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# A fire-driven shift in Canadian air quality concerns mirrors trends in the US.

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**Abstract**

The summer of 2023 was the most significant Canadian wildfire and smoke season on record. Data from five different satellite instruments going back to 2001 show that Canada and most provinces and territories experienced peak visible-wavelength aerosol optical depth and ultraviolet aerosol index values in 2023. Longer-term, we found that for weather records beginning in 1953, 2023 had the highest number of 'smoke' or 'haze' reports by a factor of two compared with the previous maximum in 1981, and by a factor of seven compared with the 1953-2022 average. These reports show an east-to-west shift in Canada's summer air pollution patterns. On one hand, smoke and haze in eastern Canada have decreased since the 1980s because of pollution control measures domestically and in the US. On the other hand, wildfire smoke has increased in the Northwest Territories, British Columbia, Alberta, and Saskatchewan since the 2010s, and is now the main air quality concern in western Canada. Interpreting the analysis here for Canada alongside previous work over the US, we see a shift over the whole of North America in summer air quality concerns from the east to the west. Drought, soil moisture, fire weather and burned area projections suggest more wildfire-driven smoke in the future throughout North America, particularly in the west. In contrast to air pollution from smokestacks and tailpipes that can be addressed at the source through government regulation, a future with more wildfire smoke will require downwind mitigation and will be the responsibility of public health officials.

**Significance Statement**

We used satellite data and weather reports to show that the extreme smoke over Canada in summer of 2023 was in fact part of longer-term trends. Since the 1980s, air pollution concerns have shifted from eastern Canada, which is more industrialized but where regulation has made fossil fuel burning cleaner, to the west, where more wildland fires have made summers more polluted. Nationally, air quality over Canada was cleanest during the 2000s, when burned area was low and pollution controls had taken effect. From climate model projections and similar studies over the US, these trends toward smokier air are expected to continue across North America.

## Main Text

### Introduction

Each year in Canada, smoke conditions from wildfires seem more unprecedented than the last, with smoky summers now the norm. The 2023 fire season in Canada was extraordinary: 15 Mha burned compared with a previous 1986-2022 maximum of 6.7 Mha in 1989 (1). Smoke from biomass burning impacted Canada from May to September of 2023 (Fig. 1). There were high aerosol emissions in northwestern Canada and Québec (Fig. 1A) where the large fires were (1). The fires caused high aerosol optical depth (AOD) (Fig. 1B) near the source and downwind, extending to the midwest and northeast US (2–5). Surface monitor particulate matter (PM) with diameter less than 2.5 microns ($PM_{2.5}$) (Fig. 1C) shows low concentrations along the west coast, increasing eastward to a maximum May-September average of 58 μg $m^{-3}$ in Fort Chipewyan in northeastern Alberta, more than double the Canadian 24-hour standard of 27 μg $m^{-3}$. The same pattern can be seen in the frequency of 'smoke' and 'haze' reports at 276 Environment Canada and Climate Change (ECCC) weather stations, which have more dense coverage (Fig. 1D), model estimates of $PM_{2.5}$ exceedances (1, 6) and total column carbon monoxide (7). Nationally, there were 5016 air quality bulletins compared to between 485 and 1833 over 2017-2021 (1).

We used aerosol retrievals from five different satellite instruments since 2001, and longer records of smoke and haze at ECCC weather stations since 1953 (Table S1) to show that 2023 was part of longer term fire and air quality trends over Canada. Ours follows work showing a climate-driven increase over Canada in severe wildfire since the 2000s (8), and over the US showing how climate-driven wildfire smoke in the west is offsetting gains in air quality made from regulating non-fire sources of pollution (9–11). While ours is not an epidemiological study with health impact estimates (12), it is motivated by the fact that air pollution, including wildfire smoke, is bad for Canadian communities small and large.

**2023 had the highest satellite-retrieved aerosols over Canada in data since 2001**

Multiple satellite data products, averaged over all of Canada for May-September, show the anomalous conditions in 2023 (Fig. 2). Aerosol loads measured from satellite instruments retrieving in the ultraviolet (Fig. 2 A and B) and visible ranges (Fig. 2C) were highest in 2023 relative to the records of each, which agreed closely in their interannual variation because of the common retrieval heritage. Average Terra Moderate Resolution Imaging Spectroradiometer (MODIS) AOD in 2023 was 0.37, compared to a previous range of 0.13 to 0.23 from 2001-2022. Interannually, the high 2023 satellite aerosol data are roughly in proportion to the 2023 2-15 Mt estimated organic carbon aerosol emissions (Fig. 2D), 2023 burned area (1), and 2023 carbon emissions (7).

The 2023 aerosols averaged over Canada reflect high values within individual provinces and territories. Burned area records were broken in the Northwest Territories (NWT), British Columbia (BC), Alberta, and Québec relative to the Landsat-adjusted record beginning in 1972 (1). With anomalous fire activity in Québec and smoke transported from burning in northwestern Canada by the prevailing westerlies, all aerosol retrievals were highest in 2023 for 12 out of 13 provinces and territories. Figure S1 shows this pattern for two representative satellite retrievals. The exception was the Yukon Territory, which had higher AOD in 2004 for the MODIS retrievals (Fig. S1B) because of active fire seasons there and a record-breaking year in Alaska. Conversely, Manitoba had a quiet fire season in 2023, but its highest AOD because of fires to the north and west. Across all provinces and territories, the 2023 MODIS AOD of 0.52 in Alberta was the biggest absolute departure from its 2001-2022 range of 0.10 to 0.27. The consistency with which 2023 stands out in such different satellite data in Fig. 2 reflects an unprecedented amount of fire and smoke. For western Canada, 2023 continues trends that began in the 2000s seen in satellite AOD (13, 14) and surface $PM_{2.5}$ (15). These trends decrease in strength from west to east and include the effects of smoke from US wildfires.

**2023 had the most smoke and haze reports at weather stations compared to the past 70 years**

The ECCC smoke-haze records in Fig. 1D go back to 1953, and allow us to understand how 2023 compared with the previous 70 years in relation to burned area and longer-term regional air quality changes across Canada. Nationally (Fig. 3A), the average smoke-haze frequency in 2023 from May to September (4.3%, or the equivalent of 7 days) was more than double the previous maximum 1.6% in 1981, and over 7 times the 1953-2022 average of 0.6%, both factors roughly in proportion to the 2023 burned area relative to its historical range since 1959.

The country-wide changes mask different provincial and territorial changes (Fig. 3B-N). In the Yukon Territory (Fig. 3B) and Northwest Territories (NWT) (Fig. 3C), there was low smoke-haze most years, punctuated by higher smoke-haze when burned area was high. In the NWT, 2023 burned area was almost 4 Mha, and the 9% smoke-haze was well outside the 1950-2022 range of 0% to 3% during high burned area years. In British Columbia (BC) (Fig. 3E), higher smoke-haze in the 1950s and 1960s reflects the polluted conditions in the southwestern part of the province at that time, mainly from transportation emissions (16) and the forestry sector (17, 18). 2017 and 2018 were departures from the previous four decades in BC, with over 1 Mha burned, 3% smoke-haze, and anomalously high $PM_{2.5}$ (15), with contributions from western US fires (12). The 5% smoke-haze in 2023 was the highest on record because of 2.4 M ha burned area in the southern interior and the northeastern part of that province (Fig. 1A). In Alberta (Fig. 3F), periodic high burned area and smoke haze years began in 1979 from fires in the province and in the NWT. A relatively quiet period through 2013 was followed by high smoke-haze years ranging from 2-4% because of a combination of fires in the province, and transboundary smoke transport from fires in the NWT in 2014 (19, 20), BC in 2017 and 2018, and the western US in 2020 (21, 22), culminating in the 11% smoke-haze in 2023. In Saskatchewan (Fig. 3G), there was high smoke-haze during a severe drought in 1961 (23), and otherwise a similar smoke-haze history as the NWT and Alberta, including the 8% smoke-haze in 2023. In Manitoba (Fig. 3H), the 5% smoke-haze in 2023 was comparable to that during the record breaking 1989 fire season despite a quiet fire year in the province, and instead because of smoke from fires to the north and west (Fig. 1).

Eastern Canada has a much different smoke-haze history than northern and western Canada. Ontario (Fig. 3I) is Canada's most populated and industrialized province. The higher baseline of smoke-haze reports through the 1990s reflects polluted conditions in southern Ontario because of local and US non-fire sources. The 4% smoke-haze in 1961 and 1989 from fires in northern Ontario (24), Manitoba, and Québec perhaps stand out, but other fire years are less apparent because of the non-fire pollution in southern Ontario, which is more frequently reported as 'haze' (Fig. S2I) and the low burned area relative to the size of the province. The 3% smoke-haze in 2023 stands out from the cleaner background alongside 2021 (25), but was typical of a summer from the 1950s to 1980s. Québec (Fig. 3J) also had more polluted conditions until the 1980s. The 3% smoke-haze in 2023 was similar to 1989, the first significant fire year to stand out in the record since 1953. The Maritime provinces (Fig. 3K-N) have similar smoke-haze histories until the 1990s as Ontario and Québec, but are not strongly affected by smoke from fires either upstream or within these provinces. Across all provinces and territories, there is no association over time between reports of smoke and haze and the station coverage, as represented by the average distance from grid points to the closest weather station (Fig. S2).

Table 1 lists the Theil-Sen trends in May-September smoke-haze frequency for different periods during 1953-2023. We emphasize the trends ending in 2022 because 2023 was so exceptional. Over all of Canada, there was a statistically significant but weak -0.006% $yr^{-1}$ decrease in smoke-haze over 1953-2022, which was the net trend from weaker positive trends in the NWT, Alberta, and Saskatchewan, and stronger negative trends for eastern Canadian provinces, especially Ontario. These trends are sensitive to the period considered. In southeastern Canada, the strongest negative trends in smoke haze are from 1976-1999, and were -0.078 % $yr^{-1}$ in Ontario and -0.041 % $yr^{-1}$ in Québec. In western Canada, the strongest positive trends in smoke haze were over 2000-2022 and were 0.058 % $yr^{-1}$ in Alberta, 0.055 % $yr^{-1}$ in Saskatchewan and 0.035 % $yr^{-1}$ in BC. Trends estimated only over staffed stations (Table S2) or using ordinary least-squares regression (Table S3) were similar.

**A shift in air quality concerns to from eastern to western North America**

Viewed regionally, the 70 years of smoke and haze reports in Fig. 3 show a shift in summer air quality concerns from eastern to western Canada. The declines in smoke-haze over eastern Canada air are consistent with what air quality monitoring data is available. The National Air Pollution Surveillance (NAPS) had less coverage than Fig. 1C until around 2005, but what data there are show that the national average PM decreased from the mid 1970s to 2000 (26, 27). Nationally (27) and in southern Ontario (18, 25, 28), sulfate aerosol precursor concentrations measured in-situ also decreased from the early 1970s to the early 2000s, as did sulfate and nitrate aerosol precursor concentrations and $PM_{2.5}$ through the 2010s (15). Aerosol precursor concentrations also decreased over the eastern US from the 1990s to 2000s in surface monitors (29, 30) and satellite retrievals (31, 32), which is part of the reason for decreases over eastern Canada (28, 33–35). Over the whole of the US, particulate concentrations decreased from the 1970s (36) through the 2010s (37).

Air quality improvements in eastern Canada can be tied directly to reduced pollution emissions. Figure 4 shows estimated emissions of non-fire $SO_2$ and $NO_x$ aerosol precursors over southeastern Canada and the northeastern US (59) since 1950. Summer smoke-haze increases over eastern Canada in the 1950s and 1960s (Fig. 3I-N) track with increases in $SO_2$ (Fig. 4A) and $NO_x$ (Fig. 4B) emissions driven by post-war industrialization (17). The decreases in eastern Canadian air pollution since the 1970s are ultimately because of declining industrial emissions locally and upwind in the northeastern US driven by provincial, national, bilateral and US regulation to reduce air pollution, chief among them the US Clean Air Act and its amendments (28, 35, 38–40).

In western Canada over 2005-2019, there were decreasing surface $NO_2$ and $SO_2$ trends as in the east, but an opposite, fire-driven increase in annual peak $PM_{2.5}$ (15), which is reflected in the positive smoke-haze trends over 2000-2022 (Fig. 3C, E-H, Table 1). The positive trends in $PM_{2.5}$ and smoke-haze reports are because of more burned area. Trends in MODIS burned area across western Canada from 2001-2020 are mixed, with increasing burned area in boreal and temperate forests and decreasing burned area in western croplands (21). In longer records, burned area increased over most of the western taiga and boreal regions of northwestern Canada and Alaska (41–43), which since the 2000s has been driven by more severe burning in drier fuels (8, 44, 45), with smoke emissions likely amplified if we consider that drier conditions increase the fuel available for combustion and emissions per unit burned area (46).

In the national average since 1953, our analysis has shown that air quality over Canada was at its best during the 2000s – a decade of low burned area and when non-fire emissions regulations had taken effect. Model estimates spanning 1980-2015 suggest the dominant contributor to national, population-weighted $PM_{2.5}$ over Canada changed from energy production around 2000 to wildfire smoke around 2010 as $SO_2$ emissions from power generation decreased and wildfire emissions increased (*35*), which increased the proportional contribution of wildfire smoke to premature mortality from $PM_{2.5}$ exposure (47). This parallels changes in the US, where more high fire danger days (22), more overnight burning (*52*, *53*), and more extreme fires (*50*), have led to an increase in burned area since the 1980s (51) and higher $PM_{2.5}$ in the west (9–11, 52), offsetting air quality gains from cleaner fossil fuel burning.

Between the analysis here for Canada and previous work over the US, we conclude that there has been a shift in the 2000s over the whole of North America in summer air quality concerns from the east, which is more industrialized but where regulation has made fossil fuel burning cleaner, to the west, where a climate-driven increase in burned area has led to more smoke.

**Climate change will make parts of North America more flammable and smokier during the summer**

Burned area in 2023 was related to anomalously hot and dry conditions, whether characterized by indices of drought and fire weather (1), or anomalies of temperature, precipitation, and vapor pressure deficit (7). A major factor in 2023 was how much of the country had synchronous high fire danger, especially in May and June (1). Normal sharing of fire-fighters across jurisdictions that relies on some provinces and territories having both low fire activity and low fire danger was exhausted (53), which we interpret as a climate-driven crossing of the fire management tipping point (54) that led to unprecedented levels of smoke.

The obvious question is how much smokier the environment will be in the future. It is hard to ignore that the record-breaking 2023 fire weather, burned area, and smoke occurred during what was, at the time, the hottest year on record globally (55). The 2023 fire weather was estimated to have been 50% more intense over Québec in May and June (56), and nationally 2.9-3.6 times more likely in June (57) because of anthropogenic climate change. The area burned in 2023 was found to be significantly more likely due to climate change across most of Canada, with the southwest and east having more than two-fold increases (58). Future fire activity over Canada was suggested to increase based on Coupled Model Intercomparison Project Phase 6 (CMIP6) climate projections of surface temperature and precipitation (7). Under the shared socioeconomic pathway (SSP) 2-4.5 using the Canadian Fire Weather Index (FWI) calculated from downscaled CMIP6 projections, strong increases are projected into the 2040s in southern British Columbia, weaker changes are projected across the rest of fire-prone Canada, and no changes are projected over most of Québec (59). Depending on the global warming level and metric, there is also lower projected mean FWI over northern Canada and higher projected CMIP6 FWI in BC and Alberta (60), which is consistent with earlier CMIP5-based FWI projections (61, 62) for their high-emissions Representative Concentration Pathway (RCP) 8.5 scenario.

Drought and soil moisture projections are worth interpreting alongside the FWI projections as proxy for landscape flammability, and when thinking about how early the 2023 fire season started after a fast snow melt (1). Modeled soil moisture has the advantage over the FWI system of a more physical representation of overwintering memory on early fire season conditions compared to simplified spring 'startup' procedures for the FWI System's Duff Moisture and Drought Codes that track soil moisture (60, 63, 64). In CMIP6 projections (65), no robust summer surface soil moisture decrease is projected over inland northwestern Canada, as the temperature increase is offset to some extent by more precipitation. This is consistent with weaker projected FWI increases in that region. Elsewhere, summer soil moisture is projected to decrease. This decrease is robust in the SSP 1-2.6 scenario, strongest over parts of the Yukon, British Columbia, Alberta and Québec, and becomes stronger for the higher-emissions SSPs. A similar north-south gradient in changes in summer surface soil moisture for SSP2-4.5 was projected (66), but with the strongest decreases centered over BC, and especially northern Ontario and Québec, where shorter-term (30-day) summer 'flash-drought' frequencies were also projected to increase most significantly depending on the SSP (67). The development of more comprehensive fire projections capturing changing vegetation, human activity and lightning patterns are still in their infancy (68), but recent estimates using single prognostic fire models forced by multiple climate models for the higher emissions SSPs range from an average annual burned area greater than 10 Mha by 2080 and centered on the Boreal Shield (69) to 1 in 100 year extreme burned area events becoming 5 times more likely in parts of the Yukon and Northwest Territories (62).

All projections are strongly dependent on future greenhouse gas emissions scenarios and on balance suggest that there will be more burned area in Canada, but it is hard to say where, or how often the extent of areas with high fire danger or fire activity will approach that seen in 2023.

**More smoke mitigation will be needed in the future**

Wildfire smoke presents substantial costs. From 1981-2021, 17% of wildfire evacuations were due to smoke rather than the direct threat of wildfire (70). The most detailed estimates of health costs come from the severe 2017 wildfire season in western Canada. Smoke was responsible for an estimated 2700 premature deaths, thousands of emergency room visits and hospital admissions, and millions of person-days of cardiorespiratory symptoms and restricted activity (12). The total associated health costs were estimated at more than $C 23B. In comparison, there were no deaths directly attributed to the fires that year, the national fire protection costs were valued at approximately $C 1.5B (71), and the BC insured losses were valued at approximately $C 130M (72). Health impact estimates are not yet available for the 2023 season, which affected tens of millions of people in Canada and the US (2, 3), but we can expect a consistent pattern where the health costs of the smoke far outweigh those directly attributable to the fires (71).

Despite the sheer magnitude of the impacts, wildfire management in Canada generally does not consider smoke. It is not part of the Action Plan 2021-2026 to implement the Canadian Wildland Fire Strategy (73), and in BC at least, smoke is not part of post-2023 strategies to transform fire management (74). Operationally, the protection of life, property, critical infrastructure, ecological health, cultural values, and forest timber overtake smoke as a priority (54). Even if it were prioritized, wildfire smoke cannot realistically be regulated using the same policies that have successfully curtailed emissions from smokestacks and tailpipes. The future frequency of smoke seasons like 2023 will therefore: 1) follow the long-term failure or success of new approaches to fire management and the capacity of wildfire management agencies, 2) depend on how fire danger in Canada changes with climate change, and 3) depend on changes in fire and smoke in the US, which in the northwest, are projected to increase with the strength of future warming (9, 75, 76).

Downwind mitigation should be the priority to reduce negative impacts of wildfire smoke in Canada. Forecasts of smoke exposure timing, location, and duration (77, 78) must be further improved to retrospectively (79) and prospectively (80) assess health risks, and run over a full North American domain to capture transboundary smoke transport. Air cleaning technologies are needed at the personal (respiratory protection), room (portable air cleaners), and building (code changes) scales to reduce smoke exposure (70, 81–83), as is education on smoke health effects and equitable access to protective measures (84). Finally, we must look to the behavioral sciences to support the personal behavioral changes required to reduce wildfire smoke exposure and its health impacts (85) on individuals and the entire population.

## Materials and Methods

The main data we used (Table S1) were aerosol retrievals from five different satellite instruments, reports of 'smoke' and 'haze' at Environment Canada and Climate Change (ECCC) weather stations, and burned area totals from the Canadian Forest Service National Fire Database (NFDB). All data were averaged for May to September (12, 86), nationally and over each province and territory. May-September captures 97% of the 2002-2023 annual area burned over Canada (87) from the MODIS land Collection (19) and 91% of the combined Canada and Alaska burned area from the enhanced Global Fire Emissions Database version 5 over 2001-2020 (21). Provincial and territorial boundaries included marine areas (88) to capture the full extent of the smoke in the satellite retrievals.

**Satellite aerosol retrievals**: We analyzed aerosols from five different satellite instruments, all sensitive to total aerosol loads rather than surface conditions only (Supplementary Information S1). Ultraviolet aerosol index (UVAI) and aerosol optical depth (AOD) at 388 nm were available from the Ozone Monitoring Instrument (OMI) since 2005 and from the Earth Polychromatic Imaging Camera (EPIC) since 2016. AOD at 500 nm was available from Terra MODIS since 2001, Aqua MODIS since 2002 and the Suomi National Polar-orbiting Partnership (SNPP) Visible Near Infrared Radiometer Suite (VIIRS) since 2012. All instruments are in low Earth polar orbits, except for EPIC, which is on board the Deep Space Climate Observatory (DSCOVR) at Lagrange point 1, 1.5 M km away between the Earth and the Sun.

**Reports of 'Smoke' and 'Haze' at weather stations since 1953 and $PM_{2.5}$ for 2023:** To understand how 2023 compared with years before the modern satellite record and more directly at the surface, we used hourly reports of 'smoke' or 'haze' at ECCC weather stations operating over different periods since 1953. This provides a qualitative constraint on air quality, but with better spatial and temporal coverage than the Canadian National Air Pollution Surveillance (NAPS) network, especially going back further in time (28, 89). National, provincial, and territorial smoke-haze frequency during the summer was estimated using a combination of spatial interpolation and bootstrap resampling to capture the uncertainty due to uneven and changing spatial station distribution and the subjectivity of present weather observations (Supplementary Information S2). Regional trends in summer smoke-haze were calculated using the Theil-Sen estimator in place of ordinary least squares linear regression (44, 45, 52) to guard against outlier effects. We used OpenAQ $PM_{2.5}$ to see the extent of smoke at the surface in 2023 (90). OpenAQ aggregates openly released air quality data from a combination of governmental and private sources. We used hourly $PM_{2.5}$ for the 174 government sensors available in Canada in OpenAQ for May to September 2023, taking the mean of each. We otherwise referred to the literature to compare regional smoke-haze trends to $PM_{2.5}$ and aerosol precursors.

**Burned area estimates**: We used national, provincial and territorial burned area totals from the Canadian National Fire Database (NFDB) (41) available from 1959-2023. NFDB estimates are higher than the National Burned Area Composite (NBAC), which includes Landsat-based corrections (91, 92), which, for example, remove unburnt islands within fire perimeters, but which are only available since 1972 (93). The NFDB before the 1980s is less reliable due to missing fires, particularly for smaller fires, and conversely, possible overestimations in burned area because of unburned islands within coarsely-mapped fire perimeters (94), but is useful for large-scale analyses (41).

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## References

1. P. Jain, *et al.*, Drivers and Impacts of the Record-Breaking 2023 Wildfire Season in Canada. *Nat. Commun.* **15**, 6764 (2024).
2. C. E. McArdle, Asthma-Associated Emergency Department Visits During the Canadian Wildfire Smoke Episodes — United States, April– August 2023. *MMWR Morb. Mortal. Wkly. Rep.* **72** (2023).
3. M. Yu, S. Zhang, H. Ning, Z. Li, K. Zhang, Assessing the 2023 Canadian wildfire smoke impact in Northeastern US: Air quality, exposure and environmental justice. *Sci. Total Environ.* **926**, 171853 (2024).
4. O. Torres, C. Ahn, Local and Regional Diurnal Variability of Aerosol Properties Retrieved by DSCOVR/EPIC UV Algorithm. *J. Geophys. Res. Atmospheres* **129**, e2023JD039908 (2024).
5. O. R. Cooper, *et al.*, Early Season 2023 Wildfires Generated Record-Breaking Surface Ozone Anomalies Across the U.S. Upper Midwest. *Geophys. Res. Lett.* **51**, e2024GL111481 (2024).
6. Z. Wang, *et al.*, Severe Global Environmental Issues Caused by Canada's Record-Breaking Wildfires in 2023. *Adv. Atmospheric Sci.* **41**, 565–571 (2024).
7. B. Byrne, *et al.*, Carbon emissions from the 2023 Canadian wildfires. *Nature* **633**, 835–839 (2024).
8. W. Wang, *et al.*, Canadian forests are more conducive to high-severity fires in recent decades. *Science* **387**, 91–97 (2025).
9. M. Burke, *et al.*, The contribution of wildfire to PM2.5 trends in the USA. *Nature* **622**, 761–766 (2023).
10. C. D. McClure, D. A. Jaffe, US particulate matter air quality improves except in wildfire-prone areas. *Proc. Natl. Acad. Sci.* **115**, 7901–7906 (2018).
11. T. Y. Wilmot, D. V. Mallia, A. G. Hallar, J. C. Lin, Wildfire activity is driving summertime air quality degradation across the western US: a model-based attribution to smoke source regions. *Environ. Res. Lett.* **17**, 114014 (2022).
12. C. J. Matz, *et al.*, Health impact analysis of PM2.5 from wildfire smoke in Canada (2013–2015, 2017–2018). *Sci. Total Environ.* **725**, 138506 (2020).
13. H. Che, *et al.*, Large contribution of meteorological factors to inter-decadal changes in regional aerosol optical depth. *Atmospheric Chem. Phys.* **19**, 10497–10523 (2019).
14. R. R. Buchholz, *et al.*, New seasonal pattern of pollution emerges from changing North American wildfires. *Nat. Commun.* **13**, 2043 (2022).
15. ECCC, "Air Quality - Canadian Environmental Sustainability Indicators" (Environment and Climate Change Canada, 2023).
16. T. Oke, J. Hay, *The Climate of Vancouver*, 2nd Ed. (University of British Columbia, 1994).
17. M. Katz, Air Pollution in Canada—Current Status Report. *Am. J. Public Health Nations Health* **53**, 173–184 (1963).

18. D. V. Bates, Community air pollution in Canada: a review and predictions for the 1980s. *Can. Med. Assoc. J.* **120**, 1252–1256 (1979).
19. L. Giglio, W. Schroeder, C. O. Justice, The collection 6 MODIS active fire detection algorithm and fire products. *Remote Sens. Environ.* **178**, 31–41 (2016).
20. R. C. Scholten, S. Veraverbeke, R. Jandt, E. A. Miller, B. M. Rogers, ABoVE: Ignitions, Burned Area, and Emissions of Fires in AK, YT, and NWT, 2001-2018. *ORNL DAAC* (2021). https://doi.org/10.3334/ORNLDAAC/1812.
21. Y. Chen, *et al.*, Multi-decadal trends and variability in burned area from the fifth version of the Global Fire Emissions Database (GFED5). *Earth Syst. Sci. Data* **15**, 5227–5259 (2023).
22. J. T. Abatzoglou, C. S. Juang, A. P. Williams, C. A. Kolden, A. L. Westerling, Increasing Synchronous Fire Danger in Forests of the Western United States. *Geophys. Res. Lett.* **48**, e2020GL091377 (2021).
23. B. R. Bonsal, X. Zhang, W. D. Hogg, Canadian Prairie growing season precipitation variability and associated atmospheric circulation. *Clim. Res.* **11**, 191–208 (1999).
24. P. Gzowski, 1961: Summer of the Angry Forest Fires. *Macleans* **74**, 17-18,65-66 (1961).
25. OMECP, "Air Quality in Ontario 2021 Report" (Ontario Ministry of the Environment, Conservation and Parks, 2023).
26. Statistics Canada, "Human Activity and the Environment Annual Statistics 2002" (2002).
27. Environment Canada, "National Urban Air Quality Trends, 1978-1987" (1990).
28. D. D. Yap, D. N. Reid, G. D. Brou, D. R. Bloxam, "Transboundary Air Pollution in Ontario" (Ontario Ministry of the Environment, 2005).
29. J. Feng, E. Chan, R. Vet, Air quality in the eastern United States and Eastern Canada for 1990–2015: 25 years of change in response to emission reductions of $SO_2$ and $NO_x$ in the region. *Atmospheric Chem. Phys.* **20**, 3107–3134 (2020).
30. J. L. Hand, B. A. Schichtel, W. C. Malm, M. L. Pitchford, Particulate sulfate ion concentration and $SO_2$ emission trends in the United States from the early 1990s through 2010. *Atmospheric Chem. Phys.* **12**, 10353–10365 (2012).
31. N. A. Krotkov, *et al.*, Aura OMI observations of regional $SO_2$ and $NO_2$ pollution changes from 2005 to 2015. *Atmospheric Chem. Phys.* **16**, 4605–4629 (2016).
32. M. S. Hammer, *et al.*, Assessment of the impact of discontinuity in satellite instruments and retrievals on global PM2.5 estimates. *Remote Sens. Environ.* **294**, 113624 (2023).
33. J. R. Brook, C. D. Lillyman, M. F. Shepherd, A. Mamedov, Regional Transport and Urban Contributions to Fine Particle Concentrations in Southeastern Canada. *J. Air Waste Manag. Assoc.* **52**, 855–866 (2002).
34. D. Johnson, D. Mignacca, D. Herod, D. Jutzi, H. Miller, Characterization and Identification of Trends in Average Ambient Ozone and Fine Particulate Matter Levels through Trajectory Cluster Analysis in Eastern Canada. *J. Air Waste Manag. Assoc.* **57**, 907–918 (2007).
35. C. H. Whaley, *et al.*, Toronto area ozone: Long-term measurements and modeled sources of poor air quality events. *J. Geophys. Res. Atmospheres* **120**, 11,368-11,390 (2015).
36. K. Chay, M. Greenstone, "Air Quality Infant Mortality, and the Clean Air Act of 1970" (National Bureau of Economic Research, 2003).
37. J. Meng, *et al.*, Source Contributions to Ambient Fine Particulate Matter for Canada. *Environ. Sci. Technol.* **53**, 10269–10278 (2019).
38. W. A. Gough, C. Lillyman, J. Karagatzides, L. J. S. Tsuji, Determining the Validity of using Summer Monitoring to Estimate Annual Deposition of Acidic Pollutants in Southern Ontario, Canada. *Water. Air. Soil Pollut.* **137**, 305–316 (2002).
39. G. D. Thurston, *et al.*, The Nature and Origins of Acid Summer Haze Air Pollution in Metropolitan Toronto, Ontario. *Environ. Res.* **65**, 254–270 (1994).
40. J. Currie, R. Walker, What Do Economists Have to Say about the Clean Air Act 50 Years after the Establishment of the Environmental Protection Agency? *J. Econ. Perspect.* **33**, 3–26 (2019).

41. C. C. Hanes, *et al.*, Fire-regime changes in Canada over the last half century. *Can. J. For. Res.* **49**, 256–269 (2019).
42. J. A. Wang, *et al.*, Extensive land cover change across Arctic–Boreal Northwestern North America from disturbance and climate forcing. *Glob. Change Biol.* **26**, 807–822 (2020).
43. J. A. Wang, A. Baccini, M. Farina, J. T. Randerson, M. A. Friedl, Disturbance suppresses the aboveground carbon sink in North American boreal forests. *Nat. Clim. Change* **11**, 435–441 (2021).
44. E. Whitman, S. A. Parks, L. M. Holsinger, M.-A. Parisien, Climate-induced fire regime amplification in Alberta, Canada. *Environ. Res. Lett.* **17**, 055003 (2022).
45. M.-A. Parisien, *et al.*, Abrupt, climate-induced increase in wildfires in British Columbia since the mid-2000s. *Commun. Earth Environ.* **4**, 1–11 (2023).
46. B. D. Amiro, *et al.*, Direct carbon emissions from Canadian forest fires, 1959-1999. *Can. J. For. Res.* **31**, 512–525 (2001).
47. C. Y. Park, *et al.*, Attributing human mortality from fire PM2.5 to climate change. *Nat. Clim. Change* **14**, 1193–1200 (2024).
48. J. K. Balch, *et al.*, Warming weakens the night-time barrier to global fire. *Nature* **602**, 442–448 (2022).
49. K. Luo, X. Wang, M. de Jong, M. Flannigan, Drought triggers and sustains overnight fires in North America. *Nature* **627**, 321–327 (2024).
50. C. X. Cunningham, G. J. Williamson, D. M. J. S. Bowman, Increasing frequency and intensity of the most extreme wildfires on Earth. *Nat. Ecol. Evol.* **8**, 1420–1425 (2024).
51. J. T. Abatzoglou, A. P. Williams, Impact of anthropogenic climate change on wildfire across western US forests. *Proc. Natl. Acad. Sci.* **113**, 11770–11775 (2016).
52. K. O'Dell, B. Ford, E. V. Fischer, J. R. Pierce, Contribution of Wildland-Fire Smoke to US PM2.5 and Its Influence on Recent Trends. *Environ. Sci. Technol.* **53**, 1797–1804 (2019).
53. H. Simpson, Overview 2023: Canada - Standing Together. *Wildfire* 22–27 (2023).
54. C. Tymstra, B. J. Stocks, X. Cai, M. D. Flannigan, Wildfire management in Canada: Review, challenges and opportunities. *Prog. Disaster Sci.* **5**, 100045 (2020).
55. G. Schmidt, Climate models can't explain 2023's huge heat anomaly — we could be in uncharted territory. *Nature* **627**, 467–467 (2024).
56. C. Barnes, *et al.*, "Climate change more than doubled the likelihood of extreme fire weather conditions in Eastern Canada" (Grantham Institute, Imperial College, 2024).
57. M. W. Jones, *et al.*, State of Wildfires 2023–2024. *Earth Syst. Sci. Data* **16**, 3601–3685 (2024).
58. M. C. Kirchmeier-Young, *et al.*, Human driven climate change increased the likelihood of the 2023 record area burned in Canada. *Npj Clim. Atmospheric Sci.* **7**, 1–12 (2024).
59. T. Park, *et al.*, What Does Global Land Climate Look Like at 2°C Warming? *Earths Future* **11**, e2022EF003330 (2023).
60. Y. Quilcaille, F. Batibeniz, A. F. S. Ribeiro, R. S. Padrón, S. I. Seneviratne, Fire weather index data under historical and shared socioeconomic pathway projections in the 6th phase of the Coupled Model Intercomparison Project from 1850 to 2100. *Earth Syst. Sci. Data* **15**, 2153–2177 (2023).
61. J. T. Abatzoglou, A. P. Williams, R. Barbero, Global Emergence of Anthropogenic Climate Change in Fire Weather Indices. *Geophys. Res. Lett.* **46**, 326–336 (2019).
62. M. W. Jones, *et al.*, Global and Regional Trends and Drivers of Fire Under Climate Change. *Rev. Geophys.* **60**, e2020RG000726 (2022).
63. R. D. Field, Evaluation of Global Fire Weather Database reanalysis and short-term forecast products. *Nat. Hazards Earth Syst. Sci.* **20**, 1123–1147 (2020).
64. M. McElhinny, J. F. Beckers, C. Hanes, M. Flannigan, P. Jain, A high-resolution reanalysis of global fire weather from 1979 to 2018 – overwintering the Drought Code. *Earth Syst. Sci. Data* **12**, 1823–1833 (2020).
65. B. I. Cook, *et al.*, Twenty-First Century Drought Projections in the CMIP6 Forcing Scenarios. *Earths Future* **8**, e2019EF001461 (2020).

66. T. Zhao, A. Dai, CMIP6 Model-Projected Hydroclimatic and Drought Changes and Their Causes in the Twenty-First Century. *J. Clim.* **35**, 897–921 (2022).
67. J. I. Christian, *et al.*, Global projections of flash drought show increased risk in a warming climate. *Commun. Earth Environ.* **4**, 1–10 (2023).
68. S. Hantson, *et al.*, Quantitative assessment of fire and vegetation properties in simulations with fire-enabled vegetation models from the Fire Model Intercomparison Project. *Geosci. Model Dev.* **13**, 3299–3318 (2020).
69. S. R. Curasi, J. R. Melton, V. K. Arora, E. R. Humphreys, C. H. Whaley, Global climate change below 2 °C avoids large end century increases in burned area in Canada. *Npj Clim. Atmospheric Sci.* **7**, 1–11 (2024).
70. A. C. Christianson, *et al.*, Wildland fire evacuations in Canada from 1980 to 2021. *Int. J. Wildland Fire* **33** (2024).
71. E. S. Hope, D. W. McKenney, L. M. Johnston, J. M. Johnston, A cost-benefit analysis of WildFireSat, a wildfire monitoring satellite mission for Canada. *PLOS ONE* **19**, e0302699 (2024).
72. Canadian Underwriters, BC wildfires cause more than $127 million in insured damage: CatIQ. (2017). Available at: https://www.canadianunderwriter.ca/insurance/b-c-wildfires-cause-127-million-insured-damage-ibc-1004121154/ [Accessed 18 October 2024].
73. Canadian Council of Forest Ministers Wildland Fire Management Working Group, "Action Plan 2021-2026: A Roadmap for Implementing the Canadian WIldland Fire Strategy Using a Whole-of-Government Approach" (2021).
74. L. D. Daniels, *et al.*, The 2023 wildfires in British Columbia, Canada: impacts, drivers, and transformations to coexist with wildfire. *Can. J. For. Res.* **55**, 1–18 (2025).
75. J. E. Neumann, *et al.*, Estimating PM2.5-related premature mortality and morbidity associated with future wildfire emissions in the western US. *Environ. Res. Lett.* **16**, 035019 (2021).
76. Y. Xie, *et al.*, Tripling of western US particulate pollution from wildfires in a warming climate. *Proc. Natl. Acad. Sci.* **119**, e2111372119 (2022).
77. J. Chen, *et al.*, The FireWork v2.0 air quality forecast system with biomass burning emissions from the Canadian Forest Fire Emissions Prediction System v2.03. *Geosci. Model Dev.* **12**, 3283–3310 (2019).
78. S. Sankey, *Blueprint for wildland fire science in Canada (2019-2029).* (2018).
79. J. Yao, M. Brauer, S. B. Henderson, Evaluation of a Wildfire Smoke Forecasting System as a Tool for Public Health Protection. *Environ. Health Perspect.* **121**, 1142–1147 (2013).
80. S. B. Henderson, *et al.*, Staying Ahead of the Epidemiologic Curve: Evaluation of the British Columbia Asthma Prediction System (BCAPS) During the Unprecedented 2018 Wildfire Season. *Front. Public Health* **9** (2021).
81. P. K. Barn, *et al.*, Portable air cleaners should be at the forefront of the public health response to landscape fire smoke. *Environ. Health* **15**, 116 (2016).
82. W. J. Fisk, W. R. Chan, Health benefits and costs of filtration interventions that reduce indoor exposure to PM2.5 during wildfires. *Indoor Air* **27**, 191–204 (2017).
83. J. K. Kodros, *et al.*, Quantifying the Health Benefits of Face Masks and Respirators to Mitigate Exposure to Severe Air Pollution. *GeoHealth* **5**, e2021GH000482 (2021).
84. M. B. Rice, *et al.*, Respiratory Impacts of Wildland Fire Smoke: Future Challenges and Policy Opportunities. An Official American Thoracic Society Workshop Report. *Ann. Am. Thorac. Soc.* **18**, 921–930 (2021).
85. M. Burke, *et al.*, Exposures and behavioural responses to wildfire smoke. *Nat. Hum. Behav.* **6**, 1351–1361 (2022).
86. T. S. Carter, *et al.*, How emissions uncertainty influences the distribution and radiative impacts of smoke from fires in North America. *Atmospheric Chem. Phys.* **20**, 2073–2097 (2020).
87. GWIS, Global Wildfire Information System, Canada Country Profile. Deposited 2024.
88. Statistics Canada, 2021 Census - Boundary Files. Deposited 2021.
89. Environment Canada, "Canadian Environmental Sustainability Indicators" (2005).

90. OpenAQ, OpenAQ Surface station PM2.5 data. Deposited 2024.
91. R. J. Hall, *et al.*, Generating annual estimates of forest fire disturbance in Canada: the National Burned Area Composite. *Int. J. Wildland Fire* **29**, 878–891 (2020).
92. R. Skakun, E. Whitman, J. M. Little, M.-A. Parisien, Area burned adjustments to historical wildland fires in Canada. *Environ. Res. Lett.* **16**, 064014 (2021).
93. R. Skakun, G. Castilla, P. Jain, Mapping wildfires in Canada with Landsat MSS to extend the National Burned Area Composite (NBAC) time series back to 1972. *Int. J. Wildland Fire* **33** (2024).
94. B. J. Stocks, *et al.*, Large forest fires in Canada, 1959–1997. *J. Geophys. Res. Atmospheres* **107**, FFR 5-1-FFR 5-12 (2002).
95. R. M. Hoesly, *et al.*, Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS). *Geosci. Model Dev.* **11**, 369–408 (2018).

## Figures and Tables

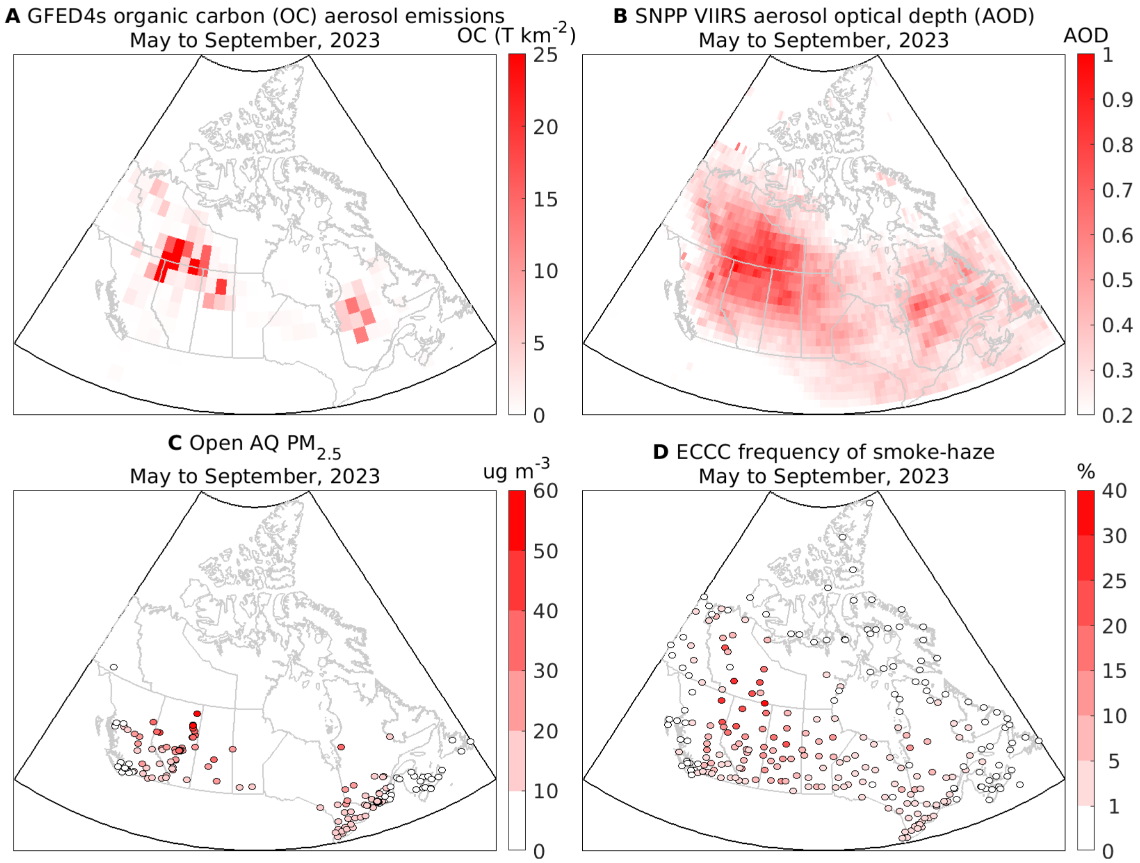


**Figure 1. Smoke from 2023 fires in Canada from satellite *(A, B)* and surface measurements *(C, D)*.** *(A)* Global Fire Emissions Database v4 (GFED4s) organic carbon (OC) aerosol emissions, *(B)* Suomi-National Polar-orbiting Partnership (SNPP) Visible Near Infrared Radiometer Suite (VIIRS) average aerosol optical depth (AOD), *(C)* average particulate matter with diameter less than 2.5 microns ($PM_{2.5}$) from Canadian government sensors in OpenAQ, and *(D)* Environment and Climate Change Canada (ECCC) frequency of smoke-haze reports at weather stations, expressed as a percentage of all hourly reports.

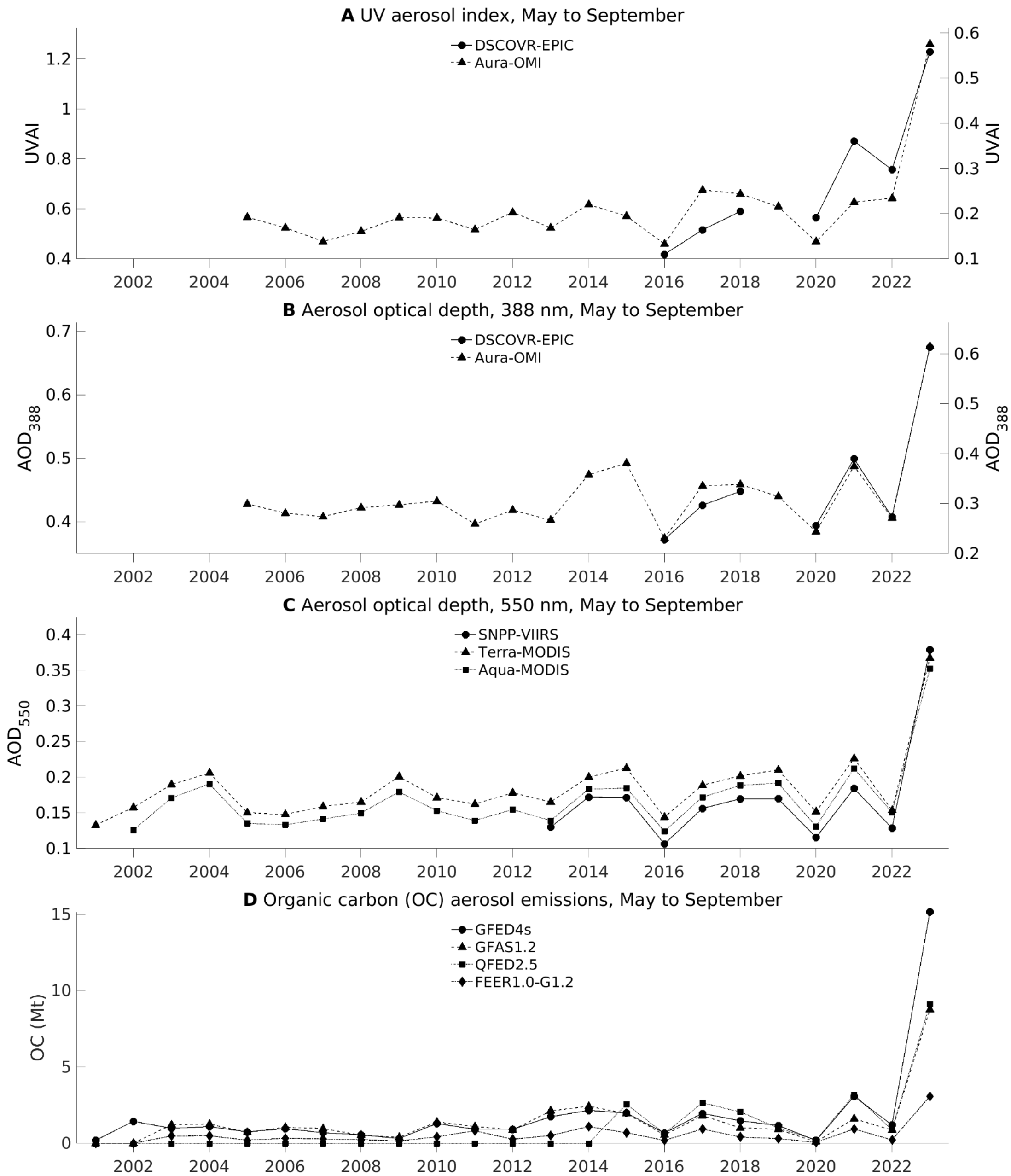


**Figure 2. Satellite-based aerosol retrievals and fire emissions averaged over all of Canada for May-September showing the record 2023 levels of smoke.** *(A)* Deep Space Climate Observatory (DSCOVR) Earth Polychromatic Imaging Camera (EPIC) and Aura Ozone Monitoring Instrument (OMI) ultraviolet aerosol index (UVAI), *(B)* DSCOVR EPIC and Aura OMI aerosol optical depth (AOD) at 388 nm, *(C)* Suomi-National Polar-orbiting Partnership (SNPP) Visible Near Infrared Radiometer Suite (VIIRS), Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) AOD at 550 nm and, *(D)* satellite-based organic carbon (OC) biomass burning aerosol emissions from the Global Fire Emissions Database v4 (GFED4s), the Global Fire Assimilation System v1.2 (GFAS1.2), Quick Fire Emissions Database v2.5 (QFED2.5), and Fire Energetics and Research (FEER) v1.0-G1.2.

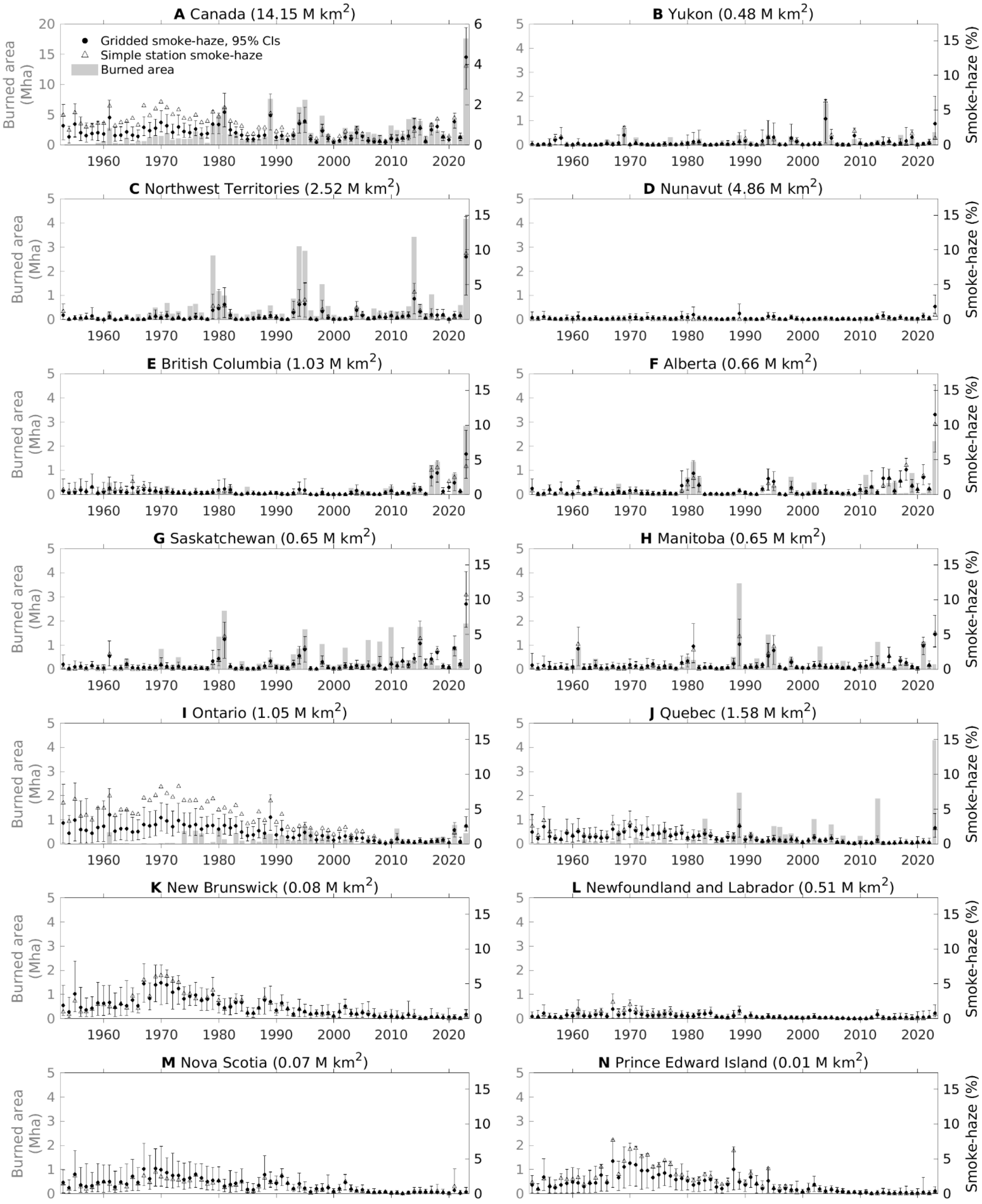


**Figure 3. Long-term records of smoke-haze show air pollution increases in western Canada and decreases in eastern Canada.** Each panel shows the Environment Canada and Climate Change (ECCC) May-September smoke-haze frequency since 1953 and the Canadian Forest Service National Fire Database (NFDB) annual burned area since 1959 *(A)* nationally and *(B-N)* by province and territory. Provincial and territorial areas shown in the captions include surrounding marine areas. Mean ECCC smoke-haze is shown for the gridded estimate with 95% confidence intervals and for the simple average across stations in each province and territory.

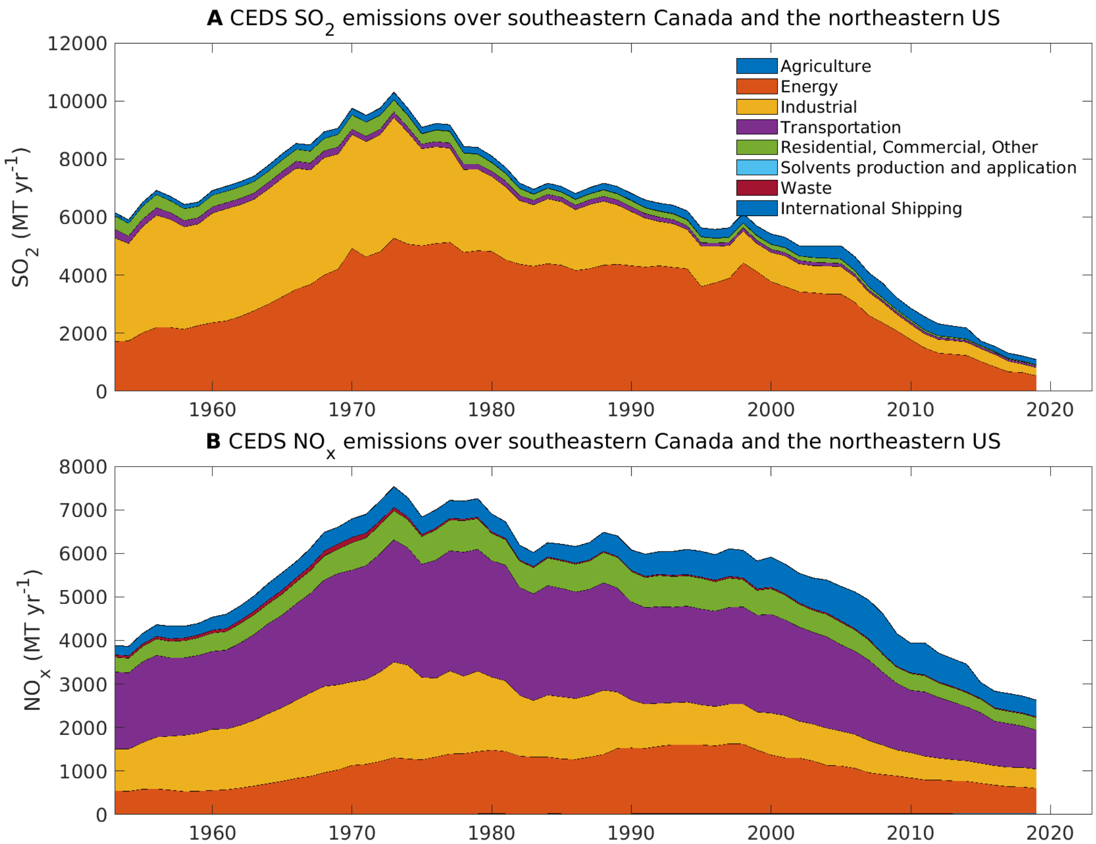


**Figure 4. Air quality improvements in eastern Canada since the 1970s were driven by declining non-fire emissions.** Community Emissions Data System (CEDS) (95) May-September total non-biomass burning emissions estimates of *(A)* sulfur dioxide ($SO_2$) and *(B)* nitrogen oxides ($NO_x$) across eight major sectors for southeastern Canada and the northeast US (39°N to 50°N, 85°W to 50°W).

**Table 1. Theil-Sen trends in May-September Environment Canada and Climate Change (ECCC) smoke-haze frequency (% $yr^{-1}$) for different periods during 1953-2023.** Only trends significant at a 95% confidence level are shown. Trends ending in 2022 are more meaningful because of the strong influence of 2023. All types of weather stations are included. Provincial and territorial abbreviations are: Yukon Territory (YT), Northwest Territories (NWT), Nunavut (Nvt), British Columbia (BC), Alberta (Alta), Saskatchewan (Sask), Manitoba (Man), Ontario (Ont), Québec (Que), New Brunswick (NB), Newfoundland and Labrador (NL), Nova Scotia (NS), and Prince Edward Island (PEI).

| | Area (M $km^2$) | 1959-1990 | 1991-2022 | 1991-2023 | 1953-1975 | 1976-1999 | 2000-2022 | 2000-2023 | 1953-2022 | 1953-2023 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Canada** | 14.15 | | | | | | 0.016 | 0.021 | -0.006 | -0.005 |
| **YT** | 0.48 | 0.005 | | | | | | | 0.002 | 0.002 |
| **NWT** | 2.52 | 0.007 | 0.014 | 0.018 | | | 0.025 | 0.029 | 0.004 | 0.005 |
| **Nvt** | 4.86 | | | | | | 0.007 | 0.008 | | |
| **BC** | 1.03 | -0.010 | 0.016 | 0.020 | | | 0.035 | 0.049 | | |
| **Alta** | 0.66 | | 0.027 | 0.032 | | | 0.058 | 0.070 | 0.005 | 0.006 |
| **Sask** | 0.65 | | 0.024 | 0.029 | | | 0.055 | 0.066 | 0.005 | 0.006 |
| **Man** | 0.65 | | | | | | 0.024 | 0.029 | | |
| **Ont** | 1.05 | | -0.031 | -0.029 | | -0.078 | | | -0.041 | -0.040 |
| **Que** | 1.58 | | -0.015 | -0.013 | | -0.041 | | | -0.022 | -0.021 |
| **NB** | 0.08 | | -0.037 | -0.034 | 0.114 | -0.093 | -0.032 | -0.028 | -0.041 | -0.041 |
| **NL** | 0.51 | | | | 0.014 | -0.016 | | | -0.007 | -0.006 |
| **NS** | 0.07 | | -0.031 | -0.029 | 0.070 | -0.057 | -0.016 | -0.014 | -0.033 | -0.032 |
| **PEI** | 0.01 | | -0.028 | -0.027 | 0.107 | -0.079 | -0.017 | -0.015 | -0.033 | -0.032 |

PNAS

## Supporting Information for

# A fire-driven shift in Canadian air quality concerns mirrors trends in the US.

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Supporting text
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## Supporting Information Text

### S1. Aerosol retrievals and emissions estimates

The Ozone Monitoring Instrument (OMI) on board Aura measures ultraviolet and visible radiances with a 2600 km wide swath at a nadir resolution of 13 x 16 $km^2$ resolution. We used the latest Collection 4 version of the qualitative OMI-OMAERUV ultraviolet aerosol index (UVAI) and the aerosol optical depth (AOD), both available from 2005-present (1, 2). The UVAI is observed over all scenes and surfaces, including above-cloud aerosols. The all-sky retrieval combines AOD at 388 nm in cloud-free and above-cloud atmospheres (3, 4).The first 23 rows of OMI were used in the AOD level-3 calculations to avoid sampling and scan biases caused by the instrumental row anomaly issue encountered after 2008. UVAI and AOD at 388nm retrievals are available from the Earth Polychromatic Imaging Camera (EPIC) on board the Deep Space Climate Observatory (DSCOVR) since 2016 (5, 6). We used the version 3 of EPICAERUV UVAI product and the Level-3 AOD product, which both draw on the OMI heritage in retrieving aerosols in clear sky and above-cloud atmospheres, averaging over the full diurnal cycle observed during the sunlit part of the day (7).

The Moderate Resolution Imaging Spectroradiometers (MODIS) have been observing from Terra since 2000 and from Aqua since 2002. From MODIS's multispectral observations, aerosols over the ocean and darker land are retrieved using the "Dark Target" (DT) algorithm (8, 9), and the "Deep Blue" (DB) algorithm over all land (10, 11), including deserts. The two retrievals are combined into a joint level-2 DT/DB product (10) at 10 km resolution (nominal, along the nadir satellite track) and aggregated onto a 1°x1° level 3 product (12). Here we use the Collection 6.1 (C61) MODIS Level 3 daily products at 550 nm. The maximum valid AOD for the standard product is set as 5.0, so that some extreme smoke cases may not be successfully retrieved (13). The first Visible Near Infrared Radiometer Suite (VIIRS) has been observing from Suomi-National Polar-orbiting Partnership (SNPP) since 2012. VIIRS is similar to MODIS, however with some small differences in wavelength bands, spatial resolution, and viewing swaths. Because of interest in continuing the MODIS-era time series into the 2030s and beyond, both the DT and DB retrieval algorithms have been ported to VIIRS, with Level 2 products provided at 6 km resolution (at nadir). Here, we use the DB-only Level 3 daily AERDT_D3_VIIRS_SNPP product (11, 14) beginning in 2013.

Satellite-based estimates of biomass burning emissions from Global Fire Emissions Database v4 with a 'small-fire boost' (GFED4s) (15), the Global Fire Assimilation System v1.2 (GFAS1.2) (16), Quick Fire Emissions Database v2.5 (QFED2.5) (17) and Fire Energetics and Research (FEER) v1.0-G1.2 (18), starting at various points after 2001 to see how direct fire OC emissions in 2023 varied over their records through 2023. We used the Community Emissions Data System (CEDS) (19) to understand non-fire emissions changes in eastern North America since the 1950s for $SO_2$ and nitrogen oxides ($NO_x$) aerosol precursors.

### S2. Reports of 'Smoke' and 'Haze' at Environment Canada and Climate Change (ECCC) weather stations since 1953

Operational weather reports contain coded qualitative descriptions of present weather, primarily to monitor conditions which obscure visibility and affect aviation. Smoke is defined as "a suspension in the air of small particles produced by combustion" and haze is defined as "…a suspension of extremely small, dry particles invisible to the naked eye and sufficiently numerous to give the air an opalescent (milky or pearly) appearance" (20). We included reports of 'haze' for a more complete understanding of air pollution historically and to account for 'smoke' being reported as 'haze' at some stations. Following ECCC's definition of a 'smoke-hour' (D. McClenann, ECCC, pers. comm.), we further required that horizontal visibility was less than 9.7 km to be counted as 'smoke-haze'. Reports of sand, dust and volcanic ash were not considered.

We used as much hourly station data as possible, estimating the combined uncertainty due to changing and spatially uneven weather station coverage, present-weather observing differences between stations, and changing station identifiers for the same or close physical locations. There were a minimum of 179 weather stations reporting in 1953, a maximum of 359 in 2014, and 276 in 2023. Missing weather reports from the ECCC archives were supplemented by those from NOAA National Center for Environmental Information's Integrated Surface Database of global hourly weather observations (21). Later in the record, particularly after 2010, some staffed stations were replaced with automatic stations, where haze is reported whenever visibility is less than 11.3 km, the dew point depression is greater than 2 $^{o}$C to distinguish from fog, and there is no precipitation reported (22). Transitions from staffed to automatic stations can introduce artifacts into these types of time series (23). Sensitivity tests showed no significant effects from these transitions.

For each unique station identifier, we calculated the frequency of hourly weather observations reporting 'smoke' or 'haze' from May to September of each year. To get provincial averages and their uncertainty, the average frequency of smoke-haze hours for each summer between 1953 and 2023 was gridded from the stations using bootstrapping (24). For each bootstrap iteration, a random sample with replacement of 20% of the stations was interpolated to a 1$^{o}$ x 1$^{o}$ grid over Canada. The provincial and territorial average smoke-haze frequency for each year was calculated from these grid cells, each weighted by the cosine of the grid cell's latitude as a means of area-weighting. This process was repeated 500 times, each time using a different random sample of stations. The provincial and territorial averages and their 95% confidence intervals were taken from this 500 resample distribution.

We have not calibrated the smoke-haze data in the same way that horizontal visibility has been used as a $PM_{2.5}$ proxy (25) or to estimate pre-satellite biomass burning emissions (26). Rather, we use smoke-haze to distinguish between pollution conditions each summer between years and regions in the absence of continuous, spatially-representative PM measurements (27).

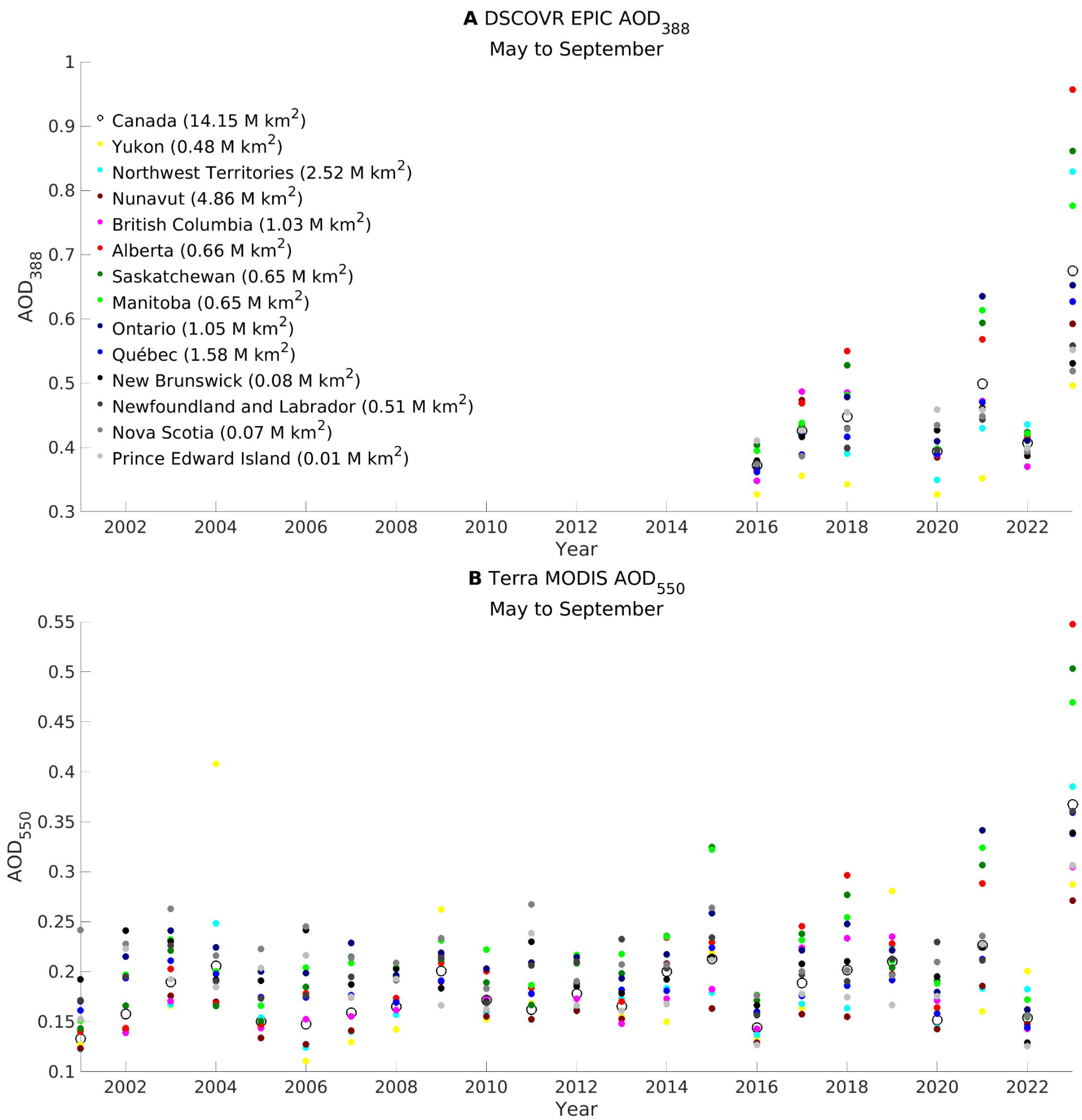


**Fig. S1.** May-September aerosol optical depth (AOD) by province and territory for *(A)* Earth Polychromatic Imaging Camera (EPIC) at 388 nm on board the Deep Space Climate Observatory (DSCOVR) 1.5 M km away from the Earth between the sun and *(B)* since 2001 from the Moderate Resolution Imaging Spectroradiometer (MODIS) at 550 nm on board Terra.

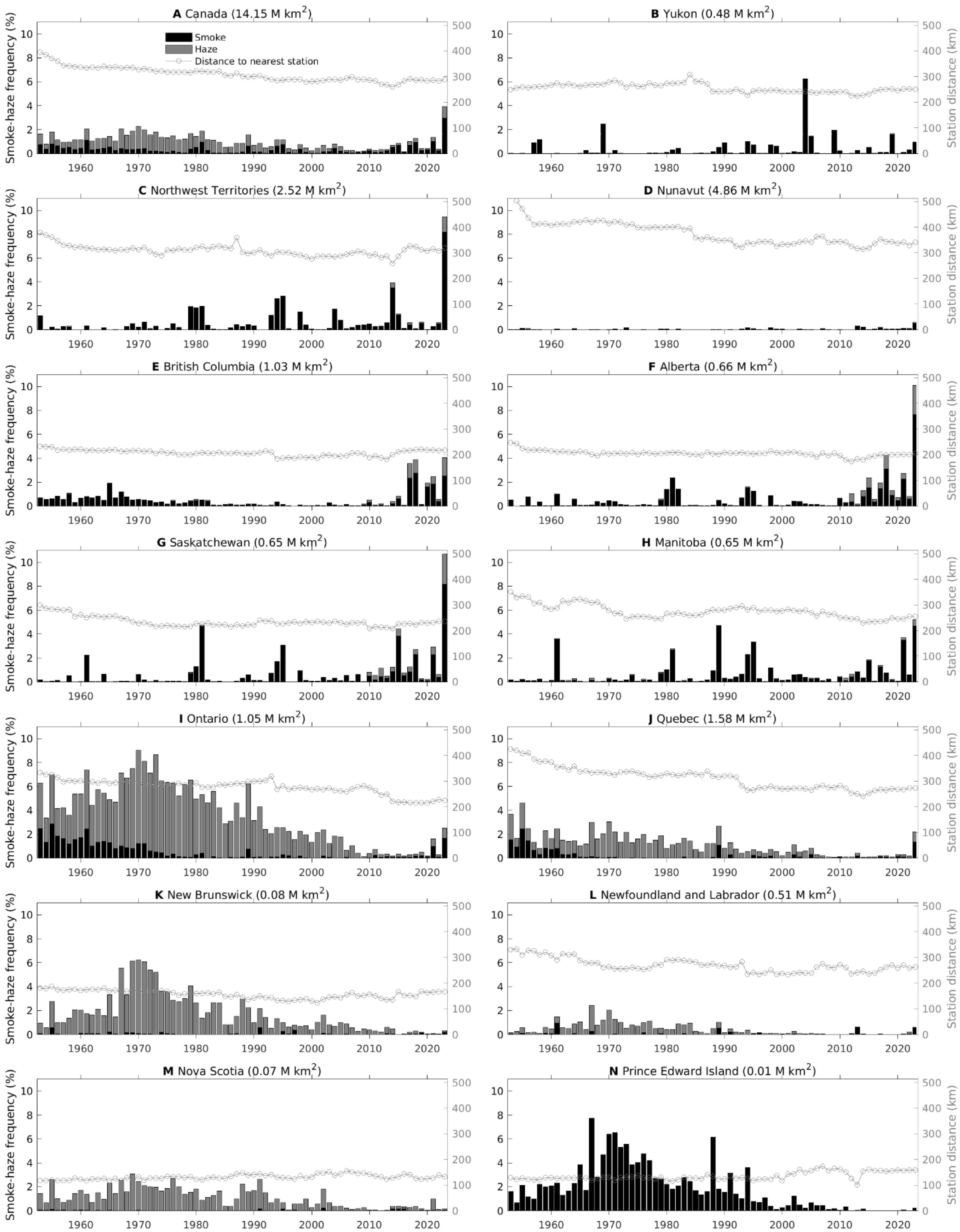


**Fig. S2.** Breakdown between smoke and haze reports, and average distance to nearest ECCC station across *(A)* all of Canada and *(B-N)* over each province and territory. Lower average distances to stations indicate more complete station coverage.

**Table S1.** Summary of data used in study.

| Source | Products | Period | Description |
|---|---|---|---|
| Terra Moderate Resolution Imaging Spectroradiometer (MODIS) | Aerosol optical depth (AOD) | 2001-2023 | Column aerosol loads, mostly in troposphere, limited retrieval ability in clouds and thick smoke |
| Aqua MODIS | AOD | 2002-2023 | Column aerosol loads, mostly in troposphere, limited retrieval ability in clouds and thick smoke |
| Aura Ozone Monitoring Instrument (OMI) | Ultraviolet aerosol index (UVAI), AOD | 2005-2023 | UV and visible, meant for ozone, limited ability in clouds and thick smoke |
| Suomi-National Polar-orbiting Partnership (SNPP) Visible Near Infrared Radiometer Suite (VIIRS) | AOD | 2012-2023 | Successor to MODIS |
| Deep Space Climate Observatory (DSCOVR) Earth Polychromatic Imaging Camera (EPIC) | UVAI, AOD | | Located at Lagrange point 1, 1.5 M km away from Earth toward the sun, data every 15 minutes, OMI aerosol retrieval heritage |
| | | | |
| Canadian Forest Service (CFS) National Fire Database (NFDB) | Annual burned area from provinces and territorial agencies | 1959-2023 | Records from fire-fighting agencies |
| Environment Canada and Climate Change Weather stations | Reports of ‘smoke’ and ‘haze’ from present weather section | 1953-2023 | Qualitative codes in weather records and horizontal visibility |

**Table S2.** Same as Table 1, but for staffed stations only.

| | Area (M km$^2$) | 1959-1990 | 1991-2022 | 1991-2023 | 1953-1975 | 1976-1999 | 2000-2022 | 2000-2023 | 1953-2022 | 1953-2023 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Canada** | 14.15 | | | | | | | 0.057 | -0.005 | |
| **YT** | 0.48 | | | | | 0.023 | | | | 0.009 |
| **NWT** | 2.52 | | | | | | | | 0.009 | 0.018 |
| **Nvt** | 4.86 | | | | | | | 0.028 | | |
| **BC** | 1.03 | -0.010 | 0.037 | 0.063 | | | 0.065 | 0.111 | | 0.011 |
| **Alta** | 0.66 | | 0.038 | 0.091 | | | 0.090 | 0.184 | 0.014 | 0.026 |
| **Sask** | 0.65 | | | 0.072 | | | 0.075 | 0.153 | 0.013 | 0.023 |
| **Man** | 0.65 | | | | | | | 0.088 | | |
| **Ont** | 1.05 | | -0.035 | | | -0.070 | | | -0.040 | -0.037 |
| **Que** | 1.58 | | -0.024 | | | -0.042 | -0.028 | | -0.024 | -0.022 |
| **NB** | 0.08 | | -0.050 | -0.044 | 0.127 | -0.094 | -0.052 | -0.042 | -0.047 | -0.046 |
| **NL** | 0.51 | | -0.009 | | 0.021 | -0.019 | | | -0.009 | -0.009 |
| **NS** | 0.07 | | -0.053 | -0.050 | 0.082 | -0.053 | -0.044 | -0.040 | -0.036 | -0.035 |
| **PEI** | 0.01 | | -0.052 | 0.048 | 0.128 | -0.070 | -0.038 | -0.033 | -0.038 | -0.038 |

**Table S3.** Same as Table 1, but using ordinary least-squares linear regression trend estimates in place of Theil-Sen trend estimator.

| | Area (M $km^2$) | 1959-1990 | 1991-2022 | 1991-2023 | 1953-1975 | 1976-1999 | 2000-2022 | 2000-2023 | 1953-2022 | 1953-2023 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Canada** | 14.15 | | | | | | .0021 | 0.058 | -0.005 | |
| **YT** | 0.48 | | | | | 0.021 | | | | 0.008 |
| **NWT** | 2.52 | | | | | | | 0.106 | 0.008 | 0.017 |
| **Nvt** | 4.86 | | | 0.012 | | | 0.010 | 0.026 | | |
| **BC** | 1.03 | -0.010 | 0.038 | 0.063 | | | 0.067 | 0.111 | | 0.010 |
| **Alta** | 0.66 | | 0.041 | 0.094 | | | 0.090 | 0.186 | 0.013 | 0.025 |
| **Sask** | 0.65 | | | 0.073 | | | 0.075 | 0.151 | 0.012 | 0.022 |
| **Man** | 0.65 | | | | | | 0.049 | 0.087 | | |
| **Ont** | 1.05 | | -0.029 | | | -0.073 | | | -0.040 | -0.037 |
| **Que** | 1.58 | | -0.017 | | | -0.041 | -0.016 | | -0.023 | -0.020 |
| **NB** | 0.08 | | -0.043 | -0.039 | 0.128 | -0.093 | -0.039 | -0.033 | -0.046 | -0.045 |
| **NL** | 0.51 | | | | | -0.019 | | | -0.007 | -0.007 |
| **NS** | 0.07 | | -0.042 | -0.040 | 0.075 | -0.055 | -0.028 | -0.025 | -0.033 | -0.033 |
| **PEI** | 0.01 | | -0.043 | -0.040 | 0.126 | -0.073 | -0.028 | -0.024 | -0.037 | -0.037 |

**SI References**


1. O. Torres, *et al.*, Aerosols and surface UV products from Ozone Monitoring Instrument observations: An overview. *J. Geophys. Res. Atmospheres* **112** (2007).
2. O. Torres, C. Ahn, Z. Chen, Improvements to the OMI near-UV aerosol algorithm using A-train CALIOP and AIRS observations. *Atmospheric Meas. Tech.* **6**, 3257–3270 (2013).
3. H. Jethva, O. Torres, C. Ahn, A 12-year long global record of optical depth of absorbing aerosols above the clouds derived from the OMI/OMACA algorithm. *Atmospheric Meas. Tech.* **11**, 5837–5864 (2018).
4. O. Torres, H. Jethva, P. K. Bhartia, Retrieval of Aerosol Optical Depth above Clouds from OMI Observations: Sensitivity Analysis and Case Studies. *J. Atmospheric Sci.* **69**, 1037–1053 (2012).
5. C. Ahn, O. Torres, H. Jethva, R. Tiruchirapalli, L.-K. Huang, Evaluation of Aerosol Properties Observed by DSCOVR/EPIC Instrument From the Earth-Sun Lagrange 1 Orbit. *J. Geophys. Res. Atmospheres* **126**, e2020JD033651 (2021).
6. A. Marshak, *et al.*, Earth Observations from DSCOVR EPIC Instrument. *Bull. Am. Meteorol. Soc.* **99**, 1829–1850 (2018).
7. O. Torres, C. Ahn, Local and Regional Diurnal Variability of Aerosol Properties Retrieved by DSCOVR/EPIC UV Algorithm. *J. Geophys. Res. Atmospheres* **129**, e2023JD039908 (2024).
8. R. C. Levy, *et al.*, The Collection 6 MODIS aerosol products over land and ocean. *Atmospheric Meas. Tech.* **6**, 2989–3034 (2013).
9. R. C. Levy, *et al.*, Exploring systematic offsets between aerosol products from the two MODIS sensors. *Atmospheric Meas. Tech.* **11**, 4073–4092 (2018).
10. A. M. Sayer, *et al.*, MODIS Collection 6 aerosol products: Comparison between Aqua's e-Deep Blue, Dark Target, and "merged" data sets, and usage recommendations. *J. Geophys. Res. Atmospheres* **119**, 13,965-13,989 (2014).
11. A. M. Sayer, N. C. Hsu, J. Lee, W. V. Kim, S. T. Dutcher, Validation, Stability, and Consistency of MODIS Collection 6.1 and VIIRS Version 1 Deep Blue Aerosol Data Over Land. *J. Geophys. Res. Atmospheres* **124**, 4658–4688 (2019).
12. R. C. Levy, *et al.*, A Critical Look at Deriving Monthly Aerosol Optical Depth From Satellite Data. *IEEE Trans. Geosci. Remote Sens.* **47**, 2942–2956 (2009).
13. Y. R. Shi, *et al.*, Characterizing the 2015 Indonesia fire event using modified MODIS aerosol retrievals. *Atmospheric Chem. Phys.* **19**, 259–274 (2019).
14. N. C. Hsu, *et al.*, VIIRS Deep Blue Aerosol Products Over Land: Extending the EOS Long-Term Aerosol Data Records. *J. Geophys. Res. Atmospheres* **124**, 4026–4053 (2019).
15. G. R. van der Werf, *et al.*, Global fire emissions estimates during 1997–2016. *Earth Syst. Sci. Data* **9**, 697–720 (2017).
16. J. W. Kaiser, *et al.*, Biomass burning emissions estimated with a global fire assimilation system based on observed fire radiative power. *Biogeosciences* **9**, 527–554 (2012).
17. A. S. Darmenov, A. M. da Silva, "The Quick Fire Emissions Dataset (QFED):Documentation of Versions 2.1, 2.2 and 2.4" (NASA, 2015).
18. C. Ichoku, L. Ellison, Global top-down smoke-aerosol emissions estimation using satellite fire radiative power measurements. *Atmospheric Chem. Phys.* **14**, 6643–6667 (2014).
19. R. M. Hoesly, *et al.*, Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS). *Geosci. Model Dev.* **11**, 369–408 (2018).
20. ECCC, "MANOBS Manual of Surface Weather Observation Standards" (Environment and Climate Change Canada, 2023).
21. A. Smith, N. Lott, R. Vose, The Integrated Surface Database: Recent Developments and Partnerships. *Bull. Am. Meteorol. Soc.* **92**, 704–708 (2011).
22. NOAA, "Automated Surface Observing System (ASOS) User's Guide" (1998).
23. Y. Yu, Z. Ren, X. Meng, Reconstruction of daily haze data across China between 1961 and 2020. *Int. J. Climatol.* **42**, 5629–5643 (2022).

24. B. Efron, G. Gong, A Leisurely Look at the Bootstrap, the Jackknife, and Cross-Validation. *Am. Stat.* **37**, 36–48 (1983).
25. H. Jethva, *et al.*, Connecting Crop Productivity, Residue Fires, and Air Quality over Northern India. *Sci. Rep.* **9**, 16594 (2019).
26. M. J. E. van Marle, *et al.*, Historic global biomass burning emissions for CMIP6 (BB4CMIP) based on merging satellite observations with proxies and fire models (1750–2015). *Geosci. Model Dev.* **10**, 3329–3357 (2017).
27. Environment Canada, “Canadian Environmental Sustainability Indicators” (2005).