) for May 15–30 June 2023 (bottom) and May 15–30 June 2013–2022 (top). The metric is the number of days in this 6-week period that an ozone monitor exceeds 70 ppbv (MDA8), or that a PM monitor exceeds 35 μg m^{-3}; 2013–2022 exceedances are presented as a 10-year average. The bounds of the Northwest, North Central and Northeast regions are shown in (a).

et al., 2022). An additional view of the extreme nature of the 2023 ozone and $PM_{2.5}$ levels across the North Central region is provided in Figure S9 of Supporting Information S1.

4. Discussion and Conclusions

This record-breaking ozone episode coincides with the presence of widespread and persistent $PM_{2.5}$ enhancements caused by wildfire smoke plumes originating in western Canada. As ozone production from wildfire smoke is a well-established phenomenon, we attribute the 2023 ozone enhancements across the North Central region to the smoke plumes. We provide two additional pieces of supporting evidence that demonstrate that the Canadian fires were capable of strong ozone production. (a) The OMI satellite instrument showed strong NO_2 anomalies above some of the burn areas (Figure S10 in Supporting Information S1), demonstrating that these fires were emitting high levels of NO_x, an important ozone precursor. While OMI did not detect NO_2 above all of the fires, previous work has shown that NO_2 is commonly emitted throughout the lifetime of a wildfire, but mainly during the flaming periods (Anderson et al., 2023; Jin et al., 2023; Yokelson et al., 1996). Furthermore, the CrIS satellite instrument detected enhancements of PANs, an important ozone precursor, within the smoke plumes (Figure 1c and Figure S2 in Supporting Information S1). (b) During the *Atmospheric Emissions and Reactions Observed from Megacities to Marine Areas* (AEROMMA) field mission (see Supporting Information S1 for further details) the NASA DC-8 research aircraft made extensive atmospheric chemistry measurements above the Midwest and Northeast during July-August 2023. While the DC-8 did not fly above the Upper Midwest during May–June, it sampled Canadian smoke plumes on multiple occasions. The DC-8 intercepted a smoke plume above Gary, Indiana on 1 August 2023, that originated in western Canada approximately 5 days earlier. Consistent with the

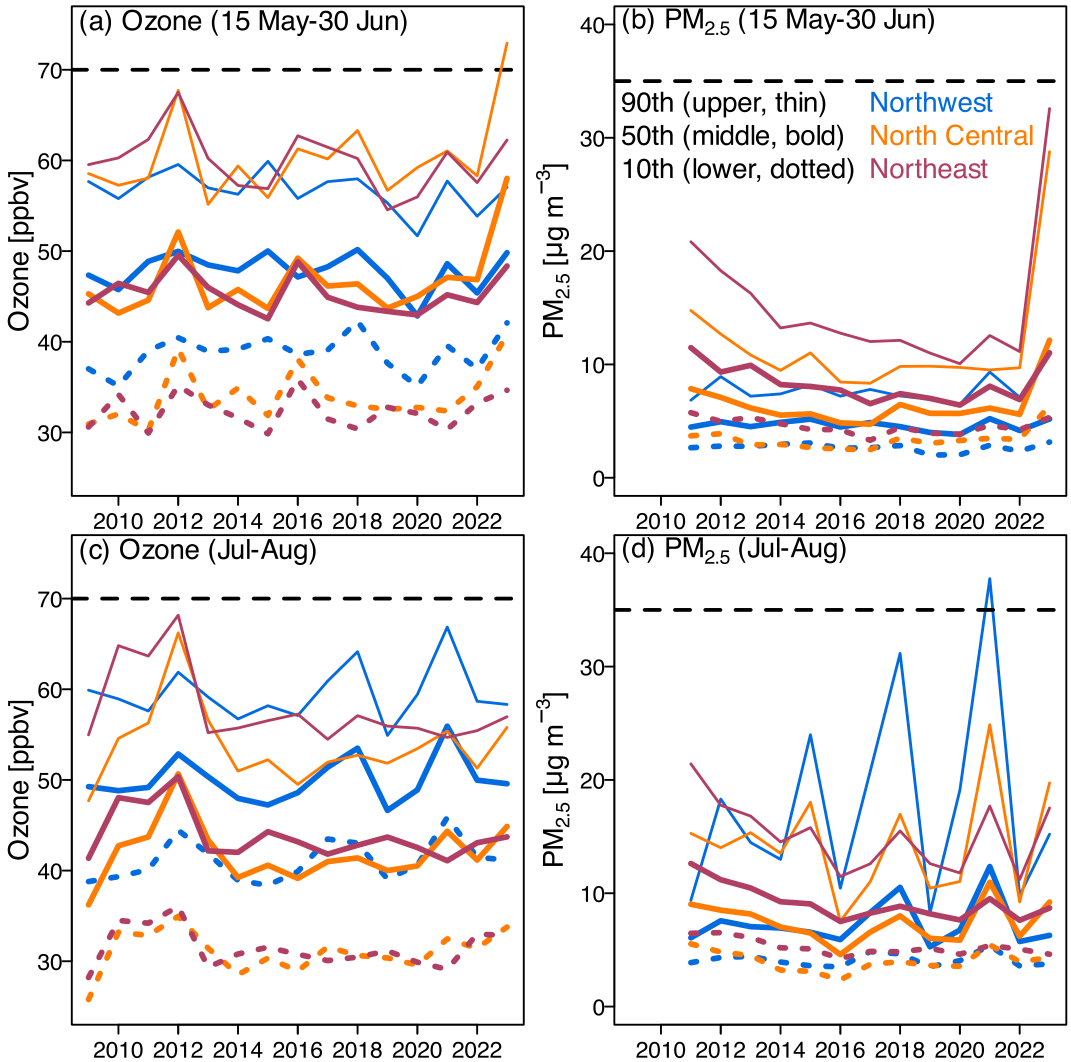

Figure 4. Seasonal percentiles during early summer (top) and late summer (bottom) of MDA8 ozone (left, 2009–2023) and 24-hr average $PM_{2.5}$ (right, 2011–2023). Data are shown as the average of the percentiles (90th, 50th, 10th) at every individual monitoring sites in the Northwest, North Central and Northeast regions of the U.S. (see Figures S5–S8 in Supporting Information S1 for the percentiles at each monitoring site).

smoke plumes observed during May and June 2023, the CrIS satellite instrument detected enhanced CO and PANs within the plume (Figure S2 in Supporting Information S1). Instruments onboard the DC-8 measured elevated CO, acetonitrile and organic aerosol levels within the plume that are typical of smoke produced by biomass burning (Figure 5). At CO levels above 0.3 ppmv (300 ppbv), ozone was greater than 75 ppbv and positively correlated with all three biomass burning tracers, indicating strong photochemical ozone production within the plume, which was isolated in the lower free troposphere, and therefore not impacted by U.S. surface emissions.

The surface ozone enhancements across the Upper Midwest during May–June 2023 were just as great at the rural monitoring sites as in urban areas, demonstrating that the biomass burning emissions alone were sufficient for strong ozone production. Smoke-related ozone enhancements at U.S. rural monitoring sites have been observed before (Lu et al., 2016; Putero et al., 2023), but never to the extent seen across the Upper Midwest during May–June 2023. Why were the 2023 ozone levels so extreme? The primary reason is that the 2023 wildfire emissions were so extensive that they simply led to more and larger smoke plumes that could repeatedly impact the same area over a relatively short period. By the end of June total carbon emissions from the Canadian wildfires reached 180 Mt, double the emissions of the average fire season that typically extends through September (CAMS, 2023).

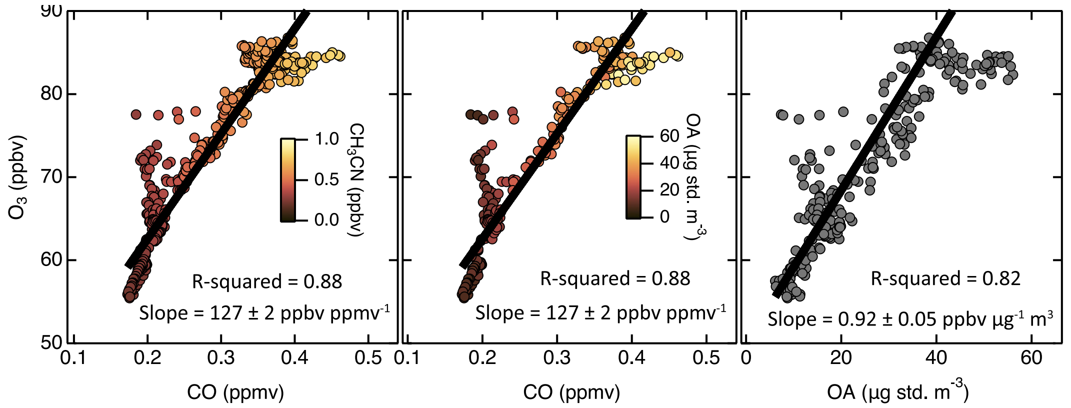

Figure 5. Scatter plots of ozone versus CO, colored by acetonitrile (CH_3CN) (left) and organic aerosol (OA) (center), and a scatter plot of ozone versus organic aerosol (right), as measured by the NASA DC-8 between 2000 and 4,000 m above sea level, over Gary, Indiana, 16:30 UTC, 1 August 2023.

Wildfire NO_x emissions are stronger during the initial flaming stage than during the later smoldering phase (Anderson et al., 2023), and a steady occurrence of new and intense fires argues for a strong and persistent source of NO_x emissions. We also note that these plumes were transported close to the surface which may allow for the conversion of peroxyacetyl nitrate (PAN) to NO_x, and therefore greater ozone production (Wang et al., 2021; Xu et al., 2021). Future work will use regional scale atmospheric chemistry models to simulate ozone production from the 2023 wildfires, and sensitivity studies could quantify the level of emissions necessary to produce the observed ozone enhancements, especially in terms of the plume height and PAN budget.

Reductions of anthropogenic emissions have led to strong ozone decreases across much of the U.S. (Simon et al., 2015; U.S.EPA, 2020; Wells et al., 2021). Our updated 90th percentile trend analysis shows strong summertime ozone decreases across the North Central and Northeastern U.S. from 1995 to 2013, with little to no decrease since 2013 (Figures S5 and S6 in Supporting Information S1). Over a 6-week period in May–June 2023, the impact of Canadian wildfires briefly negated the long-term improvements in ozone air quality, with the Upper Midwest highest ozone values (90th percentile) similar to the widespread pollution levels in the late 1990s and early 2000s. Climate change could make these fire-generated ozone events more common in the future. North American wildfire intensity has increased in recent decades (Balch et al., 2017; Cunningham et al., 2024; Jones et al., 2022; Parks & Abatzoglou, 2020), and climate change is expected to increase mid-latitude wildfire frequency and intensity for the remainder of the 21st century, regardless of emissions scenario, due to the committed warming expected from current greenhouse gas levels (Byrne et al., 2024; UNEP, 2022). Wildfire smoke is harmful to human health (O'Dell et al., 2021, 2022), and a recent study has estimated that wildfire particulate matter could double or triple across the Pacific Northwest in late summer and autumn by the end of the 21st century (Xie et al., 2022). Our analysis suggests that ozone pollution associated with wildfires could also increase in the future, with the 2023 wildfire season providing an extreme scenario for evaluating the chemistry climate models that can estimate future ozone exposure.

Data Availability Statement

NASA satellite data used in the creation of this manuscript included OMI total column NO_2 (Krotkov et al., 2019) and CrIS partial column PANs (Bowman, 2021a) and CO (Bowman, 2021b). Surface MDA8 ozone values and 24-hr average $PM_{2.5}$ values were calculated and provided by the United States Environmental Protection Agency and can be downloaded from: https://aqs.epa.gov/aqsweb/airdata/download_files.html. NASA DC-8 aircraft observations on 1 August 2023 are available here: https://csl.noaa.gov/groups/csl4/modeldata/. NOAA-20 VIIRS fire radiative power satellite data available here: https://www.ospo.noaa.gov/Products/land/hms.html. NOAA Hazard Mapping System Fire and Smoke Product produced by the NOAA Office of Satellite and Product Operations is available at: https://www.ospo.noaa.gov/Products/land/hms.html#maps. NOAA GOES-WEST satellite data are available from: https://registry.opendata.aws/noaa-goes/ and https://www.aev.class.noaa.gov/saa/products/welcome.

Acknowledgments

This research was supported in part by a NOAA Cooperative Agreement (no. NA22OAR4320151). Part of this work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA) (80NM0018D0004).

References

Anderson, L. D., Dix, B., Schnell, J., Yokelson, R., Veefkind, J. P., Ahmadov, R., & de Gouw, J. (2023). Analyzing the impact of evolving combustion conditions on the composition of wildfire emissions using satellite data. *Geophysical Research Letters*, *50*(23), e2023GL105811. https://doi.org/10.1029/2023GL105811

Balch, J. K., Bradley, B. A., Abatzoglou, J. T., Nagy, R. C., Fusco, E. J., & Mahood, A. L. (2017). Human-started wildfires expand the fire niche across the United States. *Proceedings of the National Academy of Sciences*, *114*(11), 2946–2951. https://doi.org/10.1073/pnas.1617394114

Berrocal, V. J., Gelfand, A. E., & Holland, D. M. (2012). Space-time data fusion under error in computer model output: An application to modeling air quality. *Biometrics*, *68*(3), 837–848. https://doi.org/10.1111/j.1541-0420.2011.01725.x

Bourgeois, I., Peischl, J., Neuman, J. A., Brown, S. S., Thompson, C. R., Aikin, K. C., et al. (2021). Large contribution of biomass burning emissions to ozone throughout the global remote troposphere. *Proceedings of the National Academy of Sciences*, *118*(52), e2109628118. https://doi.org/10.1073/pnas.2109628118

Bowman, K. W. (2021a). TROPESS CrIS-JPSS1 L2 peroxyacetyl nitrate for forward stream, standard product V1 [Dataset]. Goddard Earth Sciences Data and Information Services Center (GES DISC). https://doi.org/10.5067/W0W6L8M6J85X

Bowman, K. W. (2021b). TROPESS CrIS-JPSS1 L2 carbon monoxide for forward stream, standard product V1 [Dataset]. Goddard Earth Sciences Data and Information Services Center (GES DISC). https://doi.org/10.5067/BYIIUV3PR9L6

Bowman, K. W., Jones, D. B. A., Logan, J. A., Worden, H., Boersma, F., Chang, R., et al. (2009). The Zonal structure of tropical O_3 and CO as observed by the Tropospheric Emission Spectrometer in November 2004 – Part 2: Impact of surface emissions on O3 and its precursors. *Atmospheric Chemistry and Physics*, *9*(11), 3563–3582. https://doi.org/10.5194/acp-9-3563-2009

Buchholz, R. R., Park, M., Worden, H. M., Tang, W., Edwards, D. P., Gaubert, B., et al. (2022). New seasonal pattern of pollution emerges from changing North American wildfires. *Nature Communications*, *13*(1), 2043. https://doi.org/10.1038/s41467-022-29623-8

Buysse, C. E., Kaulfus, A., Nair, U., & Jaffe, D. A. (2019). Relationships between particulate matter, ozone, and nitrogen oxides during urban smoke events in the western US. *Environmental Science & Technology*, *53*(21), 12519–12528. https://doi.org/10.1021/acs.est.9b05241

Byrne, B., Liu, J., Bowman, K. W., Pascolini-Campbell, M., Chatterjee, A., Pandey, S., et al. (2024). Carbon emissions from the 2023 Canadian wildfires. *Nature*, *633*(8031), 1–5. https://doi.org/10.1038/s41586-024-07878-z

CAMS (Copernicus Atmosphere Monitoring Service). (2023). CAMS GFASv1.2. Retrieved from https://atmosphere.copernicus.eu/copernicus-canada-produced-23-global-wildfire-carbon-emissions-2023

Chang, K.-L., Cooper, O. R., Rodriguez, G., Iraci, L. T., Yates, E. L., Johnson, M. S., et al. (2023). Diverging ozone trends above western North America: Boundary layer decreases versus free tropospheric increases. *Journal of Geophysical Research: Atmospheres*, *128*(8), e2022JD038090. https://doi.org/10.1029/2022JD038090

Chang, K. L., Schultz, M. G., Lan, X., McClure-Begley, A., Petropavlovskikh, I., Xu, X., & Ziemke, J. R. (2021). Trend detection of atmospheric time series: Incorporating appropriate uncertainty estimates and handling extreme events. *Elem Sci Anth*, *9*(1), 00035. https://doi.org/10.1525/elementa.2021.00035

Cleary, P. A., Dickens, A., McIlquham, M., Sanchez, M., Geib, K., Hedberg, C., et al. (2022). Impacts of lake breeze meteorology on ozone gradient observations along Lake Michigan shorelines in Wisconsin. *Atmospheric Environment*, *269*, 118834. https://doi.org/10.1016/j.atmosenv.2021.118834

Crutzen, P. J., Delany, A. C., Greenberg, J., Haagenson, P., Heidt, L., Lueb, R., et al. (1985). Tropospheric chemical composition measurements in Brazil during the dry season. *Journal of Atmospheric Chemistry*, *2*(3), 233–256. https://doi.org/10.1007/bf00051075

Crutzen, P. J., Heidt, L. E., Krasnec, J. P., Pollock, W. H., & Seiler, W. (1979). Biomass burning as a source of atmospheric gases CO, H2, N2O, NO, CH3Cl and COS. *Nature*, *282*(5736), 253–256. https://doi.org/10.1038/282253a0

Cunningham, C. X., Williamson, G. J., & Bowman, D. M. J. S. (2024). Increasing frequency and intensity of the most extreme wildfires on Earth. *Nat Ecol Evol*, *8*(8), 1420–1425. https://doi.org/10.1038/s41559-024-02452-2

Darley, E. F., Burleson, F. R., Mateer, E. H., Middleton, J. T., & Osterli, V. P. (1966). Contribution of burning of agricultural wastes to photochemical air pollution. *Journal of the Air Pollution Control Association*, *16*(12), 685–690. https://doi.org/10.1080/00022470.1966.10468533

Duncan, B. N., Bey, I., Chin, M., Mickley, L. J., Fairlie, T. D., Martin, R. V., & Matsueda, H. (2003). Indonesian wildfires of 1997: Impact on tropospheric chemistry. *Journal of Geophysical Research*, *108*(D15), 4458. https://doi.org/10.1029/2002jd003195

R. J. H. Dunn, J. Blannin, N. Gobron, J. B Miller, & K. M. Willett (Eds.) (2024). Global climate [in "State of the climate in 2023"]. Bulletin America Meteorology Social, *105*(8), S12–S155. https://doi.org/10.1175/BAMS-D-24-0116.1

Evans, L. F., King, N. K., Packham, D. R., & Stephens, E. T. (1974). Ozone measurements in smoke from forest fires. *Environmental Science & Technology*, *8*(1), 75–76. https://doi.org/10.1021/es60086a013

Evans, L. F., Weeks, I. A., Eccleston, A. J., & Packham, D. R. (1977). Photochemical ozone in smoke from prescribed burning of forests. *Environmental Science & Technology*, *11*(9), 896–900. https://doi.org/10.1021/es60132a006

Feldstein, M., Duckworth, S., Wohlers, H. C., & Linsky, B. (1963). The contribution of the open burning of land clearing debris to air pollution. *Journal of the Air Pollution Control Association*, *13*(11), 542–564. https://doi.org/10.1080/00022470.1963.10468217

Fiore, A. M., Hancock, S. E., Jean-François, L., Correa, G. P., Chang, K.-L., Ru, M., et al. (2022). Understanding recent tropospheric ozone trends in the context of large internal variability: A new perspective from chemistry-climate model ensembles. *Environmental Research: Climate*, *1*(2), 025008. https://doi.org/10.1088/2752-5295/ac9cc2

Fishman, J., Fakhruzzaman, F., Cros, B., & Nganga, D. (1991). Identification of widespread pollution in the southern hemisphere from satellite analyses. *Science*, *252*(5013), 1693–1696. https://doi.org/10.1126/science.252.5013.1693

Fishman, J., Minnis, P., & Reichle Jr, H. G. (1986). Use of satellite data to study tropospheric ozone in the tropics. *Journal of Geophysical Research*, *91*(D13), 14451–14465. https://doi.org/10.1029/jd091id13p14451

Fleming, Z. L., Doherty, R. M., von Schneidemesser, E., Malley, C. S., Cooper, O. R., Pinto, J. P., et al. (2018). Tropospheric Ozone Assessment Report: Present-day ozone distribution and trends relevant to human health. *Elem Sci Anth*, *6*, 12. https://doi.org/10.1525/elementa.273

Jaffe, D. A., O'Neill, S. M., Larkin, N. K., Holder, A. L., Peterson, D. L., Halofsky, J. E., & Rappold, A. G. (2020). Wildfire and prescribed burning impacts on air quality in the United States. *Journal of the Air and Waste Management Association*, *70*(6), 583–615. https://doi.org/10.1080/10962247.2020.1749731

Jaffe, D. A., Wigder, N., Downey, N., Pfister, G., Boynard, A., & Reid, S. B. (2013). Impact of wildfires on ozone exceptional events in the western US. *Environmental Science & Technology*, *47*(19), 11065–11072. https://doi.org/10.1021/es402164f

Jin, X., Fiore, A. M., & Cohen, R. C. (2023). Space-based observations of ozone precursors within California wildfire plumes and the impacts on ozone-NOx-VOC chemistry. *Environmental Science & Technology*, *57*(39), 14648–14660. https://doi.org/10.1021/acs.est.3c04411

Johnson, M. S., Strawbridge, K., Knowland, K. E., Keller, C., & Travis, M. (2021). Long-range transport of Siberian biomass burning emissions to North America during FIREX-AQ. *Atmospheric Environment*, *252*, 118241. https://doi.org/10.1016/j.atmosenv.2021.118241

Jones, M. W., Abatzoglou, J. T., Veraverbeke, S., Andela, N., Lasslop, G., Forkel, M., et al. (2022). Global and regional trends and drivers of fire under climate change. *Reviews of Geophysics*, *60*(3), e2020RG000726. https://doi.org/10.1029/2020RG000726

Juncosa Calahorrano, J. F., Payne, V. H., Kulawik, S., Ford, B., Flocke, F., Campos, T., & Fischer, E. V. (2021). Evolution of acyl peroxynitrite (PANs) in wildfire smoke plumes detected by the Cross-Track Infrared Sounder (CrIS) over the western U.S. during summer 2018. *Geophysical Research Letters*, *48*(23), e2021GL093405. https://doi.org/10.1029/2021GL093405

Krotkov, N. A., Lamsal, L. N., Marchenko, S. V., Bucsela, E. J., Swartz, W. H., & Joiner, J., & the OMI core team. (2019). OMI/Aura nitrogen dioxide (NO2) total and tropospheric column 1-orbit L2 swath 13x24 km V003 [Dataset]. Goddard Earth Sciences Data and Information Services Center (GES DISC). https://doi.org/10.5067/Aura/OMI/DATA2017

Langford, A. O., Senff, C. J., Alvarez, R. J. I. I., Aikin, K. C., Ahmadov, R., Angevine, W. M., et al. (2023). Were wildfires responsible for the unusually high surface ozone in Colorado during 2021? *Journal of Geophysical Research: Atmospheres*, *128*(12), e2022JD037700. https://doi.org/10.1029/2022JD037700

Lee, H., & Jaffe, D. A. (2024). Impact of wildfire smoke on ozone concentrations using a Generalized Additive model in Salt Lake City, Utah, USA, 2006–2022. *Journal of the Air and Waste Management Association*, *74*(2), 116–130. https://doi.org/10.1080/10962247.2023.2291197

Lill, E., Lindaas, J., Calahorrano, J. F. J., Campos, T., Flocke, F., Apel, E. C., et al. (2022). Wildfire-driven changes in the abundance of gas-phase pollutants in the city of Boise, ID during summer 2018. *Atmospheric Pollution Research*, *13*(1), 101269. https://doi.org/10.1016/j.apr.2021.101269

Lu, X., Zhang, L., Yue, X., Zhang, J., Jaffe, D. A., Stohl, A., et al. (2016). Wildfire influences on the variability and trend of summer surface ozone in the mountainous western United States. *Atmospheric Chemistry and Physics*, *16*(22), 14687–14702. https://doi.org/10.5194/acp-16-14687-2016

McKeen, S. A., Wotawa, G., Parrish, D. D., Holloway, J. S., Buhr, M. P., Hübler, G., et al. (2002). Ozone production from Canadian wildfires during June and July of 1995. *Journal of Geophysical Research*, *107*(D14). https://doi.org/10.1029/2001JD000697

Miyazaki, K., Bowman, K., Sekiya, T., Takigawa, M., Neu, J. L., Sudo, K., et al. (2021). Global tropospheric ozone responses to reduced NOx emissions linked to the COVID-19 worldwide lockdowns. *Science Advances*, *7*(24), eabf7460. https://doi.org/10.1126/sciadv.abf7460

Moxim, W. J., & Levy, H. (2000). A model analysis of the tropical South Atlantic Ocean tropospheric ozone maximum: The interaction of transport and chemistry. *Journal of Geophysical Research*, *105*(D13), 17393–17415. https://doi.org/10.1029/2000jd900175

O'Dell, K., Bilsback, K., Ford, B., Martenies, S. E., Magzamen, S., Fischer, E. V., & Pierce, J. R. (2021). Estimated mortality and morbidity attributable to smoke plumes in the United States: Not just a western US problem. *GeoHealth*, *5*(9), e2021GH000457. https://doi.org/10.1029/2021GH000457

O'Dell, K., Ford, B., Burkhardt, J., Magzamen, S., Anenberg, S. C., Bayham, J., et al. (2022). Outside in: The relationship between indoor and outdoor particulate air quality during wildfire smoke events in western US cities. *Environmental Research: Health*, *1*(1), 015003. https://doi.org/10.1088/2752-5309/ac7d69

O'Dell, K., Hornbrook, R. S., Permar, W., Levin, E. J., Garofalo, L. A., Apel, E. C., et al. (2020). Hazardous air pollutants in fresh and aged western US wildfire smoke and implications for long-term exposure. *Environmental Science & Technology*, *54*(19), 11838–11847. https://doi.org/10.1021/acs.est.0c04497

Parks, S. A., & Abatzoglou, J. T. (2020). Warmer and drier fire seasons contribute to increases in area burned at high severity in western US forests from 1985 to 2017. *Geophysical Research Letters*, *47*(22), e2020GL089858. https://doi.org/10.1029/2020GL089858

Peischl, J., Aikin, K. C., McDonald, B. C., Harkins, C., Middlebrook, A. M., Langford, A. O., et al. (2023). Quantifying anomalies of air pollutants in 9 U.S. cities during 2020 due to COVID-19 lockdowns and wildfires based on decadal trends. *Elem Sci Anth*, *11*, 1. https://doi.org/10.1525/elementa.2023.00029

Pollack, I. B., Helmig, D., O'Dell, K., & Fischer, E. V. (2021). Weekend-weekday implications and the impact of wildfire smoke on ozone and its precursors at Boulder Reservoir, Colorado between 2017 and 2019. *Journal of Geophysical Research: Atmospheres*, *126*(17), e2021JD035221. https://doi.org/10.1029/2021jd035221

Putero, D., Cristofanelli, P., Chang, K.-L., Dufour, G., Beachley, G., Couret, C., et al. (2023). Fingerprints of the COVID-19 economic downturn and recovery on ozone anomalies at high-elevation sites in North America and Western Europe. *Atmospheric Chemistry and Physics*, *23*(24), 15693–15709. https://doi.org/10.5194/acp-23-15693-2023

Rickly, P. S., Coggon, M. M., Aikin, K. C., Alvarez, R. J., Baidar, S., Gilman, J. B., et al. (2023). Influence of wildfire on urban ozone: An observationally constrained box modeling study at a site in the Colorado front range. *Environmental Science & Technology*, *57*(3), 1257–1267. https://doi.org/10.1021/acs.est.2c06157

Robinson, M. A., Decker, Z. C. J., Barsanti, K. C., Coggon, M. M., Flocke, F. M., Franchin, A., et al. (2021). Variability and time of day dependence of ozone photochemistry in Western wildfire plumes. *Environmental Science & Technology*, *55*(15), 10280–10290. https://doi.org/10.1021/acs.est.1c01963

Rowlinson, M. J., Rap, A., Arnold, S. R., Pope, R. J., Chipperfield, M. P., McNorton, J., et al. (2019). Impact of El Niño–Southern Oscillation on the interannual variability of methane and tropospheric ozone. *Atmospheric Chemistry and Physics*, *19*(13), 8669–8686. https://doi.org/10.5194/acp-19-8669-2019

Sauvage, B., Martin, R. V., Van Donkelaar, A., & Ziemke, J. R. (2007). Quantification of the factors controlling tropical tropospheric ozone and the South Atlantic maximum. *Journal of Geophysical Research*, *112*(D11). https://doi.org/10.1029/2006jd008008

Schultz, M. G., Jacob, D. J., Wang, Y., Logan, J. A., Atlas, E. L., Blake, D. R., et al. (1999). On the origin of tropospheric ozone and NOx over the tropical South Pacific. *Journal of Geophysical Research*, *104*(D5), 5829–5843. https://doi.org/10.1029/98jd02309

Simon, H., Reff, A., Wells, B., Xing, J., & Frank, N. (2015). Ozone trends across the United States over a period of decreasing NOx and VOC emissions. *Environmental Science and Technology*, *49*(1), 186–195. https://doi.org/10.1021/es504514z

Thompson, A. M., Pickering, K. E., McNamara, D. P., Schoeberl, M. R., Hudson, R. D., Kim, J. H., et al. (1996). Where did tropospheric ozone over southern Africa and the tropical Atlantic come from in October 1992? Insights from TOMS, GTE TRACE A, and SAFARI 1992. *Journal of Geophysical Research*, *101*(D19), 24251–24278. https://doi.org/10.1029/96jd01463

UNEP (United Nations Environment Programme). (2022). *Spreading like wildfire: The rising threat of extraordinary landscape fires*. UNEP. Retrieved from https://wedocs.unep.org/bitstream/handle/20.500.11822/38372/wildfire_RRA.pdf

U.S.EPA. (2020). Integrated science assessment for ozone and related photochemical oxidants. *Federal Register*, *85 FR 21849*. Retrieved from https://www.federalregister.gov/documents/2020/04/20/2020-08333/integrated-science-assessment-for-ozone-and-related-photochemical-oxidants

Wang, S., Coggon, M. M., Gkatzelis, G. I., Warneke, C., Bourgeois, I., Ryerson, T., et al. (2021). Chemical tomography in a fresh wildland fire plume: A large eddy simulation (LES) study. *Journal of Geophysical Research: Atmospheres*, *126*(18), e2021JD035203. https://doi.org/10.1029/2021JD035203

Warneke, C., Schwarz, J. P., Dibb, J., Kalashnikova, O., Frost, G., Al-Saad, J., et al. (2023). Fire influence on regional to global Environments and air quality (FIREX-AQ). *Journal of Geophysical Research: Atmospheres*, *128*(2), e2022JD037758. https://doi.org/10.1029/2022jd037758

Wells, B., Dolwick, P., Eder, B., Evangelista, M., Foley, K., Mannshardt, E., et al. (2021). Improved estimation of trends in U.S. ozone concentrations adjusted for interannual variability in meteorological conditions. *Atmospheric Environment*, *248*, 118234. https://doi.org/10.1016/j.atmosenv.2021.118234

Wood, S. N. (2017). *Generalized additive models: An introduction with R*. Chapman and Hall/CRC.

Wotawa, G., & Trainer, M. (2000). The influence of Canadian forest fires on pollutant concentrations in the United States. *Science*, *288*(5464), 324–328. https://doi.org/10.1126/science.288.5464.324

Xie, Y., Lin, M., Decharme, B., Delire, C., Horowitz, L. W., Lawrence, D. M., et al. (2022). Tripling of western US particulate pollution from wildfires in a warming climate. *Proceedings of the National Academy of Sciences*, *119*(14), e2111372119. https://doi.org/10.1073/pnas.2111372119

Xu, L., Crounse, J. D., Vasquez, K. T., Allen, H., Wennberg, P. O., Bourgeois, I., et al. (2021). Ozone chemistry in western US wildfire plumes. *Science Advances*, *7*(50), eabl3648. https://doi.org/10.1126/sciadv.abl3648

Yokelson, R. J., Griffith, D. W. T., & Ward, D. E. (1996). Open-path Fourier transform infrared studies of large-scale laboratory biomass fires. *Journal of Geophysical Research*, *101*(D15), 21067–21080. https://doi.org/10.1029/96JD01800

References From the Supporting Information

Bahreini, R., Dunlea, E. J., Matthew, B. M., Simons, C., Docherty, K. S., DeCarlo, P. F., et al. (2008). Design and operation of a pressure-controlled inlet for airborne sampling with an aerodynamic aerosol lens. *Aerosol Science & Technology*, *42*(6), 465–471. https://doi.org/10.1080/02786820802178514

Bahreini, R., Ervens, B., Middlebrook, A. M., Warneke, C., de Gouw, J. A., DeCarlo, P. F., et al. (2009). Organic aerosol formation in urban and industrial plumes near Houston and Dallas, Texas. *Journal of Geophysical Research*, *114*(D7), D00F16. https://doi.org/10.1029/2008JD011493

Bourgeois, I., Peischl, J., Thompson, C. R., Aikin, K. C., Campos, T., Clark, H., et al. (2020). Global-scale distribution of ozone in the remote troposphere from the ATom and HIPPO airborne field missions. *Atmospheric Chemistry and Physics*, *20*(17), 10611–10635. https://doi.org/10.5194/acp-20-10611-2020

Bourgeois, I., Peischl, J., Neuman, J. A., Brown, S. S., Allen, H. M., Campuzano-Jost, P., et al. (2022). Comparison of airborne measurements of NO, NO2, HONO, NOy, and CO during FIREX-AQ. *Atmospheric Measurement Techniques*, *15*(16), 4901–4930. https://doi.org/10.5194/amt-15-4901-2022

Bowman, K. W., Rodgers, C. D., Kulawik, S. S., Worden, J., Sarkissian, E., Osterman, G., et al. (2006). Tropospheric emission spectrometer: Retrieval method and error analysis. *IEEE Transactions on Geoscience and Remote Sensing*, *44*(5), 1297–1307. https://doi.org/10.1109/tgrs.2006.871234

DeCarlo, P. F., Kimmel, J. R., Trimborn, A., Northway, M. J., Jayne, J. T., Aiken, A. C., et al. (2006). Field-deployable, high-resolution, time-of-flight aerosol mass spectrometer. *Analytical Chemistry*, *78*(24), 8281–8289. https://doi.org/10.1021/ac061249n

Guo, H., Campuzano-Jost, P., Nault, B. A., Day, D. A., Schroder, J. C., Kim, D., et al. (2021). The importance of size ranges in aerosol instrument intercomparisons: A case study for the atmospheric tomography mission. *Atmospheric Measurement Techniques*, *14*(5), 3631–3655. https://doi.org/10.5194/amt-14-3631-2021

Jing, P., Lu, Z., & Steiner, A. L. (2017). The ozone-climate penalty in the Midwestern US. *Atmospheric Environment*, *170*, 130–142. https://doi.org/10.1016/j.atmosenv.2017.09.038

Luo, M., Worden, H. M., Field, R. D., Tsigaridis, K., & Elsaesser, G. S. (2024). TROPESS-CrIS CO single-pixel vertical profiles: Intercomparisons with MOPITT and model simulations for 2020 western US wildfires. *Atmospheric Measurement Techniques*, *17*(9), 2611–2624. https://doi.org/10.5194/amt-17-2611-2024

Payne, V. H., Kulawik, S. S., Fischer, E. V., Brewer, J. F., Huey, L. G., Miyazaki, K., et al. (2022). Satellite measurements of peroxyacetyl nitrate from the cross-track infrared sounder: Comparison with Atom aircraft measurements. *Atmospheric Measurement Techniques*, *15*(11), 3497–3511. https://doi.org/10.5194/amt-15-3497-2022

Rad, M. A., Abatzoglou, J. T., Kreitler, J., Alizadeh, M. R., AghaKouchak, A., Hudyma, N., et al. (2023). Human and infrastructure exposure to large wildfires in the United States. *Nature Sustainability*, *6*(11), 1343–1351. https://doi.org/10.1038/s41893-023-01163-z

Worden, J., Wecht, K., Frankenberg, C., Alvarado, M., Bowman, K., Kort, E., et al. (2013). CH4 and CO distributions over tropical fires during October 2006 observed by the Aura TES satellite instrument and modeled by GEOS-Chem. *Atmospheric Chemistry and Physics*, *13*(7), 3679–3692. https://doi.org/10.5194/acp-13-3679-2013

Worden, H. M., Francis, G. L., Kulawik, S. S., Bowman, K. W., Cady-Pereira, K., Fu, D., et al. (2022). TROPESS/CrIS carbon monoxide profile validation with NOAA GML and ATom in situ aircraft observations. *Atmospheric Measurement Techniques*, *15*(18), 5383–5398. https://doi.org/10.5194/amt-15-5383-2022