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LETTER

Record-breaking persistent high-pressure systems fueled unprecedented Canadian wildfire disasters in 2023

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Abstract

Canada experienced its most severe wildfire season on record in 2023, with nearly 5% of its forested land burned-almost four times the previous record set in 1995. Our analysis indicated that fire severity, strongly correlated with the monthly Fire Weather Index (FWI), was most intense in the western provinces and territories during May and July, whereas in the eastern provinces, it peaked in June, leading to a seasonal and areal average of more than 3.5 standard deviations (STD). This unprecedented fire activity was fueled by record-breaking, persistent high-pressure systems, with both their frequency and intensities surpassing 3 STD, along with variable winds. These abnormal atmospheric patterns exacerbated dry conditions, reduced cloud cover, and increased surface solar radiation, driving record-high temperatures and FWI values, all exceeding $\pm$3 STD. The extreme high-pressure events were primarily linked to a combination of climatological standing waves and exceptionally strong, transient quasi-stationary waves. The dominant patterns in the mid-troposphere were characterized by large-scale planetary waves at low zonal wavenumbers (1–4). Long-term warming trends also contributed, though they played a lesser role, accounting for roughly 10–20% of the overall anomalies. These findings provide critical insights into the atmospheric dynamics driving Canada's unprecedented wildfire season.

1. Introduction

The Canadian wildfires in the summer of 2023 (red bar in figure 1(a); CWFIS; Jain *et al* 2024) burned 185,000 km^2 of forest, representing around 5% of the nation's total forest area and exceeding by a factor of 3.6 the previous record set in 1995 (black bar in figure 1(a), MacCarthy *et al* 2024). These unprecedented wildfires triggered significant disasters (Adu *et al* 2024, Byrne *et al* 2024, Lowe and Garfin 2023, MacCarthy *et al* 2024, Wang *et al* 2024), including intense wildfire smoke in early June from Quebec that blanketed the Northeastern USA. The maximum daily $PM_{2.5}$ concentration reached 150 μg m^{-3}, the highest recorded in this region during the past 50 years (Wang *et al* 2024). The fires released around 1.44 Pg CO_2 and equivalents, more than doubling Canada's planned cumulative greenhouse gas reduction for the next decade (Byrne *et al* 2024). Additionally, the wildfires significantly increased the ozone (Schneider *et al* 2024), carbon monoxide (Shakoor *et al* 2023), and smoke levels in the lower atmosphere, posing serious public health risks (Adu *et al* 2024, Lowe and Garfin 2023). Understanding the factors driving these record-breaking wildfires is essential for future prediction (Guindon *et al* 2021), preparedness (Hoffman *et al* 2022, Karimi 2024), and management (Lyons *et al* 2023, Mihalus *et al* 2024).

Recent research has linked past Canadian wildfire seasons and recent increasing trend in ignition and intensity to ongoing climate warming (Robinne *et al* 2016, Mamuji and Rozdilsky 2019, Hu *et al* 2024) and

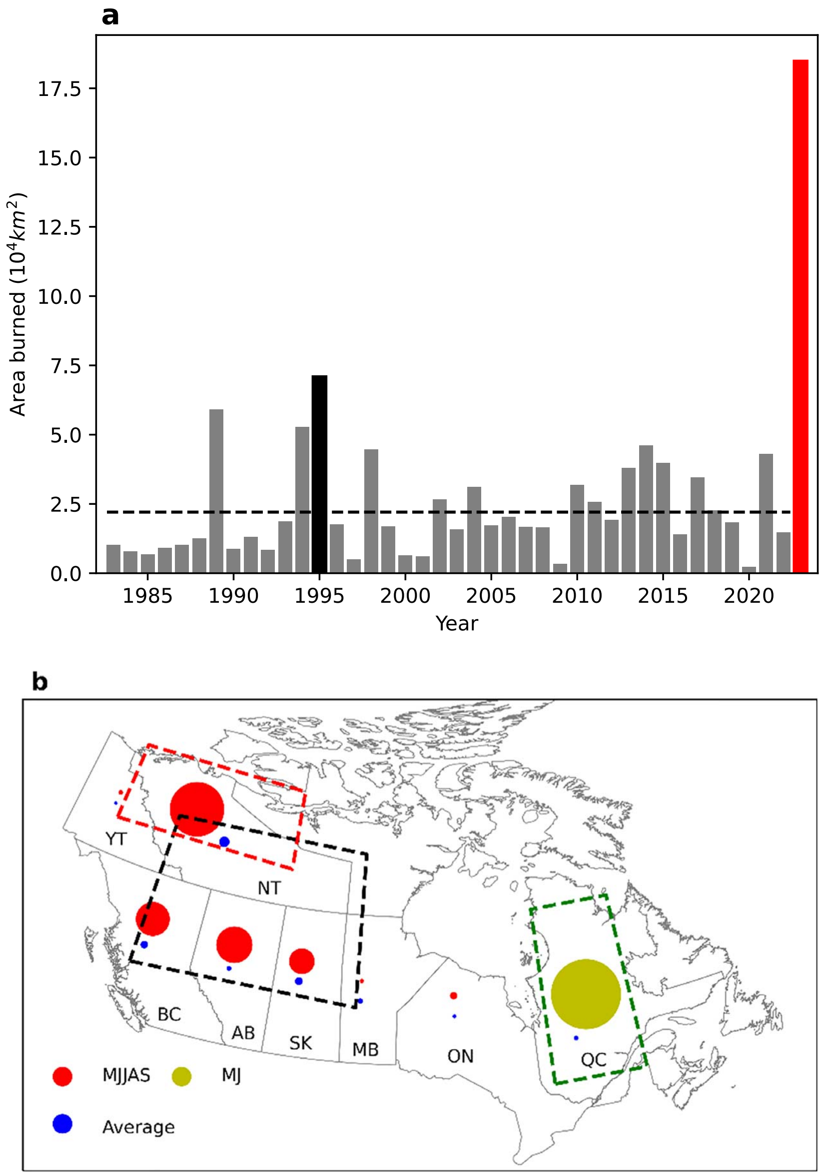

Figure 1. (a) Annual burned area in Canada (10^4 km^2) from 1983 to 2023, with dashed lines indicating the 1983–2022 average. The red bar highlights the record-breaking burned area in 2023, exceeding the previous record in 1995 (black bar). (b) Spatial distribution of burned areas across key provinces and territories during the 2023 wildfire season (May–September). Red dots represent the total burned area in 2023, yellow dots indicate areas burned in May and June, and blue dots represent the 1983–2022 average. Dot sizes correspond to the magnitude of the burned area. Major burned areas in May (black box), June (green box), and July (red box) are highlighted for further analysis.

expanding high-pressure systems in the atmosphere (Sharma *et al* 2022, Hu *et al* 2024). As a first-order approximation, climate warming is indicated by a steady increase in near-surface air temperature (T_{2m}), which is projected to double the frequency of Canadian wildfires and increase their intensity by providing warmer conditions for fire ignition and burning (Dennison *et al* 2014, Schoennagel *et al* 2017, Wotton *et al* 2017, Boulanger *et al* 2018). On the other hand, atmospheric high-pressure systems, manifested as either open ridges or blocking highs characterized by a reversal of zonal winds therein (Liu 2020), provide large-scale warming and moderately-weakened wind conditions favorable to wildfire ignition and spread, in particular when they persist for a prolonged period in the form of positive anomalies of the atmospheric flow (Sharma *et al* 2022). On average, 17% of May–September days experience persistent positive anomalies of mid-tropospheric flows in North America, where large fires (burned area of more than 500 hectares) were seven times as likely to start (Sharma *et al* 2022).

The record-breaking 2023 Canadian wildfire season did not result from an unprecedented number of ignitions, however, and the season exhibited significant variability across time and regions (CWFIS). Using the monthly average fire count over the past decade as a baseline, fire frequency in 2023 surpassed the average by 20% in May and July and by 5% in June but fell 14% below the average in August. This led to an overall seasonal ignition rate that was 8% lower than the long-term average (CWFIS). Persistent burning primarily occurred in the northwestern provinces and territories-British Columbia (BC), Alberta (AB), and Saskatchewan (SK)-in May, where the burned area was 7 to 20 times the average (figure 1(b), black box). In June, widespread fires were observed in Quebec (QC) (figure 1(b), green box), followed by extensive burning in Yukon (YT) and the Northwest Territories (NT) in July (figure 1(b), red box). Wildfire impacts began as early as May, prompting the highest National Preparedness Level 5 in eastern Canada, and intensified across the northwestern provinces in June and July, with some fires persisting into September (CWFIS). This variability highlights the need to better understand the factors driving the record-breaking wildfire persistence observed at monthly time scales, particularly from May to July, as highlighted by recent seasonal analyses (Hu *et al* 2024, Jain *et al* 2024).

The high spatial and temporal variability underscores the complexities of wildfire dynamics (Nature 2019), driven by multiple factors (Gralewicz *et al* 2012, Gaboriau *et al* 2022, Burton 2023), particularly meteorological conditions that promote dry, warm environments (Girardin and Wotton 2009, Elmes *et al* 2018, Kochtubajda *et al* 2019, Tymstra *et al* 2021, Byrne *et al* 2024). Our study examines how persistent high-pressure systems contributed to the unprecedentedly persistent dry and hot conditions in May–July 2023 and explores the dynamical origins of these systems. Additional factors (Jain *et al* 2024) influencing large wildfires in Canada-including land cover, forest composition, tree phenology (Parisien *et al* 2023), elevation, permafrost reduction (Zhang *et al* 2015), ignition sources (Gralewicz *et al* 2012b, Coogan *et al* 2020, Aftergood and Flannigan 2022) forest management, and the timing of snowmelt and green-up (Gaboriau *et al* 2022)-are beyond the scope of this analysis.

2. Data and methods

2.1. Data

The wildfire conditions from 1983 to 2023 were readily available from the Canadian Wildland Fire Information System (CWFIS, https://cwfis.cfs.nrcan.gc.ca/home). During the same period, meteorological data and Fire Weather Index (FWI) products at a daily interval and a spatial resolution of $0.25° \times 0.25°$ latitude by longitude were sourced from the ERA5 reanalysis (Hersbach *et al* 2020) archives via the Climate Data Store (https://cds.climate.copernicus.eu). Variables such as near-surface air temperature (T2m), cloud cover, and net surface solar radiation are also drawn from ERA5. Monthly precipitation at a spatial resolution of $2.5° \times 2.5°$ latitude by longitude was provided by the Global Precipitation Climatology Project (Huffman *et al* 1997).

2.2. Selection of regions

In figure 1(b) we highlight three regional boxes representing May (black), June (green), and July (red). Each box was selected to encompass the contiguous area of exceptionally high monthly FWI anomalies and frequent, persistent high-pressure systems, as determined from preliminary monthly composite maps. While these boxes loosely represent administrative boundaries (e.g., BC, AB, SK in May), their exact extents reflect where anomalous FWI and persistent high-pressure systems were strongest, which sometimes extend beyond single provinces.

2.3. Linear trend

A simple linear trend was fitted using the conventional least-squares method to relevant variables spanning 1983 to 2022, including the FWI and near-surface temperature (T2m) within each region outlined in figure 1(b). Specifically, if ΔT_{trend} is the extrapolated linear trend for 2023 (from 1983–2022), and $\Delta T_{total}(2023)$ is the observed 2023 anomaly, then the fraction of the anomaly explained by the trend is $\Delta T_{trend}/\Delta T_{total}(2023) \times 100\%$. Similar results were cross-validated with the Theil-Sen estimator.

2.4. Detection of persistent high-pressure systems

A high-pressure system appears as an open ridge or isolated high-value region at daily 500-hPa geopotential heights (Z500). It is effectively represented by contiguous positive zonal eddy anomalies in Z500, exceeding the 75th percentile of a 30-day window centered on each day from 1983–2022, after subtracting the zonal mean at each latitude. The daily zonal anomalies retain climatological standing components that are essential to forming persistent high-pressure systems, as discussed below. The persistence of these high-pressure systems is characterized by consecutive daily occurrences with overlapping areas, typically covering at least three grid points at a $2.5° \times 2.5°$ resolution (approximately 235,000 km^2) and maintaining a quasi-standing speed of under 5 m s^{-1}. The system's intensity is defined as the time-averaged zonal eddy anomalies of Z500 within the high-pressure region. More details are available in (Liu *et al* 2018, Liu 2020, Liu *et al* 2022).

2.5. Climatological standing waves (CSWs) and transient quasi-standing waves (TQSWs)

We define 'climatology' for each day of the year and each grid point by combining the long-term (1983–2022) mean plus the first four harmonics of the annual cycle. This yields a smoothly varying daily baseline at each grid point. We then subtract this climatology from the full field to derive 'transient anomalies.'

- **CSWs** (climatological standing waves): We first remove the zonal mean at each latitude from the 1983–2022 *climatology*, so that remaining deviations represent the typical stationary ridges and troughs anchored by land-sea contrasts, topography, and the atmospheric seasonal cycle (Ting 1994).
- **TQSWs** (transient quasi-standing waves): For daily 2023 data, we subtract the climatology and apply a compositing approach that filters out fast-propagating waves, thus isolating long-lived or quasi-stationary planetary-scale anomalies.
- **Wavenumbers**: We then apply a discrete Fourier transform in the zonal direction (longitude) at the latitude crossing each box's center. 'Zonal wavenumber 1' implies a single wave crest-trough pattern around 360°, while 'wavenumber 2' implies two such wave patterns, etc. Wavenumbers 1–4 typically represent large-scale planetary waves; higher wavenumbers (e.g., 6–8) can be associated with more localized or resonant heatwave events (Petoukhov *et al* 2016).

This decomposition (figure 5 below) allows us to distinguish the persistent high-pressure systems driven by (a) relatively stable, climatologically anchored ridges (CSWs) from (b) unusually strong or lingering transient waves (TQSWs). More details about the decomposition are provided in Wilks (2006).

3. Results

3.1. Record-breaking FWI and meteorological conditions

The severity, extent, and persistence of wildfires result from the combined effects of favorable environmental factors, including dry, hot atmospheric conditions, variable winds, low moisture in subsurface organic layers, and available wood fuel. This combination is effectively represented by the Canadian Fire Weather Index (FWI), which integrates a fire spread index-accounting for wind speed and fine fuel moisture—and a buildup index of the total fuel available for combustion (Van Wagner and Pickett 1985). Because these variables can only be monitored in real time over a limited network of weather and wildfire stations or incomplete satellite coverage across Canada's forested regions (Hope *et al* 2024, Zhang *et al* 2024), ERA5 has been utilized to provide continuously high-spatial resolution FWI values. This allows for the analysis and attribution of wildfires over extensive areas and extended time periods (Vitolo *et al* 2020).

In the summer of 2023, the ERA5 FWI shows abnormally high values across Canada, marked by significant spatial and temporal variations (figures 2(a)–(c). Notably, FWI conditions exceeding two standard deviations (STD) above the 1983–2022 baseline, indicated by black dots, were concentrated in western Canada in May (figure 2(a)). In June, these extreme conditions shifted, becoming dispersed across the southern and eastern regions, with peak values observed in Quebec and Ontario (figure 2(b)). By July, high FWI conditions expanded again in western Canada, particularly affecting the northwestern and southwestern regions (figure 2(c)). These exceptionally high FWI values, indicative of environmental conditions favorable for wildfire activity, closely correspond to the burned areas in the highlighted regions, making them a useful proxy for wildfires analysis. Note that Ontario's high June FWI values did not translate into large burned areas, likely due to fewer ignitions and local fuel conditions.

The elevated monthly FWI ratings were driven and sustained by record-breaking, persistent high-pressure systems in the troposphere. These systems, which strongly coincided with and created favorable conditions for wildfires at unprecedented level, occurred and lingered within or near the three designated areas for extended durations: up to 28 days in May (figure 2(d)), 22 days in June (figure 2(e)), and nearly the entire month of July (figure 2(f)). This persistence set records, exceeding 3 STD above the average in May (yellow, figures 2(d), 2 STD in June (brown, figures 2(e), and 4 STD in July (purple, figure 2(f)). When the normalized occurrence days across the three highlighted regions are combined, the anomalous persistence surpasses 3 STD (figure 3(a)), significantly higher than the value of just over 1 STD observed in 1995, when the last record for burned area by wildfires was established (cf figure 1(a)).

Dynamically, these record-breaking, persistent high-pressure systems generated anticyclonic and notably weak winds (blue vectors in figures 2(d)–(f) at 1000 hPa (approximately 100–110 m above mean sea level). This stable, persistent, and tranquil atmospheric environment fostered warm and dry conditions, which are shown in figure 3 and discussed further below, resulting in consistently severe FWI ratings that exceeded two STDs (figures 2(a)–(c). Despite the predominance of weak winds and more days below climatological wind speeds,

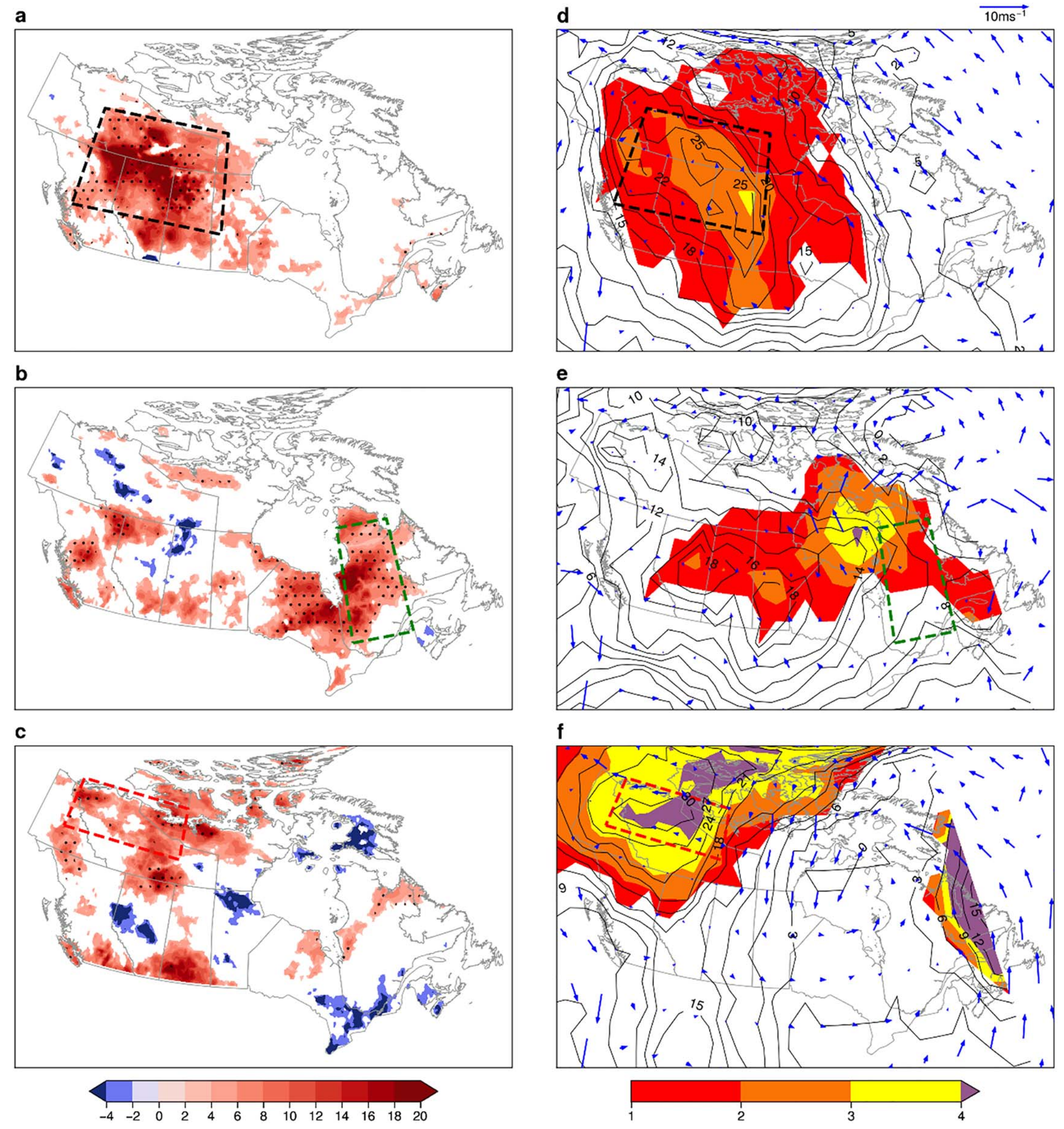

Figure 2. FWI anomalies and persistent high-pressure systems during the 2023 wildfire season. Panels (a)–(c) show monthly FWI anomalies in May, June, and July 2023, with black dots indicating regions exceeding two standard deviations (STD) above the 1983–2022 baseline. Panels (d)–(f) depict the spatial distribution of persistent high-pressure systems in the same months. Contour labels indicate the number of days high-pressure systems persisted at each grid point; shading shows how many standard deviations above (or below) the mean the persistence extended. Blue vectors represent 1000-hPa wind patterns, included to illustrate weak flow beneath these systems and how it contributed to prolonged hot, dry conditions.

intermittent episodes of stronger-than-climatology surface winds were observed (figure 4). Figure 4 shows the daily mean wind speeds averaged over each monthly box, with values below 3–5 m s^{-1} most days; we have omitted standard-deviation bars for clarity, but these daily box-averaged speeds do not preclude localized stronger gusts. The higher maximum wind speeds in June corresponded to a larger climatological mean and box's position east of the persistent high-pressure center (figure 2(e)). These localized wind episodes aligned with weaker or transitioning phases of the high-pressure systems (not shown). Even a modest increase in wind speed-on the order of 10%-can yield a roughly 10% increase in the forward spread rate of a fire (Cruz and Alexander 2019), underscoring how seemingly minor wind changes can significantly influence wildfire behavior.

The unprecedented high-pressure systems over the three-month period stand out as key drivers of extreme meteorological conditions. These systems not only persisted for an exceptional length of time but also exhibited record-breaking intensity, with their combined normalized magnitudes surpassing 3 STD, as indicated by the black and red lines in figure 3(a). The extraordinary persistence and strength of these high-pressure systems set the stage for unprecedented FWI levels and highly favorable meteorological conditions across the three highlighted regions. Specifically, the FWI (figure 3(b)) exceeded an astonishing 3.5 STD, significantly outpacing

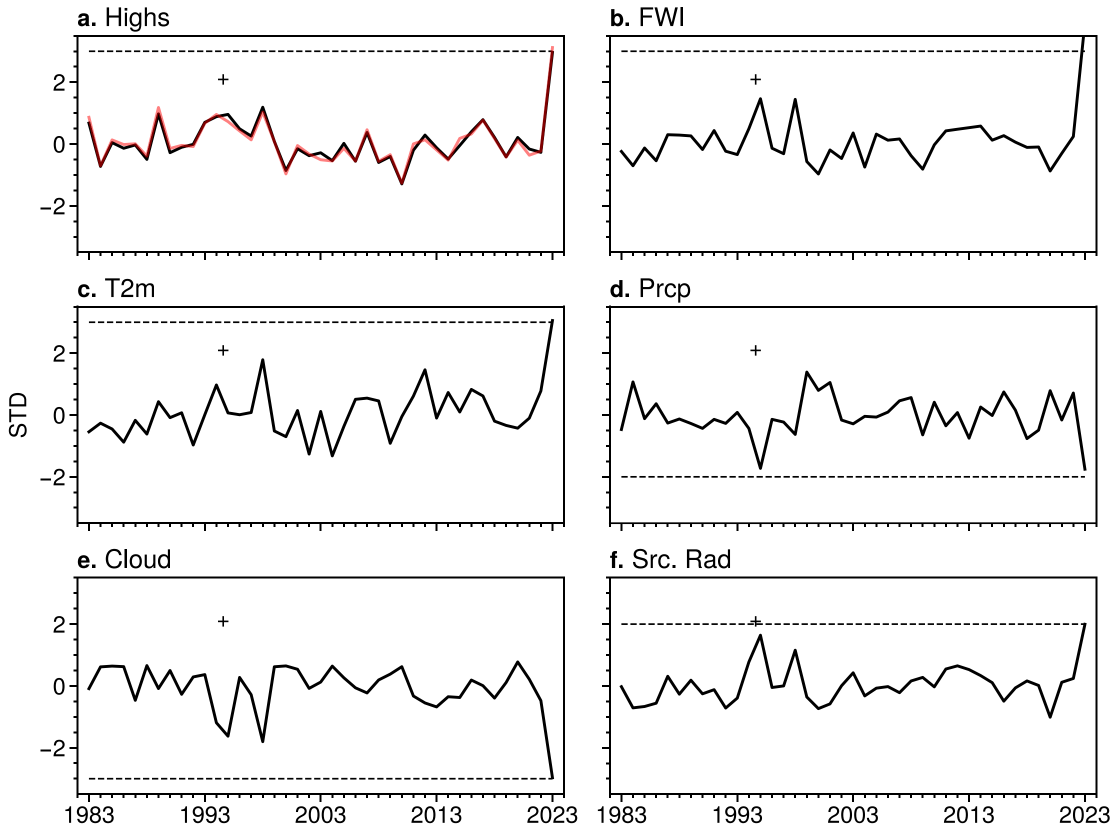

Figure 3. May–July 2023 averages of box-mean standardized variables associated with persistent high-pressure systems and wildfire conditions. (a) Occurrence (black line) and intensity (red line) of persistent high-pressure systems, both exceeding three standard deviations (STD) compared to the 1983–2022 baseline. (b)–(f) Anomalies of the Fire Weather Index (FWI), near-surface air temperature (T2m), precipitation, total cloud cover, and net surface solar radiation, all conditioned by the presence of high-pressure systems. The plus sign marks 2 STD and highlights 1995 as a reference year. The dashed horizontal lines correspond to STD thresholds discussed in section 3.1. These variables collectively underscore the extreme meteorological conditions that drove the unprecedented wildfire activity.

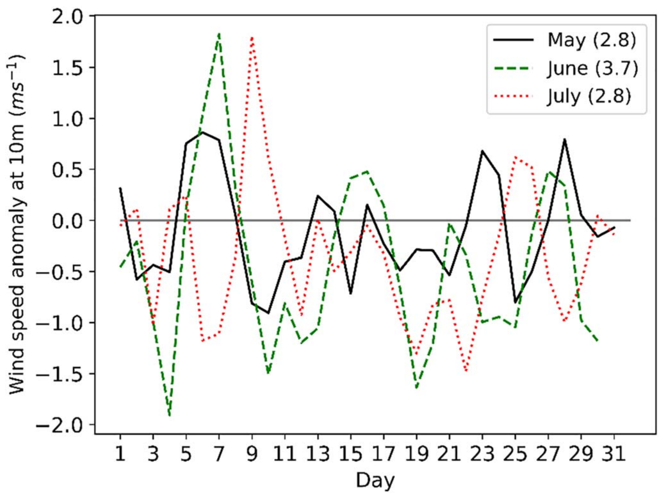

Figure 4. Daily anomalous 10-m wind speed (m s^{-1}) averaged over each monthly box during May (black), June (green), and July (red), relative to their respective daily climatologies (1983–2022; climatological values shown in the legend). Most days exhibit relatively weak box-mean winds (<5 m s^{-1}), reflecting the influence of persistent high-pressure systems. However, occasional wind speed increases above 5 m s^{-1} during transient phases of these systems, contributing to short-lived variations in fire weather conditions.

the 1 STD observed in 1995 when the previous record for burned areas was established. These extreme FWI values were accompanied by a suite of exceptional atmospheric conditions: near-surface air temperatures (T2m) rose above 3 STD (figure 3(c)), precipitation levels dropped to nearly −2 STD, comparable to the drought conditions of 1995 (figure 3(d)), total cloud cover declined sharply to -3 STD (figure 3(e)), and surface net solar radiation increased to 2 STD (figure 3(f)). Together, these factors underscore the remarkable convergence of meteorological extremes that drove the unprecedented fire activity during 2023.

3.2. Contribution from trends

Canadian wildfires are increasingly ignited and intensified by ongoing climate warming, as evidenced by a steady rise in T_{2m} (Robinne *et al* 2016, Mamuji and Rozdilsky 2019, Hu *et al* 2024). Regional T_{2m} trends are projected to double the frequency of Canadian wildfires and enhance their intensity by creating warmer conditions conducive to fire ignition and sustained burning (Dennison *et al* 2014, Schoennagel *et al* 2017, Wotton *et al* 2017, Boulanger *et al* 2018). Although disentangling the exact contribution of climate warming to the extensive burned areas during the 2023 Canadian wildfire season is complex, we estimated linear trends of box-mean variables shown in figure 3 as a first-order analysis. The most pronounced trend was observed in T_{2m} (figure 3(c)), which contributed 1.11 K, 1.0 K, and 0.58 K—representing 17%, 8%, and 13% of the total anomalies in May, June, and July, respectively. By comparison, the FWI trend accounted for 18% in May, 9% in June, and -3% in July, with a seasonal average of 10%. The seasonal trend in T_{2m} is significant at the 95% significance level by the Theil-Sen estimator, while that in FWI is not. These contributions align with the 20% amplification in wildfire severity projected under continued climate warming (Robinne *et al* 2016).

In contrast, trends in the occurrence and intensity of persistent high-pressure systems, precipitation, total cloud cover, and surface net solar radiation were minimal or negligible, suggesting trends in these factors played a lesser role in the 2023 Canadian wildfire season. Future studies utilizing climate model simulations and projections will offer more robust estimates for these trends and their impact on wildfire behavior.

3.3. Origin of extremely persistent and strong high-pressure systems

The record-breaking persistence and intensity of high-pressure systems that contributed to the 2023 Canadian wildfires show minimal discernible trends, suggesting additional influences beyond simple warming. As described in section 2.5, the planetary-scale flow can be decomposed into a climatological standing-wave component (CSWs) plus transient quasi-standing waves (TQSWs). These waves, captured as zonal eddy anomalies (or deviations from the zonal mean) at 500-hPa geopotential height, correlated with the persistent high-pressure systems each month.

In May, the CSWs (figure 5(a)) featured a ridge around 40 geopotential meters (GPMs) in the black-box region, while TQSWs (figure 5(b)) exceeded 100 GPMs, collectively producing a strong ridge. In June, the CSWs (figure 5(c)) indicated a trough (less than –80 GPMs) in the green box, while TQSWs (figure 5(d)) were large and positive (~140 GPMs), forming a net positive ridge of ~60 GPMs. In July, the CSWs (figure 5(e)) were relatively weak (~40 GPMs), whereas TQSWs (figure 5(f)) again exceeded 100 GPMs, reinforcing the ridge in the red box.

Figure 6 displays the Fourier power spectra of the 500-hPa geopotential height anomalies. Here, zonal wavenumbers 1–4 dominate the spectrum, indicating that the large-scale planetary waves are the primary contributors to the persistent high-pressure systems observed during the 2023 wildfire season. Specifically, wavenumber 1 represents one complete wave cycle around the latitude circle, capturing the broadest spatial-scale variability. Wavenumbers 2, 3, and 4 correspond to two, three, and four complete cycles, respectively, and though they represent progressively smaller scales, they still reflect the slowly evolving, quasi-stationary features that underpin the persistent high-pressure conditions. In contrast, higher wavenumbers (6–8) are generally associated with smaller-scale, transient phenomena that can amplify local heatwave conditions (Petoukhov *et al* 2016). This clarification underscores that the persistent, large-scale anomalies (wavenumbers 1–4) are central to driving the extreme atmospheric conditions leading to the unprecedented wildfires.

4. Discussion

Our findings indicate that record-breaking, persistent high-pressure systems from May to July were a key driver of the unprecedented wildfire disasters in Canada during the summer of 2023. Similar, albeit less intense and shorter-lived, systems also contributed to wildfires in August and September (not shown). Additionally, comparable high-pressure patterns, primarily active in June 1995, were linked to the previous record for burned areas (data not shown). These results expand recent correlation studies by Sharma *et al* (2022), which highlighted a positive association between wildfires in western North America and persistent positive anomalies in mid-tropospheric flow, and attribution analyses by Jain *et al* (2024) and Hu *et al* (2024), which focused on seasonal patterns.

Moreover, the unusually frequent and intense high-pressure systems observed from May to July 2023 were strongly linked to the combined influence of climatological standing waves (CSWs) and transient quasi-standing waves (TQSWs) at zonal wavenumbers 1–4. While the interactions between CSWs and TQSWs are inherently

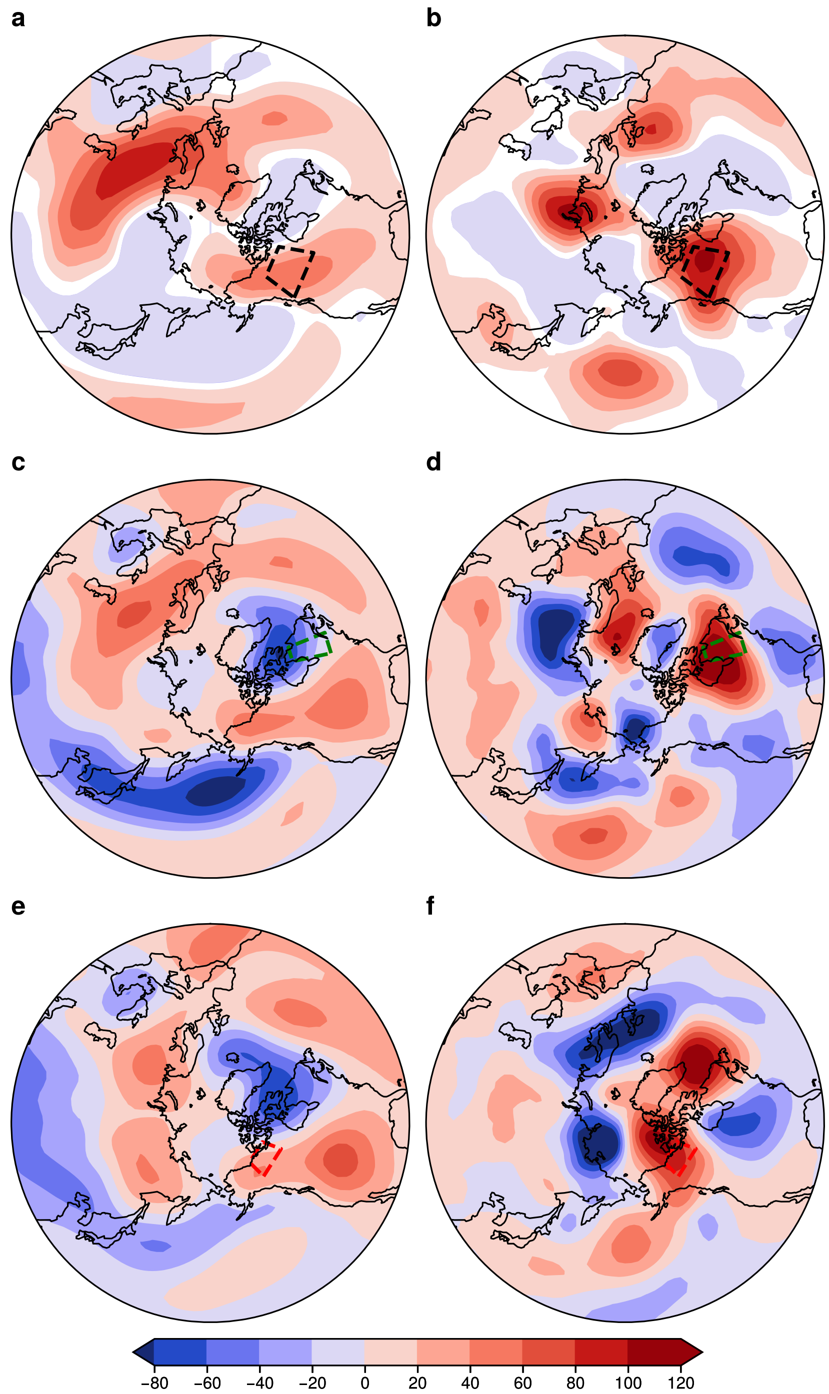

Figure 5. Composite zonal eddy anomalies of 500-hPa geopotential height (Z500) associated with persistent high-pressure systems during May, June, and July 2023. (a), (c), (e) Climatological standing waves (CSWs); (b), (d), (f) transient quasi-standing waves (TQSWs). Shading indicates the magnitude of Z500 anomalies (geopotential meters, GPM). The dashed boxes highlight regions of significant high-pressure persistence.

complex, non-linear (Nakamura and Huang 2018), and modulated by boundary fluctuations, large-scale sea surface anomalies (Wolf *et al* 2020)-particularly those associated with a moderate ENSO developing in the tropics-did not appear to play a direct role. Interestingly, mid-latitude planetary waves at zonal wavenumbers 6–8, which are often associated with the amplification of extreme heatwaves through resonance or quasi-resonance (Petoukhov *et al* 2016), seemed to have a limited influence on the 2023 Canadian wildfires. Furthermore, T2m, precipitation deficit (Jain *et al* 2024), and moisture content exhibited moderate anomalies in March and April, and their contributions, if any, were likely moderate (not shown). Finally, early snowmelt, as highlighted by Jain *et al* (2024), was recently identified as a key preconditioning factor for the extreme wildfire season.

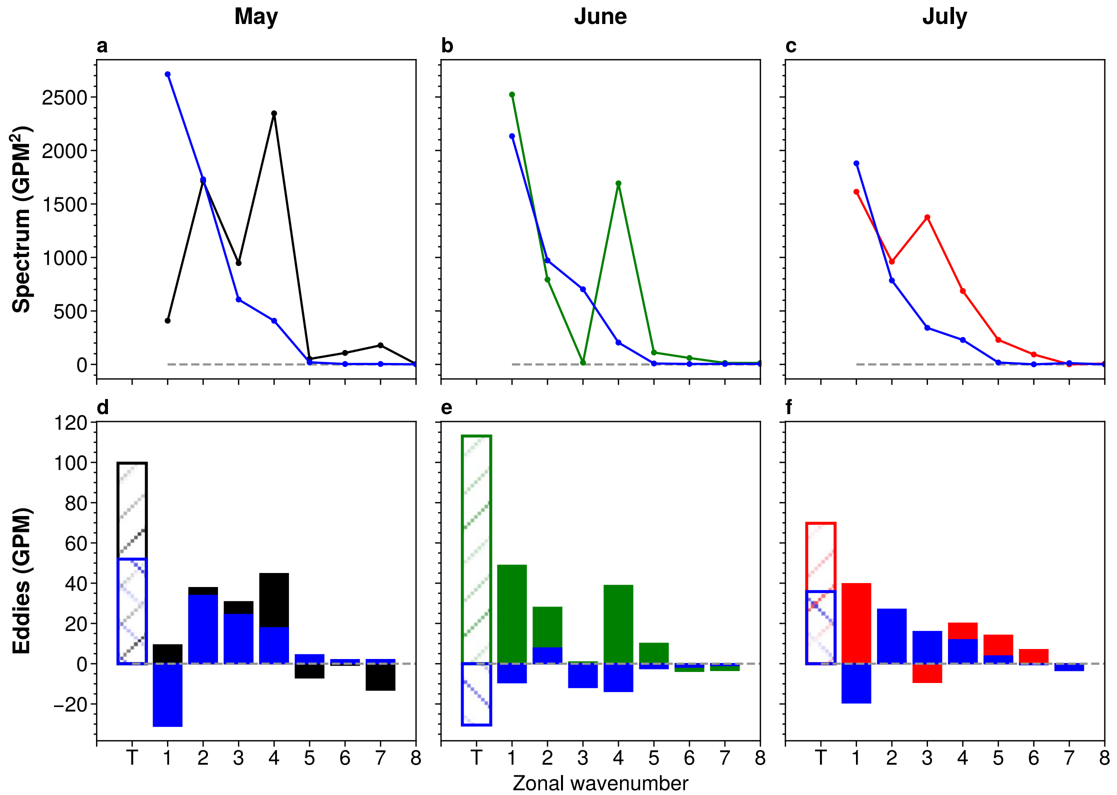

Figure 6. Power spectra and reconstructed zonal eddy anomalies of 500-hPa geopotential height (Z500) for May (a), (d), June (b), (e), and July (c), (f) 2023. Panels (a)–(c) show the power spectra of CSWs (blue) and TQSWs (other colors) across zonal wavenumbers 1–8. Panels (d)–(f) present reconstructed Z500 anomalies for each wavenumber, illustrating the dominance of wavenumbers 1–4 in generating strong, persistent ridges.

Future research will focus on numerical experiments to investigate the underlying drivers of these strong TQSWs and explore whether similar wave patterns are expected to shift under continued climate warming (Boyle 2006, Bui *et al* 2022, Chen *et al* 2023).

Code availability

Python scripts and Fortran programs are available upon request.

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Conflict of interest

The authors declare no competing interests.

Data availability statement

No new data were created or analysed in this study.

Author contributions statement

P L, K A R, M Z, S T G, N G L, L G S designed the research; P L performed analysis and illustrations; P L, K A R, B A C wrote the paper.

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