Persistent positive anomalies in geopotential heights promote wildfires in western North America

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ABSTRACT

During summer, persistent positive anomalies (PPAs) of mid-tropospheric geopotential heights in North America are often associated with extreme weather, including heatwaves. We evaluate the link between prolonged summertime PPAs in 500-hPa geopotential heights and wildfire activity across western North America and examine temporal trends in PPA characteristics. On average, 17% of May–September days experience PPA events over the study domain. Large fires (burned area > 500ha) were seven times as likely to start during a PPA, with approximately 40% of these fires ignitions coincident with PPA events. A positive correlation exists between the fraction of May–September PPA days and burned area for most of the study domain. Additionally, the presence of a PPA exerts greater influence on fire ignition and burned area in higher latitudes than lower latitudes of western North America. We find a statistically significant expansion in the spatial extent of PPA events during 1979–2020. The observed expansion of the PPAs is likely due to thermodynamic changes in mid-latitude synoptic patterns. These findings may improve our understanding of the connections between PPA events and wildfires in western North America, enhance the short-term predictability of wildfire events, and have important implications for increased fire risk in a warming climate.

KEYWORDS: wildfire; atmospheric blocking; summer; heatwave; North America
SIGNIFICANCE STATEMENT

Persistent positive anomalies (PPAs) of the upper air atmospheric flow, a slow progression of planetary waves, are synoptic-scale patterns that cause heatwaves and contribute to wildfire activity. We seek to understand how these events relate to fire weather and fire activity over western North America. The presence of PPA events increase the likelihood of fire ignition by a factor of seven, with higher likelihood over northern regions. The mean area of the PPA event has grown significantly in recent decades, exposing larger areas and populations to increased fire risks. These results improve our understanding of the connections between upper air atmospheric patterns and wildfires, signal how it may change in future warmer climate and scenarios and enhance the near future predictability of fire events in this region.
1. Introduction

An unprecedented heatwave across British Columbia (BC) in Canada, and the Pacific Northwest (PNW) region of the United States in June–July 2021 broke many daily maximum surface temperature records (Philip et al. 2021). This heatwave was dominated by an atmospheric blocking event associated with a strong upper-level ridge and anomalously high geopotential heights that persisted for longer than a week. Coincident with the event, hundreds of fires started across the region, prompting local and regional emergency declarations and the evacuation of thousands of people (BC Gov 2021).

Persistent positive anomalies (PPAs) in mid-tropospheric geopotential heights (e.g., 500-hPa geopotential height) characterize atmospheric blocking highs and ridges (Elliott and Smith 1949; Dole and Gordon 1983). Synoptically, the PPAs represent an obstruction of the flow of planetary waves and include the blocking high, open ridges and occasionally the poleward intrusion of subtropical ridges (Elliott and Smith 1949; Sousa et al. 2021). Although PPA refers to a variety of atmospheric blocking patterns, in general, it is well established that atmospheric blocking ridges have common attributes, including a persistent large anticyclonic anomaly and weakened or reversed zonal flow (Tibaldi and Molteni 1990; Liu 1994; Schwierz et al. 2004; Renwick 2005; Barriopedro et al. 2006; Woollings et al. 2018).

PPAs dynamically affect mid-latitude weather phenomena through the inertia of zonal flow and atmospheric subsidence that can lead to extreme heatwaves (Horton et al. 2015; Mann et al. 2018; Lupo et al. 2019; Steinfeld and Pfahl 2019; Francis et al. 2020). This occurs through land-atmosphere feedbacks as evident in the mega-heatwaves of 2003 and 2010 in Europe (Dole et al. 2011; Miralles et al. 2014) and summertime heatwaves over North America (Lau and Nath 2012). Given the robust influence of PPA on mid-latitude surface weather, there exist ample studies that investigate the high-pressure blocking ridges and their effects on surface variables such as temperature extremes (Woollings et al. 2014; Whan et al. 2016), precipitation (Antokhina et al. 2016), and heatwaves (Rodrigues and Woolings 2017; Schaller et al. 2018).

Synoptic-scale circulation patterns can similarly determine whether conditions are conducive for wildfire activity through their direct or indirect influence on fuel availability and moisture, receptivity to ignitions, and potential rate of fire spread. As such, several studies have identified a strong relationship between the occurrence of large wildfire events and the
stagnation of upper airflow (Flannigan and Harrington 1988; Johnson and Wowchuk 1993; Skinner et al. 2002; Gedalof et al. 2005; Fauria and Johnson 2008; Rasilla et al. 2010; Petoukhov et al. 2018; Zhao and Liu 2019; Tan et al. 2019; Zhong et al. 2020; Abatzoglou et al. 2021b; Yasunari et al. 2021; Jain and Flannigan 2021). For example, Jain and Flannigan (2021) observed the close relationship between upper-air ridges and fire spread days across North America. Likewise, extreme fire events such as the 2016 Horse River fire coincided with a large amplitude ridge (Tan et al. 2019). These examples illustrate the role of PPA in specific fire events or fire behavior such as fire spread days; however, there exist gaps in better understanding the climatological relation between PPA and fire-weather conditions, fire ignition and spread across the broad geography of western North America. Additionally, we do not understand how PPAs that favor fire weather conditions are changing and what mechanisms drive these changes.

While some studies report trends in atmospheric blocking ridges (Davini et al. 2012; Barnes et al. 2014; Gibson et al. 2020; Wazneh et al. 2021), there exist inconsistencies in these results, likely due to differences in working definitions, datasets, time, location, and season considered. Similarly, the dynamical processes resulting in blocking ridges over the Northern Hemisphere are still an active research area (Rodrigues and Woolings 2017; Riboldi et al. 2020). Some studies hypothesize the linkages between Arctic amplification (AA) — an enhanced rise in surface temperature in the Arctic compared to the remainder of the Northern Hemisphere (Francis and Vavrus 2012) — and increased weather extremes due to dynamical changes in atmospheric circulation (Francis and Vavrus 2015; Francis et al. 2018). AA has been suggested to increase the sinuosity of the Northern Hemisphere jet stream in the upper troposphere, likely due to weakening of the poleward temperature gradient (Francis and Vavrus 2015) that may favor persistent weather patterns and enhance extreme weather events in both summer and winter (Francis et al. 2018). However, other models and reanalysis-based studies have not shown strong relationships between AA and either waviness in upper airflow or mid-latitude surface weather extremes (Screen 2014; Blackport and Screen 2020; Dai and Song 2020).

In the context of the aforementioned literature and gaps, the overall goal of this work is to investigate the link between PPAs and wildfire events and explore changes in PPA over 1979–2020 in western North America. Specifically, through this work, we address the following questions: (i) What is the climatology of PPA during the main western North American fire
season? (ii) How do PPA events relate to wildfire activity and surface fire weather? And (iii) What are the trends of various PPA characteristics and what is the cause of any observed trends?

2. Data and methods

a. Study area

Our study domain is western North America covering 35°–75°N and 100°–160°W, an area that includes the western part of Canada and the contiguous United States, as well as Alaska (Fig. 1). One of the most fire-active areas globally, this region exhibits increasing trends in wildfire number and area burned (Schoennagel et al. 2017), which are expected to continue in the future, under warmer climate scenarios (Gillett et al. 2004; Flannigan et al. 2005; Balshi et al. 2009; Balch et al. 2017; Abatzoglou et al. 2021a; Kharuk et al. 2021). The 2016 Horse River Wildfire (in Fort McMurray, Alberta) (Tymstra et al. 2020), the September 2020 large fires in western Oregon (Abatzoglou et al. 2021b), the Camp fire in California (Brewer and Clements 2020) and the 2017 record-breaking BC fire season (Kirchmeier-Young et al. 2019) are a few examples of the costliest and deadliest wildfire disasters that have occurred in this region in the past decade. The recent rise in large wildfires in this region is partially attributed to the warmer and drier climates associated with increased surface air temperature, earlier snowmelt, and a surge in lightning activity, especially in the northern latitudes (Abatzoglou and Williams 2016; Holzworth et al. 2021).
Fig. 1: Map of the study domain. The blue rectangle indicates the area used for the identification of the PPA events. The map also shows the topography and indicates names of places mentioned in the main text.

b. Data

We use the 500-hPa geopotential heights (Z500 in meters–gpm) and surface variables from the European Center for Medium-Range Weather Forecast (ERA5) global reanalysis data (Hersbach et al. 2020) for the extended summer season (from May to September; May–Sep) of 1979–2020. We limited the study to the boreal summer months as the vast majority of wildfire events (92% of total fires with burned area >100 ha) within our study domain occur during these
months (Fig. 2) despite recent increases in wildfire events outside of these months (Balch et al. 2017).

![Chart](image)

**Fig. 2:** Average percentage of monthly fires (area burned > 100 ha) within the study domain.

Although the ERA5 data are available at higher spatial (0.25° × 0.25°) and temporal (hourly) resolution, we aggregated the data to 1° × 1° spatial resolution and to daily averages because the PPAs are reasonably well-represented at this coarser resolution (Barriopedro et al. 2006; Barnes et al. 2012) and this provides greater computational efficiency. Fire-related surface variables used in this analysis included the 2-meters (m) air temperature, precipitation, 2-m dew point temperature, and 10-m meridional and zonal wind components extracted for the study domain. We calculate relative humidity (RH) and vapor pressure deficit (VPD) from daily air and dew point temperature using vapor pressures following Tsonis (2013).

In addition, we use the Canadian Fire Weather Index System (Van Wagner 1987) fire weather indices that were calculated using ERA5 surface data (McElhinny et al. 2020). This system accounts for the effects of inter-seasonal drought and reflects the effect of weather on fuel moisture and potential fire behavior. The fire weather indices used include the Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC), Drought Code (DC), Initial Spread Index...
(ISI), and the Fire Weather Index (FWI). The FFMC and DMC represent moisture conditions for shaded litter fuels and decomposed organic matter underneath litter with ~16 hours and 2-weeks’ equilibrium drying time, respectively. The DC represents deeper soil moisture with about 53-days’ equilibrium drying time, and it is a useful indicator of seasonal effects of weather on fuel moisture. The ISI depends on FFMC and wind and represents the potential fire spread rate. Finally, FWI is a general index of fire danger and represents a numeric rating of potential fire intensity (Van Wagner 1987; McElhinny et al. 2020).

We used observed fire data from two data products, the Global Fire Atlas (GFA) and the fourth-generation global fire emission database (GFED4.1), as they provide different fire-related variables of interest. The GFA provides fire ignition timing and location, fire duration, size (minimum ~ 21 ha), and perimeter of individual wildfires for 2003–2018 (Andela et al. 2019), whereas GFED4.1 provides the fraction of monthly burned area at 0.25° × 0.25° spatial resolution from 1997–2016 (Giglio et al. 2013). The GFA data is based on the Moderate Resolution Imaging Spectroradiometer (MODIS) burned-area dataset at 500 m resolution (2019). Giglio et al. (2013) derived the GFED4.1 data through a combination of 500 m MODIS burned area and active fire data from the Visible Infrared Imaging Radiometer Suite (VIIRS). The GFA and GFED4.1 fire parameters are in good agreement with observed independent fire parameters, especially in forest and shrublands (Giglio et al. 2013; Andela et al. 2019), and provide a consistent fire database for our study domain.

c. Methods

1) IDENTIFICATION OF PPA

Given the class of synoptic patterns that blocking ridges represent, various definitions and identification procedures exist, perhaps owing partly to the research implications of the blocking events of choice (Woollings et al. 2018). Broadly, mid-latitude atmospheric blocking ridges are identified based on three approaches: a determination of the persistent positive departure above time-averaged geopotential height field (Dole and Gordon 1983; Renwick 2005; Gibson et al. 2020; Miller et al. 2020), use of a dynamical index based on integrated potential vorticity (Pelly and Hoskins 2003; Schwierz et al. 2004; Small et al. 2014), and measurement of
the reversal of meridional flow (Tibaldi and Molteni 1990; Pinheiro et al. 2019; Wazneh et al. 2021). The dynamic potential vorticity based approach is tied to strong polar dynamics that are not common during summer months within the study domain (Schwierz et al. 2004). The traditional blocking climatology based on measurement of reversal of meridional flow shows no or minimal blocking episodes over our study domain during the spring and/or summer months (e.g., Fig. S1) consistent with other studies (Barriopedro et al. 2006; Drouard and Woollings 2018; Pinheiro et al. 2019; Wazneh et al. 2021). We therefore follow the first approach to identify PPAs that highlights the anomalous two-dimensional area of the blocking and/or ridges and it is similar to previous studies such as Dole and Gordon (1983), Renwick (2005), Parsons et al. (2016), and Miller et al. (2020). However, we modify this approach to facilitate the identification of PPA events during Boreal summer by considering the persistence of anomalies relative to the climatological mean of geopotential heights.

To detect a PPA, first, we implement a 5-day moving filter of daily Z500 that removes noise from random temporal variations. We further weight anomalies by the sine of latitude to better represent atmospheric energy dispersion following Dole and Gordon (1983) as in equation (1):

\[
Z' = \frac{\sin 45}{\sin \varphi} (Z - Z) \quad (1)
\]

where \( \varphi \) is the latitude of the grid cell, \( Z \) is the 5-day running mean of Z500; \( \bar{Z} \) is the climatological day of year mean of Z500.

To identify PPA events from \( Z' \), we define and use a temporally varying magnitude \( M \) and fixed duration \( D \) threshold criteria modified from Dole and Gordon (1983) and (Miller et al. 2020). To obtain seasonally adjusted \( M \), we calculate the daily varying mean standard deviation \( \sigma \) of \( Z' \) updated daily within a 4-week moving window as in equation (2) following Miller et al. (2020).

\[
\sigma = \text{SD} \left[ (Z'_{(d-14)}, \ldots, Z'_{(d)}, \ldots, Z'_{(d+14)})_{1979}, \ldots, (Z'_{(d-14)}, \ldots, Z'_{(d)}, \ldots, Z'_{(d+14)})_{2020} \right] \quad (2)
\]

where \( d = \) days (1:365 (366 for leap years)) and \( Z' = Z500 \) anomaly. We use \( M = 1 \times \sigma \) and \( D = 5 \) days thresholds to separate the potential PPA grid cells from background anomalies in \( Z' \). Unlike previous studies, where \( M \) is generally fixed, we use daily varying \( M \) that accounts for
seasonal variability in Z500 (Fig. S2) which arises due to the weaker pressure gradients that occur during summer relative to the winter.

We develop and implement a feature tracking algorithm that follows the spatial and temporal extent of PPA grid cells within the study domain that satisfies the above criteria and allows us to label individual PPA events. Specifically, we identify $Z'$ grid cells that are of at least $M$ magnitude, label them as potential PPAs and only retain the resulting grid cells that persist for at least $D$ days. Then, the algorithm identifies the geometric centroid of each cluster of contiguous PPA grid cells for each day. It tracks the movement of the centroid of the PPA until the contiguous PPA area is greater than ~ 80000 km$^2$. We choose this minimum area threshold to ensure that the small events are not included. When multiple PPAs are identified within the study domain in a single day, individual clusters based on their centroid are tracked as individual PPA events. To include all PPA events that occurred within May–Sep, we allow backward (forward) tracking of the PPA events if they start (end) on May 1 (September 30). For example, the supplementary Fig. S3 shows the evolution of one of the PPA events identified following this approach. The PPA identified here are sensitive to the threshold used to define them. A sensitivity analysis with more relaxed $M$ and $D$ criteria ($M = 0.5 \times \sigma$ and $D = 3$-days) incorporates weaker PPA events, thus increasing PPA numbers by ~25%. However, it does not show a substantial difference in PPA relationships to fire weather and trends in PPA characteristics.

2) STATISTICAL ANALYSIS

We implement multiple descriptive statistics to analyze PPA-wildfire associations and PPA event characteristics. Several definitions were considered: (i) the percentage of days with PPA (PPA %-days) were defined as the fraction of days (for May–Sep) that satisfy both $M$ and $D$ criteria; (ii) the frequency of PPA was defined by counts of individual (spatially contiguous) PPA events; (iii) PPA duration is the number of days for which each PPA event is detected; (iv) the spatial extent of PPA grid cells for the duration of each PPA event provides the average area of that PPA event; and (v) the PPA strength is the product of PPA magnitude, size, and duration.

To calculate the percentage of wildfires during each PPA event, we determine whether the fire perimeter of individual large fire events (burned area > 500 ha) overlaps with at least one PPA grid cell within the fire duration or up to three days prior to the fire ignition. If there is an
overlap, we assign the fire event as a fire associated with a PPA event. Thus, the number of fires related to PPAs out of the total number of fires provides the percentage of PPA-related fire events. Similarly, the sum of PPA days that overlap with a fire duration and have at least one common grid cell between fire perimeter and PPA grid cells provides the percentage of active fire days linked to PPAs.

To further understand the synoptic conditions associated with PPA days having at least one fire ignition, we used Self-Organizing Maps (SOMs) to determine the dominant observed patterns. The SOM with four nodes (2×2 grids) provides visualization of the circulation patterns of PPA-days with at least one fire ignition within PPA extent. SOMs are widely used unsupervised artificial neural networks well adapted for pattern recognition and classification; details on SOMs can be found in Kohonen (2001). The composite of circulation patterns for each node discerns the synoptic pattern associated with PPA days. In addition, we quantify the percentage of PPA days associated with each SOM node.

We use the odds ratio (OR; (Stephenson 2000; Wilks 2011) to quantify the strength of the association between the presence of a PPA and occurrence of fire ignition at each grid cell for 2003–2018. The OR is defined as in equation (3).

\[
OR = \frac{a \times d}{b \times c}
\]

where \(a\) = presence of PPA and ignition, \(b\) = presence of ignition but no PPA, \(c\) = presence of PPA but no ignition, and \(d\) = absence of both PPAs and ignitions. We calculate the OR between PPA occurrence and wildfire ignition (with fire burned area > 500 ha) within 3-days of a PPA occurrence.

The interannual Spearman's rank correlation coefficient (\(\rho\)) correlates PPA %-days and the fraction of averaged burned area over 1997–2016. Similarly, it relates the monthly PPA %-days and monthly fire weather indices over 1979–2020. \(\rho\) assesses the monotonic relation between the variables without the assumption of normality. The difference between daily values and climatological means provide daily anomalies of fire-related variables and fire weather indices. The nonparametric Mann-Whitney-Wilcoxon (MWW) rank-sum test (Wilks 2011) shows the difference in the median of the distribution of fire-related surface variables during PPA days and non-PPA days. The MWW test is used here to determine whether the median of the anomalies in surface variables are significantly greater or less during PPA days than during
non-PPA days. Moreover, we explore the temporal evolution of the fire-related surface variables before, during, and after the PPA events. The lead-lag relationship between maximum PPA strength and daily surface variable anomalies presents the surface variable response to PPA events. We calculate the daily PPA strength from 15 days before to 15 days after the day with maximum PPA strength. We mask the grid cells of fire-related variables using the PPA area calculated on the day with maximum PPA strength. Finally, we calculate daily lead-lag average values of the fire-related variables for the masked area.

We perform the Mann-Kendall test (Mann 1945; Kendall 1975) and the Theil-Sen (Sen 1968) trend estimate over 1979–2020 that yields monotonic trends and trend magnitude of the PPA characteristics (Sen 1968). This nonparametric approach is robust to outliers and does not require data normality. We use the R programming language (R Core Team 2019) and the packages raster (Hijmans and Etten 2012), igraph (Csardi and Nepusz 2006), zyp (Bronaugh and Werner 2019), kohonen (Wehrens and Kruisselbrink 2018), and tidyverse (Wickham et al. 2019) to perform all analysis.

3. Results

a. PPA climatology and fire weather

On average, 17% (26 days) of May–Sep are PPA days with the greatest frequency occurring in the Northeastern Pacific (Figs. 1 and 3a). PPA days are relatively frequent west of the Rocky Mountains compared to the prairies and boreal plains of central North America. Higher values of PPA days exist over the Northeast Pacific Ocean and Beaufort Sea expanding inland to Alaska, BC, and the PNW region of the United States and the boreal plains respectively (Figs.1 and 3a). Spatially averaged monthly percentage of PPA days are 19% in May, 17% in June, July, and August, and 16% in September. Moreover, the Hovmöller diagram of average PPA days Z500 anomalies within the study domain indicates higher PPA amplitudes during early and late periods in the fire season relative to July and August (Fig. S4).
Fig. 3: Average percentage of PPA days, 1979–2020. The blue rectangle in (a) shows the study domain considered for the identification and tracking of the PPA events.

We identify a total of 517 PPA events during 1979–2020 (May–Sep) within our study domain, with an average of 12 (SD three) PPA events per year. The average duration of a PPA event is 12 days, with 24% and 4% of events having ≥ 15 and ≥ 31 days length, respectively.
The average magnitude and area of the PPA events are 99 m and $2.2 \times 10^6$ km$^2$, respectively.

Fig. 4: Distribution of the duration of PPA events, 1979–2020.

On average, 40% of fires with burned area > 500 ha were ignited within PPAs during 2003–2018; this association increased to 60% for fires with area burned > 20000 ha. Similarly, 29% of fire days with burned area > 500 ha were also PPA days and that number increased to 38% for fires with burned area > 20000 ha.

The SOM classification of the circulation patterns associated with PPA-days having at least one fire ignition indicates that the majority of fire ignitions co-occurred with a 500-hPa open-wave ridge over western North America (Fig. 5). Among the four nodes, nodes 1 and 3, with a small difference in the location and PPA amplitude represent 47% and 23% of fire-related PPA days where a strong ridge and positive anomalies build over northern high latitude regions including Alaska, Northern BC, Yukon, and Northwest Territories (Fig. 5). Nodes 2 and 4 represent the circulation for 16% and 14% of PPA-days with at least one fire ignition. These two nodes exhibit the strongest PPA amplitude and discern the Rex and Omega like blocking patterns, respectively. Moreover, a monthly breakdown of SOM analysis indicates small differences in the percentage of PPA-days circulation among the four nodes (Fig. S5). The
difference in the percentage of PPA-days circulation patterns among all four nodes is lower (~10%) early in the fire season, and increases to ~17% later in the fire season (Fig. S5).

Fig. 5: The 2 × 2 SOM patterns of 500-hPa geopotential height and anomalies (gpm) corresponding to fire ignition PPA days. The number at the top left of each panel indicates the percentage of the days of the occurrence of each pattern.

b. **PPA and wildfire relation**

The OR is >1 for 89% of grid cells (49% significant) within the study area (Fig. 6a). The interpretation of OR >1 is that wildfire ignitions are more likely to occur during or following (up to three days) a PPA event. On average, the odds of wildfire ignition concurrent with a PPA increases by a factor of seven across the study domain; this number is even greater for higher latitude and altitude regions (Figs. 1 and 6a). For example, the odds of fire ignition with the
presence of PPA increases by a factor of eight above 50°N latitude while it is only five below 50°N.

Fig. 6: (a) The OR of occurrence of wildfire ignition during the presence of PPA, 2003–2018. The white grid cells indicate insufficient data for OR calculation. (b) Spearman’s correlation coefficients between the average May–Sep burned area and percentage of PPA days, 1997–2016. The black dots indicate grid cells with a significant value ($p < 0.1$). The density plots on the left side indicate the distribution of mean values along the latitudes.

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Fig. 7: The Spearman’s correlation coefficients between May–Sep average fire weather indices and PPA-% days, 1979–2020. The black dots indicate grid cells with a significant correlation (p < 0.1). The density plots on the right side show the distribution of mean positive correlation coefficients as a function of latitude.

Most of the study domain exhibits a positive correlation between the average May–Sep burned area and PPA %-days during 1997–2016 (Fig. 6b). Higher latitude regions, such as Alaska, Yukon, and Northwest Territories, experience a greater interannual positive correlation between the burned area and PPA %-days (Figs. 1 and 6). This is the same region that exhibits formation of a strong 500-hPa open-wave ridge during PPA days with fire ignition (Fig. 5).
Similarly, there exists a significant positive interannual correlation between May–Sep PPA %-days and fire weather indices (Fig. 7).

The surface air temperature, VPD, and fire weather indices (FWI, FFMC, DMC, DC, ISI) show larger positive anomalies during PPA days than during non-PPA days, while the atmospheric moisture-related variables (daily RH and precipitation) show lower anomalies (Fig. 8). Spatially, the magnitudes of PPA-day surface variable anomalies are greater inland except for precipitation and wind speed. The average wind speed anomalies during PPA days are significantly lower than non-PPA days wind speed (Table S1) however few grid cells along the coast and further inland exhibit positive wind speed anomalies (Fig. 8i). Further, the MWW test results indicate that the distribution of mean air temperature, VPD, and fire weather indices anomalies during PPA days are significantly higher than during non-PPA days (Table S1). Similarly, the average RH and precipitation are significantly lower during PPA days than non-PPA days (Table S1).

The lead-lag relation (15 days before and after from the day of maximum PPA strength) between PPA strength and surface variables indicate that the temperature and VPD anomalies increase with PPA growth while the precipitation and RH anomalies decrease (Fig. 9). The peak increase (decrease) in temperature and VPD (RH) anomalies coincide with maximum PPA strength, whereas the precipitation deficit peaks two days earlier than the PPA peak (Fig. 9). For all these variables, the anomalies weaken with the weakening of PPA. The fire weather indices increase with PPA strength and decrease with its decay except for DC that has persistent high values even after the weakening of PPA events consistent with the continued drying of deeper soils after the maximum PPA strength occurs (Fig. 9).
Fig. 8: Fire-related surface variables (Temperature, Precipitation, RH, VPD and Wind) and fire weather indices (FWI, FFMC, DMC, DC, and ISI) anomalies and the distribution of anomalies averaged over 1979–2020 during PPA days. The Box and Whiskers plots show the distribution of anomalies during PPA days. The blue horizontal lines indicate median anomalies; red dots show mean anomalies; vertical lines present the range of PPA and non-PPA days anomalies within the 1.5 interquartile range. The black dots indicate outliers of the anomalies.

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Fig. 9: Lead-lag relation between PPA strength and fire-related surface variables and fire weather indices. 0-day represents the day of maximum PPA strength for each event. The red lines indicate PPA strength with maximum strength on 0-day. The blue lines indicate averaged PPA-days anomalies of each parameter.
Having examined the relationship between PPA occurrence and wildfire ignitions, we examine trends in PPA characteristics from 1979–2020. Increases in the percentage of days during May–Sep with PPAs were observed during 1979–2020 for most of the study domain, with significant increases over the Pacific and Alaska (Fig. 10). During 1979–2020 May–Sep PPA days increased by eight days on average over our study area. A significant rise in PPA days occurred over Alaska, BC, and the PNW region, whereas no significant increase was observed farther inland within our study domain (Fig. 10).

Fig. 10: The trend in May–Sep PPA-%days, 1979–2020. The black dots indicate grid cells with a significant trend magnitude value ($p < 0.1$).

The average number of PPA events shows a small statistically non-significant rise (1.6 events, $p = 0.12$) over the period of 1979–2020 (Fig. 11a). PPA events’ average duration and
magnitude exhibit small (not statistically significant) increasing trends, while the average area of the PPA events shows a statistically significant expansion of $1.06 \times 10^4$ km$^2$ year$^{-1}$ ($p = 0.08$) over 1979–2020, representing a 20% increase over the period of record (Fig. 11c).

![Fig. 11: Trends in average PPA (a) number, (b) duration, (c) area, and (d) magnitude, 1979–2020. The red lines represent trends from the Theil-Sen estimator while the inset on each plot gives the trend magnitude and corresponding $p$-value. $p < 0.1$ indicates statistically significant trends.](image)

The breakdown of PPA characteristics into different latitudinal bands reveals variations in the trends by latitude despite the latitude-dependent normalization of Z500. The number of PPA events increases significantly only along the lower latitudinal band ($30^\circ$– $45^\circ$ N; 0.04 events yr$^{-1}$) while a significant increase in the PPA duration (0.16 days yr$^{-1}$) occurs along the highest latitude band ($60^\circ$– $75^\circ$N) (Fig S6). However, the PPA area increases along all latitudinal bands, with a significant increase along the higher latitudes ($p = 0.05$) (Fig S6).

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In addition, the monthly breakdown of PPAs indicates substantial growth in the PPA area early in the fire season (May–July) (Fig. S7); other PPA characteristics namely number, magnitude and duration, do not exhibit significant monthly changes (not shown). In addition, we explore trends on only those PPA events that intersect with the land area of western North America as they directly influence surface fire weather conditions. They exhibit similar trend as that of all PPA events (Fig. S8).

4. Discussion

a. Comparison with previous studies

Differing approaches for defining PPA events (Barnes et al. 2012; Woollings et al. 2018) impede direct comparisons with previous studies. The climatology of summertime PPAs observed here is spatially consistent with previous studies based on Z500 anomaly measurement algorithms (Dunn-Sigouin et al. 2013; Miller et al. 2020) or dynamic potential vorticity based approaches (Pelly and Hoskins 2003; Small et al. 2014); however, there is a small difference in magnitude compared to our approach. For example, we find the June, July, August average PPA %-days as 17% (16 days) over the same region as our study domain. This is higher than Dunn-Sigouin et al. (2013) and Miller et al. (2020), who report ~10–12% days and <5 days summer PPA %-days with $M \times 1.5 \times \sigma$ and $2 \times \sigma$, respectively. While previous studies have used higher thresholds, our approach is less conservative in that it includes lower magnitude persistent events, especially during summer. Similarly, Small et al. (2014), using a dynamic potential vorticity-based approach, observed ~8–10% of days in summer months blocked over the Gulf of Alaska and western North America while we find 17% of days blocked for the same months (Fig. 3).

b. PPA and wildfires

Previous studies have established links between summertime blocking ridges, heatwaves (Gedalof et al. 2005; Dole et al. 2011; Miralles et al. 2014; Mann et al. 2018; Schaller et al. 2018), and wildfires (Flannigan et al. 2005; Zhong et al. 2020; Jain and Flannigan 2021;
Yasunari et al. 2021) but mostly for specific fire events and/or small regions. This study extends previous efforts relating PPAs and fire weather, fire ignition, and burned area and quantifies the role of PPAs on fire ignitions across the broad geography of western North America. There exists a substantial association between PPA and fire ignitions and fire burned area; this relation is greater in western North America’s higher latitude regions than in lower latitudes (Fig. 6). In addition, the significant increase in PPA days, PPA area, and duration that occurs in the higher latitude band (60°–75°N) in recent decades (Fig. S6) may result in enhanced surface fire weather in this region. This, in turn, leads to disproportionally higher PPA-fire associations over northern latitudes where greater surface weather anomalies are required to reach extreme fire weather conditions.

The presence of a PPA amplifies fire weather through cascading effects on surface weather conditions as a result of land-atmosphere interactions. These interactions result in enhanced air subsidence, warm air advection, and moisture diversion that leads to higher temperatures, clear skies, lower relative humidity, and low evaporative fraction (Horton et al. 2016). As a result, a positive feedback loop is created with anomalously high surface temperature. We observe strikingly high positive anomalies in temperature during PPAs (Fig. 8a) that acts as a major predictor of wildfire and area burned (Flannigan and Harrington 1988; Gillett et al. 2004). Similarly, the presence of a PPA leads to the forced diversion of jet streams and associated baroclinic disturbances leading to negative precipitation anomalies within PPA influenced area, raising air temperature and reducing RH (Gedalof et al. 2005; Gochis et al. 2015; Milrad et al. 2015; Antokhina et al. 2016; Yang et al. 2021). All these processes combined during PPA further enhance the FWI and its components; thus a PPA generates surface conditions that can sustain and contribute to the rapid spread of wildfires, whether they are lightning or human-caused.

c. **PPA expansion and mechanisms**

The increase in PPA size observed here is consistent with the findings of Lyon et al. (2019) and Nabizadeh et al. (2019); these studies indicate an increase in the size of the Northern Hemisphere blocking events and heatwaves over the contiguous United States under future climate change scenarios. The increase in PPA size affects the spatial and temporal
characteristics of extreme fire weather conditions and exposes larger areas to increased fire
danger and for a longer duration. Furthermore, from a fire management perspective, the
expansion of the PPA area makes it harder to suppress or control fires because there could be
increased fire activity in a larger domain within the same time period.

Changes in PPA characteristics may result from either dynamic changes in the
atmosphere (i.e., frequency of anticyclonic episodes) or from thermodynamic changes related to
global warming and/or other land-use changes (Horton et al. 2015). We hypothesize that the
significant expansion of the PPA observed in this study is likely due to the thermal expansion of
the atmosphere associated with background warming. To verify this hypothesis, we first
calculated the trend on Z500 anomalies and Z thickness field (difference in Z at 500 hPa and
1000 hPa) and found that they exhibit very similar trends implying that the changes observed in
the Z500 field are largely due to thermodynamic changes (Fig. 12). Then, we detrended the Z500
field and recalculated PPA characteristics and their trends. We did not find significant trends in
PPA area or other characteristics when the detrended Z500 field was used (Fig. 13), which
further confirms that the trends observed in PPA characteristics are due to thermodynamic
changes in the atmosphere. Thus, the expansion of the PPA events is due to the atmosphere’s
thermodynamic changes likely associated with an increase in lower tropospheric temperature in
recent decades (Vinnikov and Grody 2003).
Fig. 12: Trend on May–Sep daily (a) Z500 anomalies and (b) the Z thickness (difference in 500 hPa and 1000 hPa Z field), 1979–2020. The black dots indicate grid cells with a significant trend magnitude value ($p < 0.1$).
In the context of inconsistent findings on what drives changes in persistent extreme weather events in mid-latitude regions of the Northern Hemisphere (Francis and Vavrus 2012; Blackport and Screen 2020; Dai and Song 2020; Francis et al. 2020; Riboldi et al. 2020; Sun et al. 2022), we observe that the trends on PPA characteristics such as area and strength across western North America are primarily due to background warming. This agrees with previous work such as that of Riboldi et al. (2020), who found an increase in extreme temperatures due to slow progression of atmospheric flow; however, that study did not determine the role of AA in reducing the progression of atmospheric flow both in winter and summer months. Similarly, Backport and Screen (2020) report that the changes in mid-latitude temperature extremes are likely due to thermodynamic effects and not as a forced response of tropospheric waviness to AA.

Fig. 13: Trends on average PPA (a) number, (b) duration, (c) area, and (d) magnitude, 1979–2020 using the detrended Z500. The red lines represent trends while inset on each plot lists trend magnitude and \( p \)-values. \( p < 0.1 \) indicates statistically significant trends.
5. Conclusions

While the presence of atmospheric blocking ridges and extreme temperatures that include heatwave events has been studied previously (Sillmann and Croci-Maspoli 2009; Trenberth et al. 2015; Grotjahn et al. 2016; Horton et al. 2016; Rodrigues and Woolings 2017; Mann et al. 2018; Parente et al. 2018; Sousa et al. 2018; Gibson et al. 2020; Abatzoglou et al. 2021b; Jain and Flannigan 2021), this study expands our understanding of extended summertime persistent positive mid-tropospheric height anomalies and its association to both wildfire and fire weather in western North America. Although our study is limited to western North America, we expect similar relationships between PPA and fire activity in areas where summertime PPA events frequently occur. This study’s findings may improve our understanding on the connections between PPA and wildfires, signal how it may change in future warmer climate scenarios and enhance the predictability of extreme wildfire events in this region. In addition, the quantification of PPA-related fire ignition may help to improve fire weather predictability with improvements in models that are able to forecast PPAs.

To conclude, this analysis reveals that the May–Sep PPAs substantially impact fire weather conditions in western North America, with greater influence at higher latitudes. Furthermore, significant spatial expansion of PPA events over 1979–2020 exposes larger areas and populations of western North America to amplified fire weather conditions that are expected to continue expanding due to climate change. Specific key findings are as follows:

- On average, 26 out of 153 days of May–Sep experience PPAs over western North America.
- 40% (60%) of wildfire events ignitions with burned area > 500 ha (> 20000 ha) are associated with PPAs during 2003–2018.
- There is a presence of an open-wave 500-hPa ridge over the Canadian Rockies during the majority of PPA days with fire ignitions.
- The presence of PPAs significantly increases the odds of occurrence of fire ignition across most of western North America by a factor of seven; this factor is greater in higher latitudes than lower latitudes
- A strong interannual positive correlation exists between the percentage of PPA days and the average fire burned areas during 1997–2016.

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• The distribution of PPA-days anomalies of temperature, VPD, FFMC, DMC, DC, ISI, and FWI (precipitation, RH, wind speed) are significantly higher (lower) than that of non-PPA days anomalies.

• The temperature and VPD (RH) reaches a peak (minimum) on the same day as maximum PPA strength, whereas the precipitation anomalies are minimum two days earlier and the FFMC, DMC, DC, ISI, and FWI are maximum 2–6 days later than the maximum PPA strength.

• The number of PPA events, their duration, and magnitude have not changed significantly between 1979–2020; however, the area of PPAs has increased significantly during this time period.

• The spatial expansion of PPA events is largely due to thermodynamic changes in the lower atmosphere in recent decades.

This work establishes the relationship between PPA and wildfires for the historical period of 1979–2020 over western North America. However it should be noted that there exist many drivers for fire ignition and spread in addition to fire-related variables discussed in this paper such as prolonged drought, tree composition and mortality, orographic controls, and fire management strategies (Gedalof et al. 2005; Schoennagel et al. 2017). However, these variables are not directly influenced by the presence of a PPA within synoptic-scale timeframe, and are therefore not discussed in detail here. Further investigation on PPA’s influence on extreme fire weather indices, the relationship between the occurrence of PPA, teleconnections and fire events, the combined influence of PPA and prolonged drought on fire weather, and PPA fire weather relations under future climate scenarios will help to improve the predictability of wildfire events in the context of anthropogenic global warming.

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Data Availability Statement.
All data sets used in this paper are publicly available through the references cited and can be accessed through the web portals https://cds.climate.copernicus.eu/cdsapp#!/search?type=dataset (ERA5 data, accessed May 2020), https://www.globalfiredata.org/ (GFA and GEFD4.1 data, accessed May 2020) and https://zenodo.org/record/3626193#.X9pTFdhKg4s (FWI data, accessed June 2020). The R algorithm to identify and track PPA events is available by request to corresponding author.
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