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Downslope Wind-Driven Fires in the Western United States

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Key Points:

- Downslope wind-driven fires accounted for 13.4% of fire occurrence and 11.9% of total burned area in the western United States during 1992–2020
- Most structure losses and fatalities in fires 1999–2020 were during downslope winds
- Downslope wind-driven fires primarily occurred in the spring and fall, coincident with anomalously dry fuels

Supporting Information:

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

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Abstract Downslope wind-driven fires have resulted in many of the wildfire disasters in the western United States and represent a unique hazard to infrastructure and human life. We analyze the co-occurrence of wildfires and downslope winds across the western United States (US) during 1992–2020. Downslope wind-driven fires accounted for 13.4% of the wildfires and 11.9% of the burned area in the western US yet accounted for the majority of local burned area in portions of southern California, central Washington, and the front range of the Rockies. These fires were predominantly ignited by humans, occurred closer to population centers, and resulted in outsized impacts on human lives and infrastructure. Since 1999, downslope wind-driven fires have accounted for 60.1% of structures and 52.4% of human lives lost in wildfires in the western US. Downslope wind-driven fires occurred under anomalously dry fuels and exhibited a seasonality distinct from other fires—occurring primarily in the spring and fall. Over 1992–2020, we document a 25% increase in the annual number of downslope wind-driven fires and a 140% increase in their respective annual burned area, which partially reflects trends toward drier fuels. These results advance our understanding of the importance of downslope winds in driving disastrous wildfires that threaten populated regions adjacent to mountain ranges in the western US. The unique characteristics of downslope wind-driven fires require increased fire prevention and adaptation strategies to minimize losses and incorporation of changing human-ignitions, fuel availability and dryness, and downslope wind occurrence to elucidate future fire risk.

Plain Language Summary Downslope mountain winds bring locally strong winds along with dry and often warm air to downwind slopes and are a critical fire weather pattern when such winds co-occur with receptive fuels. Fires associated with downslope winds were primarily ignited by humans, exhibited distinct peaks in the shoulder seasons across the western United States, and had geographic hotspots in the front range of the Rockies, southwestern California, and eastern slope of the Washington Cascades. While wildfires typically burn upslope and away from populated regions, downslope wind events allow fires to rapidly spread downhill and often toward human settlements. Fires coincident with downslope winds accounted for most of the cumulative losses in both human lives and structures during 1999–2020. While winds are a key driver of these fires, large downslope wind-driven fires preferentially occurred with anomalously dry fuels, suggesting that conditions leading up to ignitions coincident with downslope winds play an important role in enabling large fires. Lastly, we found an increase in downslope wind-driven fires and their burned area over the past three decades. Such changes in downslope fire activity partially reflect a drying-driven extension of the fire weather season into the spring and fall when downslope winds are more common.

1. Introduction

Wildfire extent has increased markedly across the western United States (US) over the past four decades due to a well-documented constellation of factors, including accumulation of fuel due to a century of fire suppression in forested lands (North et al., 2015), and both drier fuels and longer fire seasons partially attributable to human-caused climate change (Abatzoglou & Williams, 2016). In addition to increases in burned area and the number of large fires, there is also evidence of increasing direct and indirect fire impacts on human populations and infrastructure (Burke et al., 2021; Heft-Neal et al., 2022). Contemporary wildfire regimes across the western US exhibit heterogeneity in seasonality, ignition sources, and fire behavior imparted through gradients of climate, fuels, weather, topography, and anthropogenic pressure (Balch et al., 2017; Krawchuk et al., 2009). The influences of fuel, topography, and weather produce distinct differences in potential fire behavior that affect the ability of suppression and localized fire mitigation efforts to reduce negative impacts. For example, recent studies have

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highlighted the dichotomy of fuel-driven fires, which occur with primarily contiguous dry fuels in the absence of strong winds, and wind-driven fires, which occur during strong synoptically-driven wind events (Keeley & Syphard, 2019; Kolden & Abatzoglou, 2018; Pausas & Keeley, 2021). Wind-driven fires are particularly noteworthy given their rapid rates of spread, ability to supersede both fuel and topographic barriers, and ability to impede fire suppression efforts (Moritz, 2003).

In this study we consider the influence of downslope wind events on fire activity and impacts to human lives and infrastructure in the western US. Downslope winds are a mesoscale manifestation of the interaction of synoptic meteorological patterns with topographic barriers (Brinkmann, 1971; Whiteman, 2000). Unique to downslope wind events, as compared to many other wind events, is the downward turbulent flow associated with mountain wave breaking. This leads to gusty winds as well as adiabatic subsidence, producing warming in the lee of a mountain barrier and downward advection of dry air. The trinity of windy, dry, and warm conditions associated with downslope winds is a recipe for critical fire weather conditions, although realized fire is also contingent on fuel availability, fuel dryness, and ignitions. Downslope winds further promote fuel desiccation—further increasing fire potential in the case of repetitive or long-duration wind events. The particularly hazardous nature of downslope wind-driven fires has been well-understood by fire suppression agencies for over a century. In the 21st century, many of the most catastrophic fires resulting in the loss of life lives and destruction of infrastructure in the western US occurred during downslope winds in the autumn coincident with critically dry fuels (Abatzoglou, Rupp, et al., 2021; Brewer & Clements, 2019; Nauslar et al., 2018). Previous studies have distinguished the unique fire and fire impact attributes of downslope winds in southern California, namely Santa Ana winds, from fires that occurred in the absence of such winds (Jin et al., 2014, 2015; Kolden & Abatzoglou, 2018). Yet, the influence of downslope winds on fire regimes and impacts across the broader western US has not yet been elucidated.

Geographically, downslope winds manifest in the lee of topographic ranges and are widely documented on all continents. In the western US, downslope winds preferentially occur on east or northeast slopes of prominent topographic barriers such as the Rocky Mountains, Sierra Nevada, and Cascade ranges, given the prevailing lower-tropospheric flow (Abatzoglou, Hatchett, et al., 2021). Offshore downslope winds are also evident from Washington to southern California. Downslope winds occur more frequently outside of the core summer months due to weaker lower-tropospheric thermal gradients in the summer. The seasonal minimum in fuel moisture across much of the West—outside of areas influenced by the North American monsoon—occurs in mid-to-late summer, after which precipitation increases and atmospheric dryness wanes. This produces a window of potential overlap during late summer and autumn when fuels are sufficiently dry and when downslope winds materialize. These critical fire weather conditions are most notorious and well-studied in southern California's Santa Ana winds due to the climatologically delayed onset of autumn precipitation, strong terrain focused winds, and heavy human ignition pressure with a resultant large population exposed to fire impacts. While there is little observational evidence of changing Santa Ana winds (Guzman-Morales et al., 2016), increases in fire weather season length broadly across the western US (Jolly et al., 2015) have enabled more critical fire danger days in autumn over the past few decades in the region (Goss et al., 2020; Khorshidi et al., 2020; Williams et al., 2019).

The distinct geographic and seasonal contributors to downslope wind events and subsequent impacts to fire behavior suggest that fires associated with such wind events occupy a niche in coupled human-fire landscapes. First, the seasonal overlap of dry fuels and downslope winds outside the core summer months (when lightning frequency peaks) suggests the dominance of human ignitions for such fires (Balch et al., 2017), and the potential role that fire prevention strategies such as preemptive de-energization of electrical lines play in reducing ignitions coincident with downslope winds (Abatzoglou et al., 2020). Likewise, while fuel-driven fires typically move uphill and away from human settlements in mountainous western US terrain, downslope wind allows fires to spread more easily down into populated regions in valleys. Furthermore, rapid rates of fire spread during downslope wind events render many fire suppression tactics (e.g., aircraft support) inoperative due to grounding and shift operations to prioritize evacuations.

In this study, we first characterize the geographic, seasonal, vegetation, and ignition-cause attributes of downslope wind-driven fires across the western US. Second, we quantify the contribution of downslope wind-driven fires to structure loss, loss of human life, and injuries. Last, we seek to identify both antecedent climate signals and concurrent near-surface meteorological conditions associated with downslope wind-driven fires. Collectively, we seek to characterize differences in the features between fires coincident with downslope winds and those that occur in the absence of such winds. By focusing on downslope wind-driven fires, we aim to better isolate their imprint on fire regimes and impacts in the western US, provide insight into recent changes in such downslope wind-driven fires, and allude to their potential changes in the coming decades.

2. Materials and Methods

We use three different fire databases to emphasize different attributes of fire characteristics focused on the western US, defined as the contiguous US west of 103°W. The majority of our analyses consider the Fire Program Analysis Fire-Occurrence Database (FPA-FOD; Short, 2014), which is a quality controlled database of wildfire ignitions that required federal agency response across the US during 1992–2020. These data contain information on the discovery date, ignition location, fire size, and fire cause. We restrict our analysis to fires ≥0.4 ha. We append data on direct fire losses to fires from FPA-FOD data from the ICS-209plus database of St Denis et al. (2020) that provides information on fire management costs, personnel, and a subset of human and infrastructure impacts, providing another way to discretize fire impacts beyond burned area and fire occurrence. The ICS-209plus data were limited to 1999–2020, and a subset of high-impact fire events. We specifically consider the fields of structure loss, fatalities, and injuries as the economic attributes of these data were limited to direct suppression costs, vastly underestimating true economic impacts of fire (Burke et al., 2021). Lastly, given the prominence of multi-day fire events in the region and absence of daily growth information in the FPA-FOD database, we use the daily MODIS burned area product (MOD64A1) during 2001–2020 for a complementary view of burned area contributions. While the MODIS burned area product allows us to better temporally link daily burned area to concurrent downslope winds, we focus most of the analyses on the FPA-FOD data set, given its longer time period and ability to capture discrete fire events.

We use a database of global downslope winds from Abatzoglou, Hatchett, et al. (2021) that Abatzoglou, Rupp, et al. (2021) extended through 2020. They identified downslope winds from ERA-5 reanalysis data based on a union of strong cross-barrier flow, near-mountaintop static stability, and downward vertical velocity. Their approach reasonably captured seasonal and geographic patterns of documented local downslope winds that have been more widely studied such as the Santa Ana winds in southern California (Abatzoglou et al., 2013; Guzman-Morales et al., 2016) as well as several high profile downslope wind events across the western US. Since the approach used reanalysis data at ∼30-km horizontal resolution, it may not adequately detect downslope winds associated with finer-scale terrain and is designed to capture widespread synoptically forced downslope winds.

To associate individual fire events (FPA-FOD data) and daily burned area (MODIS data) to downslope wind events, we define an impact region for downslope winds to ensure that locations in the lee of the mountain barrier would be included. The impact region is defined as a semicircle with a radius of 60-km aligned downwind of the mountaintop wind direction. Whereas the leeward fetch of downslope winds and associated meteorological impact (e.g., wind gusts, elevated temperature, depressed humidity) likely varies from event to event with mesoscale dynamics, many observational studies suggest downwind extension of near-surface impacts of ∼60-km and even further in the presence of hydraulic jumps that can occur with severe downslope winds (Hoinka, 1985). Second, given known reporting offsets in fire ignitions, we use a buffer of 1 day prior to and after downslope wind events for attributing individual fires and burned area, similar to previous studies (e.g., Kolden & Abatzoglou, 2018). This approach may omit some fires where downslope winds were the primary contributor to eventual spread, but the downslope wind event occurred several days or even weeks after ignition.

Several statistics are calculated to identify spatiotemporal and biophysical attributes as well as societal impacts of fires coincident with downslope winds. We compare these metrics against those for fires that occur in the absence of downslope winds. First, we tabulate the local contribution of downslope wind-driven fires to total fire occurrence and burned area as well as their seasonality at local-to-regional scales across the western US. Second, we examine fire-cause, dominant land-cover type, and fire impacts to human lives and infrastructure coincident with downslope winds. Third, we examine fire weather coincident to fire discovery days and both antecedent and concurrent drought conditions for fires coincident with downslope winds, to elucidate commonalities in top-down climate and weather factors associated with large (≥40 ha) and smaller (<40 ha) fires. The 40 ha size threshold for defining large fires follows previous studies (e.g., Abatzoglou et al., 2018) acknowledging that size thresholds for large fires vary geographically (Nagy et al., 2018). Finally, we calculate trends in fire metrics associated with downslope winds during 1992–2020 to provide context for changes in these fires in the last few decades. Additional detail on the data and methods for each of these comparisons is provided below.

Statistical measures of fire activity associated with downslope winds are calculated on both a quarter-degree grid (~25-km horizontal resolution) as well as at the pyrome level through a summation of individual fires with ignition locations within each grid or polygon, respectively. We use pyromes from Short et al. (2020), which are subregions of level IV Environmental Protection Agency ecoregions with similar contemporary fire regimes. We additionally identify local seasonality statistics for climatological seasons (e.g., Mar-May) based on the months with the plurality of either fire occurrence or burned area coincident with downslope winds.

We use land cover from the 30-m National Land Cover Database (NLCD; Yang et al., 2018) from the most recent year prior to each fire. Land cover is sampled within a 1-km radius of the reported point of fire origin consistent with the reported accuracy of the FPA-FOD location data (Short, 2014). We restrict our consideration of land classes to developed land, grassland, shrubland, and forest and identify the landcover with the plurality of coverage within the 1-km radius of each fire. The fire-impacts data considered herein are structures destroyed, injuries, and fatalities, and are limited to the subset of documented fires or complexes in the ICS-209plus database during 1999–2020. We tabulate the total impacts for fires associated with downslope winds relative to the full database. Additionally, as single fires can dominate loss profiles, we calculate the percent of fires that reported non-zero losses (e.g., fires with at least one structure loss) for each impact category. In doing so, we assume that fires reported in the FPA-FOD database that are not present in ICS-209plus did not incur human impacts as documented here.

We examine fire weather conditions during fire discovery days as well as antecedent and concurrent drought conditions. Two sources of near-surface meteorological data are used: (a) gridMET data at a ~4-km horizontal resolution (Abatzoglou, 2013), and (b) WRF reanalysis at a ~9-km horizontal resolution (Rahimi et al., 2022). The latter data are used exclusively for wind speed (VS) as they provide much greater realism of VS than gridMET (Rahimi et al., 2022). These data are used to calculate daily mean vapor pressure deficit (VPD), and fire danger indices of Energy Release Component (ERC), and the Burning Index (BI) from the US National Fire Danger Rating System (Cohen & Deeming, 1985). As a point of distinction, we use pressure-level ERA-5 data to identify downslope wind events, and near surface meteorological fields to quantify fire danger and fire weather. Anomalies are defined relative to 1991–2020 daily climate normals to provide context for the time of year and geographic location. Lastly, we extract the monthly Palmer Drought Severity Index (PDSI) calculated from gridMET for each fire for the period of 24-month prior to fire occurrence through the fire discovery month, given the potential antecedent and concurrent influences that slower moving moisture fluctuations have on fire potential (Westerling et al., 2003). We extract meteorological, fire danger, and drought data corresponding with the geographic coordinates and fire discovery date for each fire. Comparisons are made between conditions during the date of fire discovery for large (≥40 ha) fires and smaller (<40 ha) fires. Averages of fire weather variables, their anomalies, and PDSI are calculated for four fire categories: (a) small fires coincident with downslope winds, (b) small fires not coincident with downslope winds, (c) large fires coincident with downslope winds, and (d) large fires not coincident with downslope winds. Composites are made for fires pooled across the entire domain as well as at the pyrome level. We calculate a 95% confidence interval for each composite using resampling with replacement ($n = 1000$) and consider differences to be statistically significant in cases where the 95% confidence interval of the mean from a composite does not overlap with the mean from another composite.

Trends in fire occurrence and burned area associated with downslope winds during 1992–2020 are calculated using the Sen's slope estimator, given the approach is more robust to outliers in the data than linear least squares trends approaches. We additionally provide estimates of the percent change in fire metrics during 1992–2020 by dividing the magnitude of change over the period of record by the intercept of the fit for the initial year of data. In all cases, statistical significance of trends is specified where the two-tailed Mann-Kendall trend test had $p < 0.05$. Trends are additionally examined for the number of days of downslope winds, as well as ERC, VPD, and VS on days with downslope winds to provide context for observed changes.

3. Results

Approximately 13.4% of all western US fire ignitions during 1992–2020 occurred with downslope winds and these fires accounted for 11.9% of the region's total area burned. Downslope wind-driven wildfires, hereafter, downslope fires, exhibit a distinct geographic signature that highlights the intersection of downslope wind frequency, fuels, and human-ignition density (Figures 1a and 1b). Notably, the highest density of downslope fires occurred in southwestern California coincident with offshore Santa Ana and Sundowner winds, northern California where

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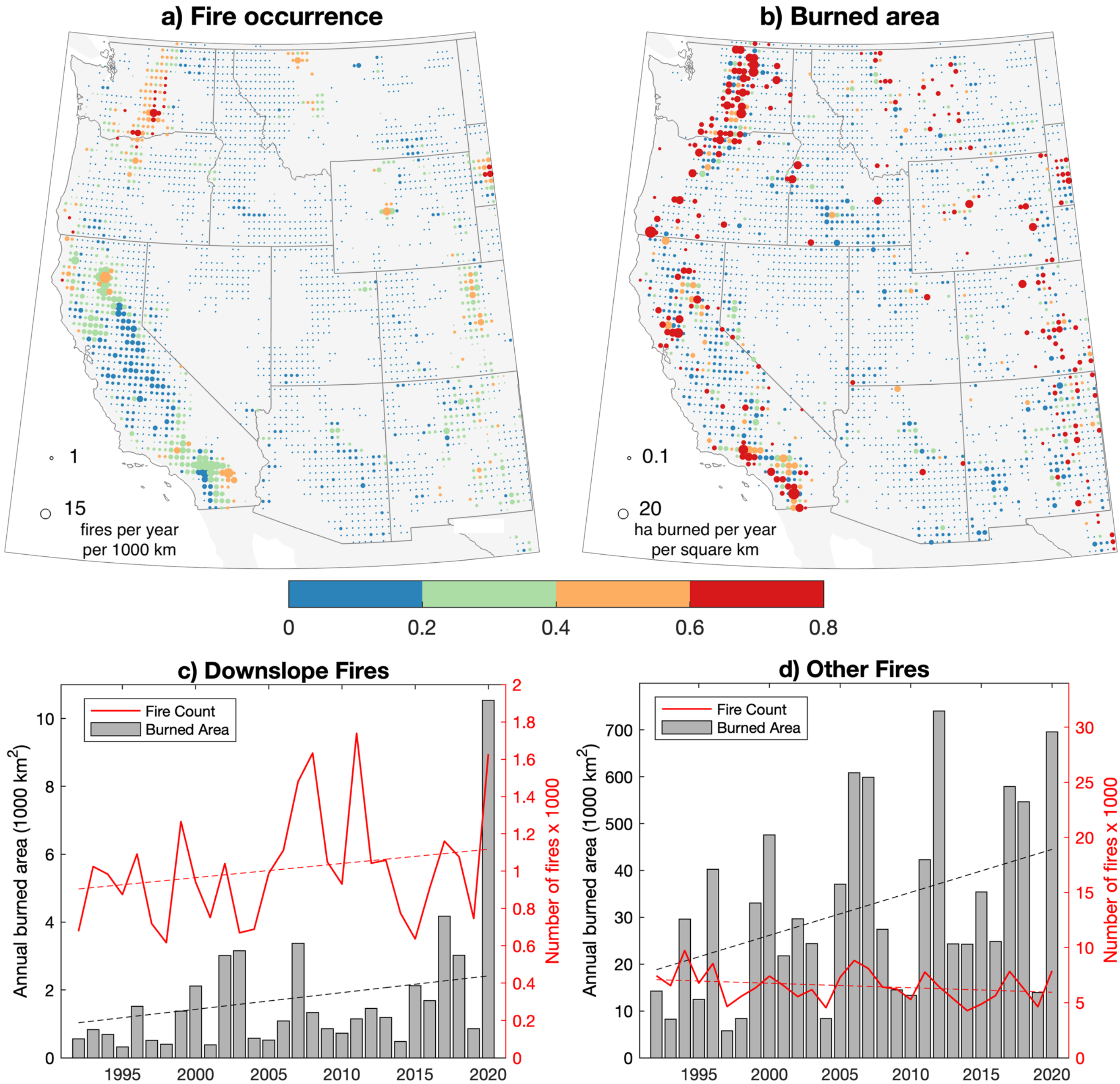

Figure 1. The fraction of (a) total fire occurrence and (b) total burned area for fires coincident with downslope winds during 1992–2020. The marker sizes scale with the (a) number and (b) total burned area of downslope fires, while the color shows the fraction of total fire activity from downslope fires. Data is aggregated to a 0.25° grid and results are only shown where there is at least 1 fire occurrence per 1000 km^2/yr or at least 0.1 ha/km^2/yr of burned area. Annual total fire occurrence (red) and burned area (gray bars) from (c) downslope fires and (d) all other fires over the western United States during 1992–2020. Dashed lines illustrate trend lines calculated with Sen's slopes for these quantities. Note that *y*-axes are different between (c) and (d).

Diablo winds have been associated with autumn fires (e.g., Nauslar et al., 2018; Smith et al., 2018), as well as along the eastern slopes of the Cascades in Washington. Locally, downslope fires accounted for over 60% of the cumulative burned area during 1992–2020 in portions of southwestern California. Other hotspots of downslope fires were along the eastern slopes of the Cascades in Washington and Oregon during westerly flow across the region, and along the front range of the Rocky Mountains from Montana to New Mexico during downslope westerly Chinook winds. Approximately 37% of the western US burned area attributable to downslope fires during 1992–2020 occurred in California. By comparison, California accounted for just 17% of western US burned area from other fires, highlighting the outsized impact of downslope winds in California fire activity. Results using the MODIS burned area data set largely mirrored the geography and fractional contribution to overall western fire activity, accounting for 15% of burned area during 2001–2020 (Figure S1 in Supporting Information S1).

Both the number and cumulative burned area associated with fires ignited during downslope winds show substantial interannual variability during 1992–2020 (Figure 1c). Many of the years with the highest annual burned area attributable to downslope fires were associated with very large autumn Santa Ana and Diablo wind-driven fires in California. Of note is 2020 when over 1 million ha of burned area was associated with downslope wind driven fires. Many of the largest downslope wind driven fires in 2020 occurred in September and October, including the Labor day fires in the western Oregon Cascades and the East Troublesome fire in Colorado (Abatzoglou, Rupp, et al., 2021; Higuera et al., 2021). We find a significant 140% increase in annual burned area from fires associated with downslope winds during 1992–2020. There was a non-significant 25% increase in the annual occurrence of downslope fires, with relatively larger increases in the occurrence of downslope fires exceeding 40 ha (+36%), exceeding 100 ha (+54%), and exceeding 1000 ha (+101%). Fires not associated with downslope winds also grew significantly, by 140%, in annual burned area during 1992–2020, but the annual frequency of these fires had non-significant decreases (−17%).

Downslope fires most frequently occurred in the shoulders of the core western US fire season during late spring and autumn, consistent with the overlap of the climatology of when downslope winds occur with sufficiently dry fuels (Figure 2; Figure S2 in Supporting Information S1). The seasonal cycle of daily burned area associated with downslope winds across the study region exhibits a more complex seasonal cycle with a few very large fire events in late summer and autumn evident in the time series. By contrast, fires that occur in the absence of downslope winds have a distinct maximum in both fire occurrence and burned area during July-August. Downslope wind-driven fires are most common in late summer in the eastern Cascades, most common in autumn across much of California, and most common in spring across portions of the southwestern US. Notably, while there are a high number of fire ignitions associated with downslope winds in the spring, they generally do not meaningfully contribute to burned area outside of the Southwest as fuels are generally too wet during green-up for fires to carry sufficiently at landscape scales.

Downslope fires were predominantly tied to human-ignitions. Human causes accounted for 91.4% of downslope fires with either human or natural causes (excluding those with a missing or undetermined general cause classification)—far in excess of the 66% of fires ignited by humans that did not occur during downslope winds (Figure 3a). Among fires with a known specific cause (i.e., excluding "Missing" or "Other" causes), debris burning (e.g., fires intended to clear land, fuels, or burn garbage) accounted for 30% of downslope fires—more than double the percent of non-downslope fires caused by debris burning. Fires attributed to arson and energy systems were associated with 10.3% and 3.5% of downslope fires, respectively. Fires attributed to energy systems (e.g., powerlines) and recreation (e.g., camp fires) were 75% and 116% more likely, respectively, as fire causes during downslope winds than fire causes without downslope winds. The leading contributors to total burned area during downslope fires were lightning (41%) and electrical distribution (16%) (Figure 3b). Notably, over half of the burned area associated with lightning-caused downslope fires occurred in Washington and Oregon where westerly downslope winds are more common in summer. Lastly, we find that downslope fires accounted for 50% of burned area attributed to energy system causes and over 25% of burned area attributed to both recreation and firework causes (Figure 3c).

Downslope fires were broadly distributed among the four primary land cover classes (Figure S3 in Supporting Information S1). A slightly higher portion of downslope fire occurrences in land cover classes dominated by developed lands than non-downslope fires. Fire ignitions in shrubland dominated lands accounted for 48% of the total burned area in downslope fires, compared to 38% for other fires. We note that the dominance of human-ignitions in fires associated with downslope winds likely confounds direct attribution to the four classes of landcovers examined here.

Fires that were ignited during downslope winds had outsized impacts on direct losses to infrastructure and lives. We found that 60.1% of the cumulative structures lost, 52.4% of the fatalities, and 14.1% of the injuries that occurred in wildland fires in the western US during 1999–2020 occurred in downslope fires (Figure 4a). By comparison, 12.8% of ignitions and 11.3% of total burned area during the 1999–2020 period were associated with downslope winds. The rates of fatalities and structure loss were significantly higher ($p < 0.05$) in downslope fires than other fires (Figure 4b). Fires that resulted in loss of life were nearly three times as likely for downslope

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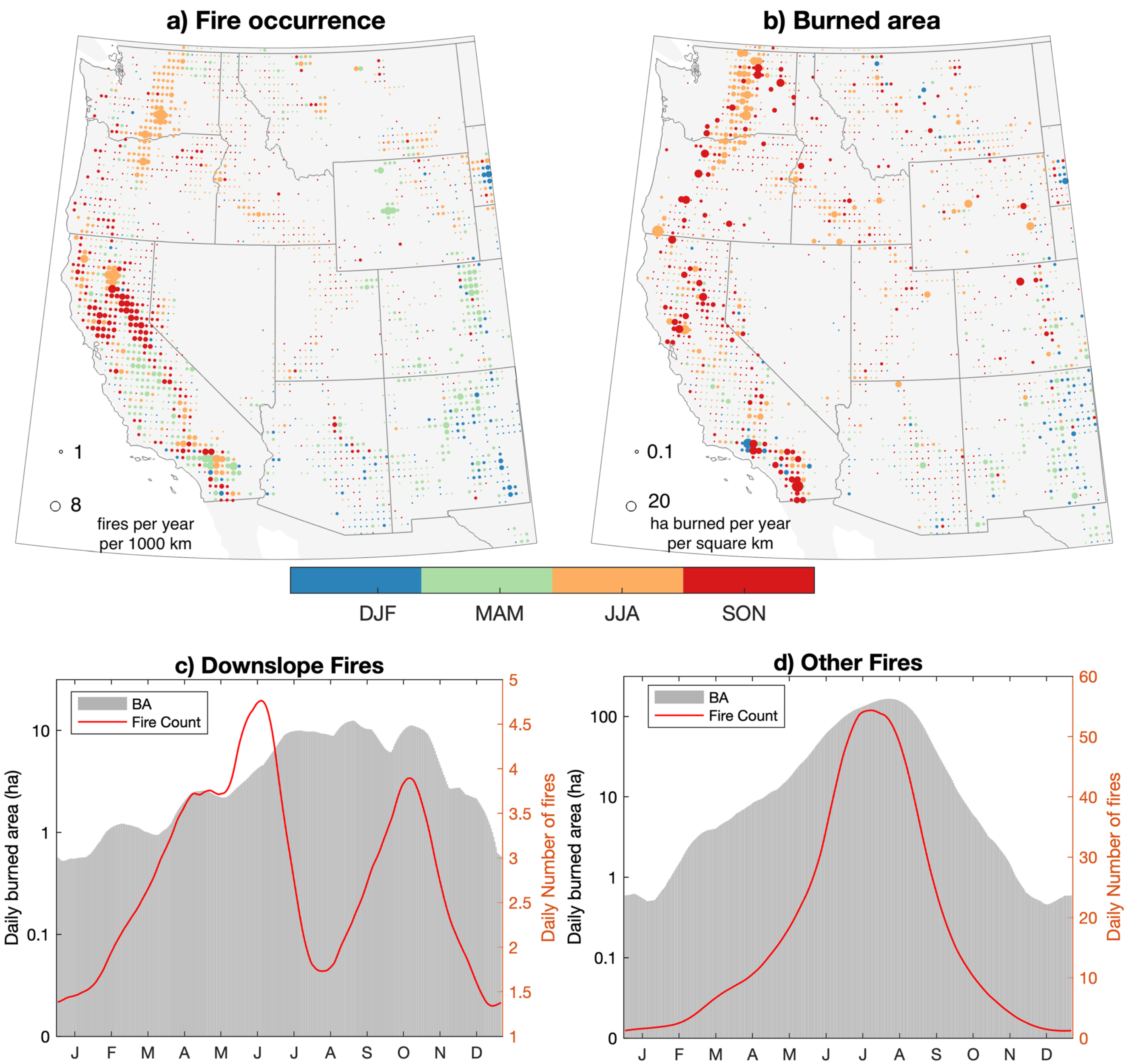

Figure 2. The seasonality of downslope wind-driven (a) fire occurrence and (b) burned area on a 0.25° grid during 1992–2020. Colors denote the climatological season with the local plurality while marker sizes scale with the fire occurrence (a) and burned area (b) in that season. The mean annual cycle of total fire counts (red) and burned area (gray bars, logarithmic axis shown) over the western United States for (c) downslope fires and (d) all other fires during 1992–2020. Daily data is smoothed in panels (c) and (d) using a 31-day centered moving average. Note that *y*-axes are different between (c) and (d).

wind-driven fires as fires that occurred in the absence of downslope winds. Fires resulting in structure loss were approximately twice as probable for downslope fires than for fire events in the absence of downslope winds.

Downslope fires occurred coincident with significantly drier fuels (positive anomalies in ERC), and significantly more conducive fire weather (positive anomalies in BI and VS) across the entire West (Figure 5; Figure S4 in Supporting Information S1). Anomalies in daily VPD were more mixed with positive anomalies for pyromes on the western flank of North American Cordillera and on the front range of the Rockies, but negative VPD anomalies in the Intermountain West.

Absolute values of fuel aridity (ERC) and atmospheric aridity (VPD) were lower for downslope fires than other fires (Figures 6a and 6c). These differences largely reflect the tendency for downslope wind fires to occur outside

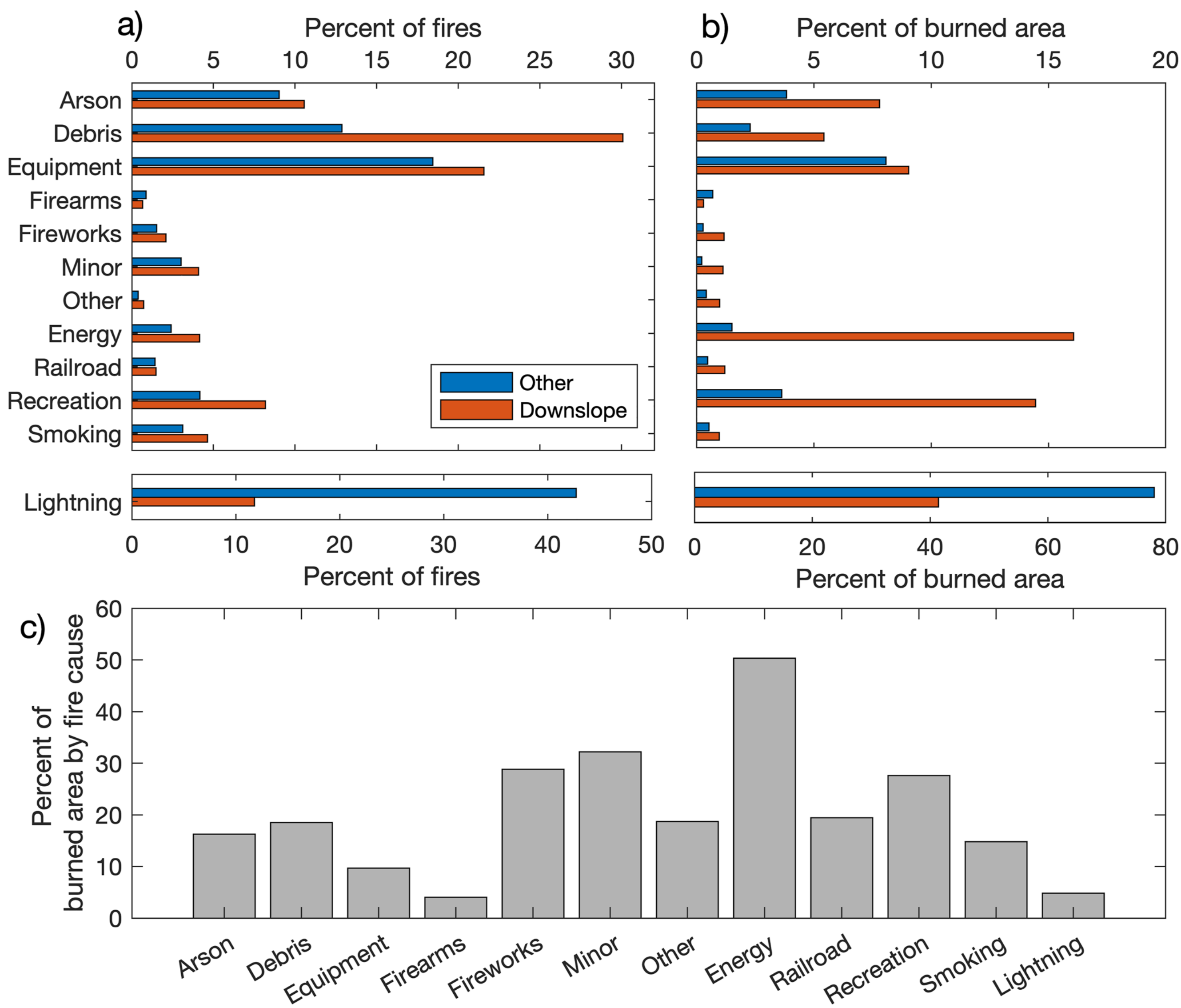

Figure 3. Percent of (a) fire occurrence and (b) burned area for downslope fires (orange) and all other fires (blue) by fire cause across the western United States. Fires of unknown or missing cause, which accounted for 29% of fires, are excluded. Statistics for lightning-ignited fires are shown on different scales. Panel (c) provides an alternative view by showing the percent of total burned area for each fire cause that is attributed to downslope fires.

of the core fire season when fuel moistures, air temperature, and VPD often reach their annual maximum. By contrast, the BI, a fire danger index that accounts for ERC and winds, was higher for downslope wind fires than other fires, with similar results seen for VS (Figures 6b and 6d). Large fires (≥40 ha) associated with downslope and non-downslope winds occurred with significantly more extreme fire weather (i.e., higher ERC, BI, VPD, and VS) than smaller fires (<40 ha). These differences were also found at the pyrome level highlighting the robustness of these west wide analyses for smaller geographic regions (Figures S5 and S6 in Supporting Information S1).

Downslope fires tended to occur during negative PDSI values, with significantly lower PDSI for large downslope fires than smaller downslope fires (Figure 6e). The same signal was found for non-downslope fires. Large non-downslope fires tended to be preceded by higher PDSI in the year prior to the fire—indicative of wetter-than-normal conditions during the previous year that may foster fine fuel growth and continuity. By contrast, no antecedent signal was found for large downslope fires.

Trends in several downslope winds, downslope fire activity, and weather characteristics coincident with downslope winds during 1992–2020 are shown in Figure 7. First, there are increases in downslope fire occurrence

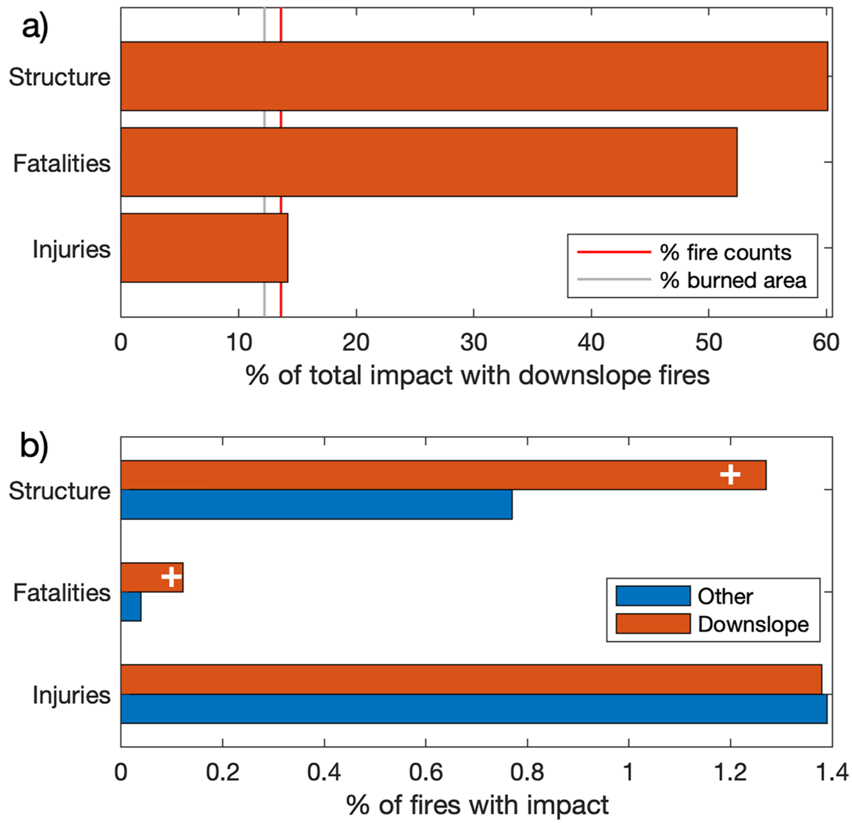

Figure 4. Fire impact statistics for fire events during 1999–2020. Panel (a) show the percent of total injuries, fatalities, and structure losses from fires associated with downslope winds. For reference, the vertical lines show the percent of fires and burned area attributed to downslope fires during 1999–2020. Panel (b) shows the percent of fires producing injuries, fatalities, and structure loss for downslope fires (orange) and all other fires (blue). Plus signs denote statistically significant differences ($p < 0.05$) between downslope fires and other fires using bootstrap resampling with replacement ($n = 1000$).

across the Front Range of the Rockies (Figure 7b). The spatial signature of increased downslope fire occurrence may partially reflect positive trends in downslope wind occurrence in these regions (Figure 7a), although these trends are generally small and not statistically significant. Significant increases in ERC and VPD on days with downslope winds were seen across much of the region; by contrast, nominal trends in VS was observed on days with downslope winds (Figures 7d–7f). This suggests that the combination of increased downslope wind occurrences in a few areas, along with drier fuels and a more arid atmosphere in most areas, especially in the southern half of the region, has contributed to heighted fire potential from downslope winds in these regions. Similar overall results are found for trends examined for specific climatological seasons (Figure S7 in Supporting Information S1).

4. Discussion and Conclusions

Wildfires associated with downslope wind events in the western US accounted for 13.4% of the total number of fires and 11.9% of the overall burned area during 1992–2018. While 37% of the burned area attributable to downslope wind fires occurred in California where Santa Ana and Diablo winds are prevalent (Jin et al., 2014; Kolden & Abatzoglou, 2018), we show the importance of downslope wind-driven fires in other hot spots across the western US, including the front range of the Rockies (Coen & Schroeder, 2015; Fovell et al., 2022) and Cascades (Abatzoglou, Rupp, et al., 2021). In these regions, fires associated with downslope winds accounted for most of the local cumulative burned area, highlighting their contribution to local fire regimes.

In most areas, downslope wind-driven fires predominantly occurred outside of the core summer fire season as synoptic conditions are less favorable for strong winds in the summer months (Abatzoglou, Hatchett, et al., 2021). Further, the prominence of downslope wind-driven fires outside of the core summer months, when

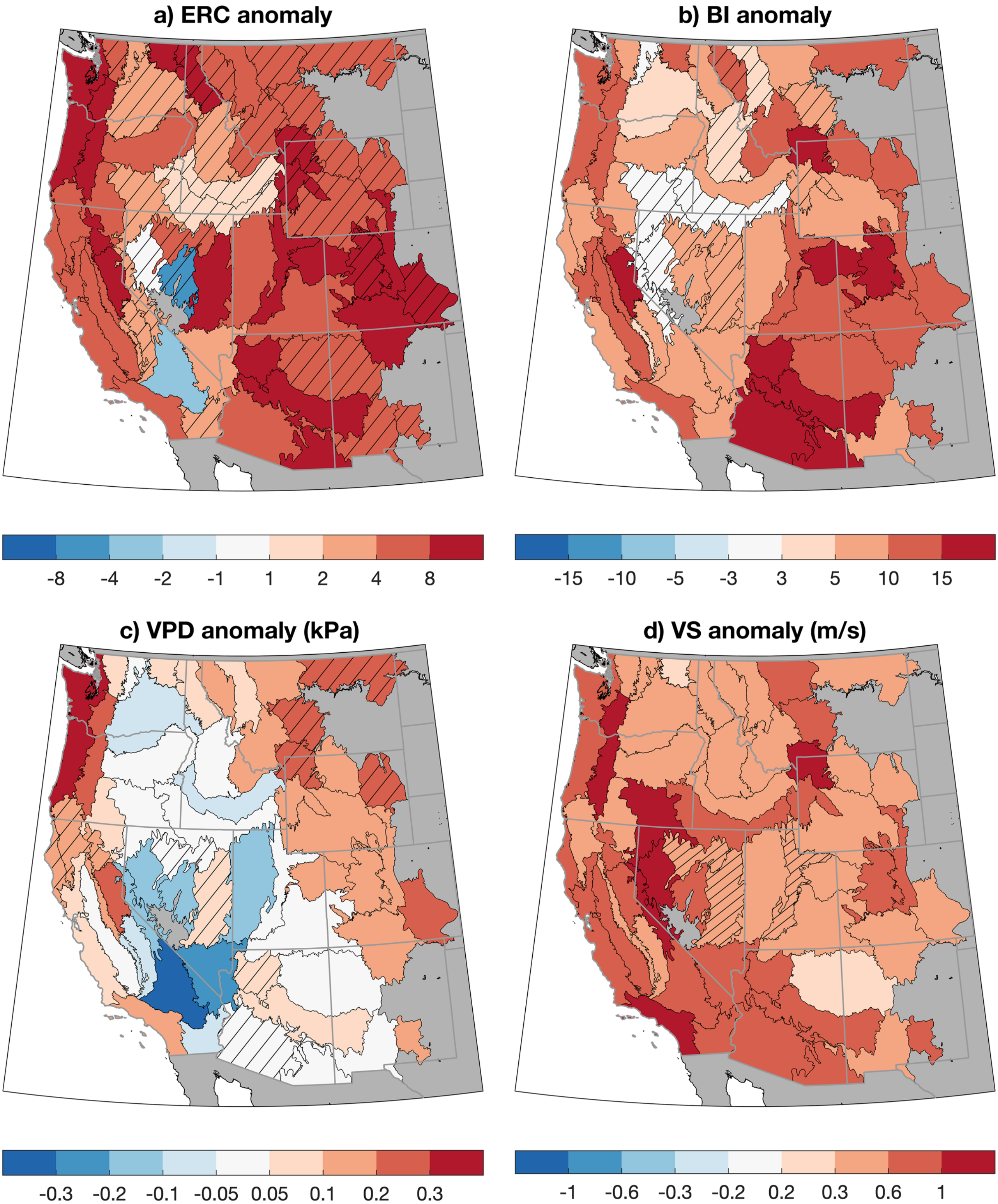

Figure 5. Composite anomalies in (a) Energy Release Component, (b) Burning Index, (c) vapor pressure deficit, and (d) wind speed on the discovery day for downslope fires across pyromes. Anomalies for each fire are computed with respect to the 1991–2020 daily averages for each fire discovery day and co-located pixel, then averaged across pyromes to create pyrome level anomalies. Hatches denoted pyromes where differences for a given metric were not statistically significant.

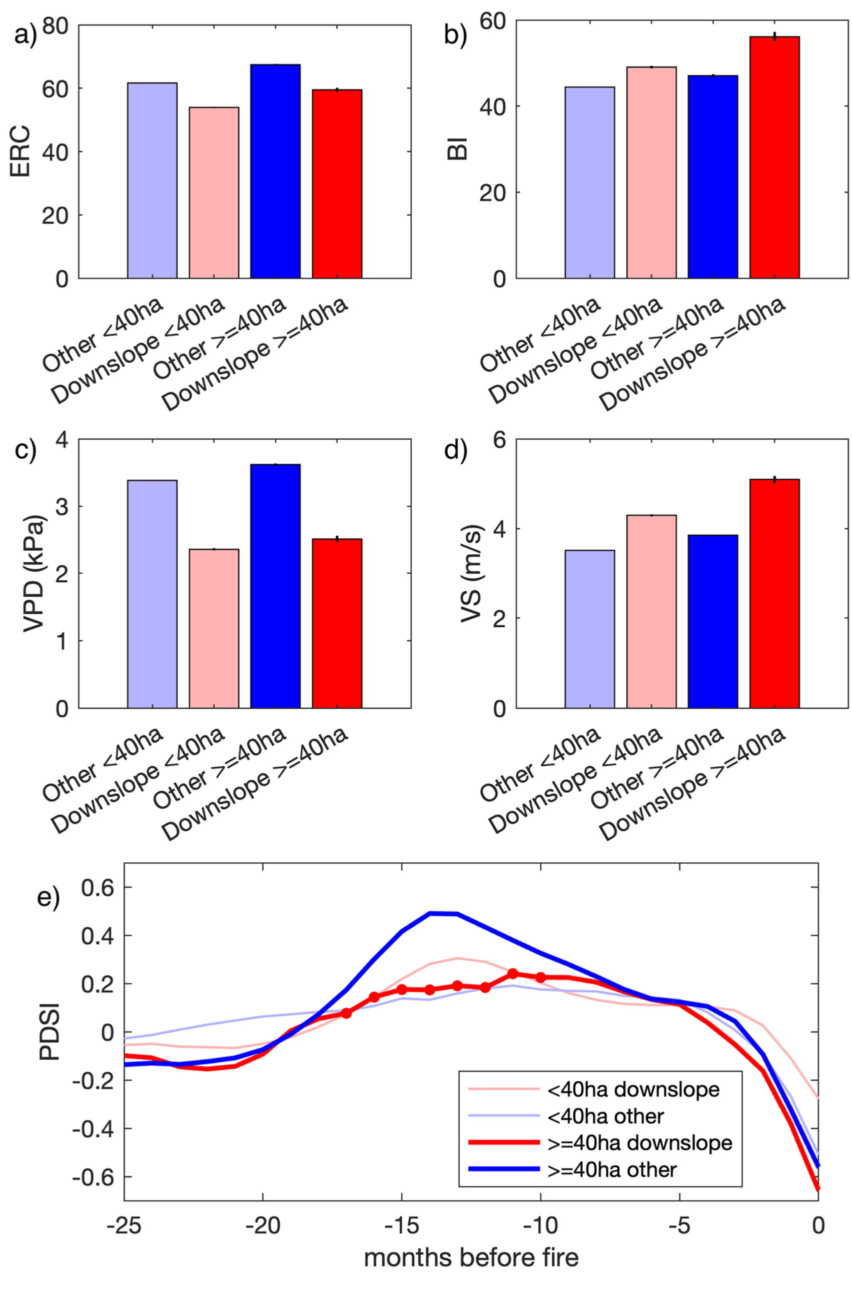

Figure 6. Mean (a) Energy Release Component, (b) Burning Index, (c) vapor pressure deficit, and (d) wind speed on the discovery day of smaller (<40 ha) and large (≥40 ha) fires in the western United States coincident with downslope winds and not coincident with downslope winds. The black vertical line provides an estimate of the 95% confidence interval of the mean for each fire category; due to large samples sizes, many of these confidence intervals are very small. Panel (e) shows mean Palmer Drought Severity Index (PDSI) for 24 months prior to through the fire discovery month. Statistically significant differences ($p < 0.05$) between mean PDSI for large downslope and all other large fires are denoted by filled circles.

lightning ignitions peak, highlights the importance of human ignitions in starting downslope wind-driven fires (Balch et al., 2017) and the potential role of fire prevention strategies in limiting such fires. Among the various human-caused ignition types, we find that debris burning was the leading cause of fire occurrence during downslope wind events. Previous studies report energy systems and arson as the leading cause of burned area in Santa Ana fires of Southern California (Keeley et al., 2021). Excluding fires with an unknown cause, lightning (41%) and energy systems (16%) were the top contributors to burned area for downslope wind-driven fires across the broader West.

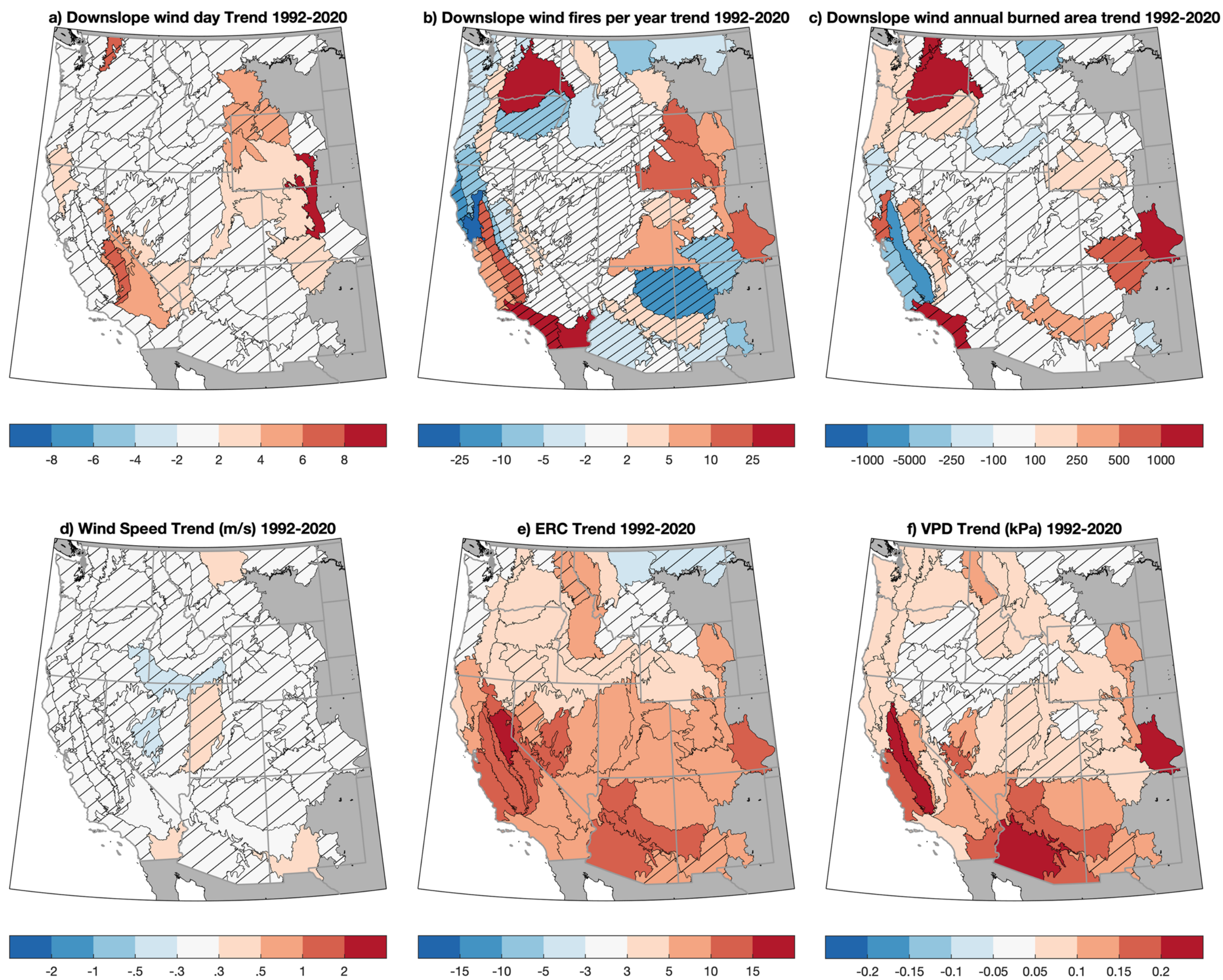

Figure 7. Linear trends at the pyrome level in (a) days per year with downslope winds, (b) annual number of downslope fires, (c) annual burned area from downslope fires, and (d) 10-m wind speed on days with downslope winds, (e) Energy Release Component on days with downslope winds, and (f) vapor pressure deficit on days with downslope winds. Trends are calculated using Sen's slope during 1992–2020. Non-significant ($p > 0.05$) are denoted by hatching.

Downslope winds had an outsized direct impact on human life and infrastructure. We found that downslope wind-driven fires were three times as likely to be associated with a fatality and twice as likely to produce structure loss than other fire events. We note that a majority of the top 20 most destructive fires in California through 2022 (CalFire, 2023) occurred coincident with downslope winds. The meteorological conditions during downslope wind-driven fires not only contribute to rapid rates of surface fire spread, but also cast embers significant distances from the fire line that can circumvent local fuel mitigation measures if structures are vulnerable (Kolden & Henson, 2019). These conditions also significantly influence fire suppression tactics that limit structure defense. Indeed, Jin et al. (2015) showed that fires associated with Santa Ana wind events accounted for approximately 80% of direct economic losses associated with fires in southern California during 1980–2009 despite accounting for only half of the burned area. Our finding of fatalities being three times more likely with downslope wind fires is consistent with reports from Australia and Europe showing that most fatalities are associated with being caught unexpectedly, and often due to late evacuation (for civilians) and extreme fire behavior (for firefighters) (Haynes et al., 2019). Given the outsized impact of downslope fires on loss of life and property, advances in both numerical weather predictions and wildfire warning systems should be tuned to this phenomenon (Fovell et al., 2022) both for fire prevention purposes as well as to increase situational awareness for fire suppression personnel and impacted communities.

Previous studies have shown negligible influences of antecedent climate relative to ignitions in significant wind-driven fires in portions of California (Keeley et al., 2021). Here, we show anomalously drier fuels leading up to the ignition for downslope wind fires (e.g., above normal ERC; Figure 5a; Figure S4a in Supporting Information S1). This is particularly evident for large downslope wind fires, and has been observed for many significant offshore downslope wind-driven fires in Oregon and California (Cayan et al., 2022; Hawkins et al., 2022). ERC is a build-up index of fuel dryness that reflects precipitation, humidity, and temperature from the previous several weeks. It is insensitive to VS and hence is not significantly influenced by downslope winds on a day-to-day basis, yet repetitive downslope winds can boost ERC levels. We also note that fuel aridity metrics such as ERC and VPD had lower values for fires associated with downslope winds compared with fires not associated with downslope winds. This is due to the tendency of downslope winds to occur outside of the core summer months in the western US when fuel aridity often reaches its apex. Overlapping periods of dry fuels in late-summer and autumn (prior to the arrival of significant precipitation) and the seasonal ramp-up of downslope winds comprises an important vulnerability window, when the ignitions can rapidly escape initial suppression and become large and potentially destructive fires (Cayan et al., 2022; Goss et al., 2020). As with previous studies, our results show large fires tended to occur with more anomalous fire weather (e.g., ERC, BI, VS) and drought (e.g., PDSI) compared to smaller fires (Abatzoglou et al., 2018; Gutierrez et al., 2022; Juang et al., 2022)—although the effects were similarly found for non-downslope wind fires. Large downslope fires tended to occur with neutral antecedent PDSI in the prior year. This differed significantly from the antecedent positive PDSI seen for large fires not coincident with downslope winds, which adhere to fuel-limited fire-climate relationships (Littell et al., 2009). The lack of an antecedent PDSI signal for large downslope fires may reflect differences in productivity constraints in geographic locations prone to such fires or the ability of wind-driven fire to supersede fuel continuity constraints (Moritz, 2003).

Numerous studies have documented the increase in burned area across the western US over the past half-century. Here, we show that both the annual number of fires and burned area attributable to fires coincident with downslope winds increased during 1992–2020. Winds are well recognized as a driver of extreme fire behavior. Using best-available data for diagnosing downslope wind events across the western US over multiple decades, this study represents a major advance in our understanding of one key phenomena, downslope wind-driven fires, that threaten populated regions in and adjacent to mountain portions of the West. Annual burned area associated with downslope wind-driven fires increased significantly and proportionate to overall annual burned area across the western US. The number of wildfires associated with downslope winds—which are predominantly human-ignited—increased by 25% during this period, while the number of fires not concurrent with downslope winds declined by 16%. We suggest this is partly due to a human failure to recognize drier, more adverse fire weather conditions in the shoulder seasons and alter risky behavior (such as debris burning) that facilitates ignitions, and observed increases in powerline ignitions in places like California (Keeley & Syphard, 2018). A coherent pattern of increased downslope wind-driven fire occurrence was noted along the eastern slopes of the Rockies in Colorado. This increase in fires may partially reflect the increase in downslope wind occurrence in this region and population growth in the wildland-urban interface (Radeloff et al., 2018). An extension in the fire weather season (e.g., Jolly et al., 2015) with higher ERC and VPD in the spring and fall when downslope winds are more common, have increased opportunities where fuels are sufficiently dry to ignite and carry fire, potential ignitions can occur, and downslope winds can propel fire spread. This has been most widely documented in California where fuels have remained dry deeper into the downslope wind season when many of the largest downslope wind driven fires have occurred (Khorshidi et al., 2020; Williams et al., 2019).

We elucidate the environmental niche of downslope winds on fire regimes across the western US and their outsized impact on human lives and infrastructure. Our study provided some empirical evidence of increases in annual occurrence and annual burned area attributed to downslope wind-driven fires and alludes to the potential roles that changes in climate and humans have played. How downslope wind-driven fires will change moving forward is a topic of active research. The growing wildland-urban interface in regions prone to downslope winds will likely contribute to both increased human ignitions and increased potential exposure to such fire, but also prompt fire-prevention efforts such as de-energization of the electrical grid to reduce ignitions during critical fire weather conditions. Human-caused climate change is projected to moderately decrease the prevalence of offshore downslope winds along the coastal western US due to weakened ocean-land heat contrasts during the cool season (Guzman-Morales & Gershunov, 2019; Hawkins et al., 2022; Hughes et al., 2011; Mass et al., 2022). But this thermodynamic mechanism may not apply to westerly downslope winds in the lee of the major mountain ranges. Continued increases in fuel aridity and broadening of the seasonal window where fuels are conducive to ignition and downslope winds occur (e.g., Goss et al., 2020) may increase occurrence of high-impact downslope wind-driven fires. A more in-depth analysis is needed to identify geographic and seasonal hotspots of increasing risk of such fires. For example, isolating where changes in climate will further enable the co-occurrence of downslope winds with critically dry fuels may help inform fire mitigation efforts tied to fire prevention, given the important role that human ignitions play in these fires. Lastly, given the important influence of human ignitions in downslope wind-driven fires and more tenuous link between anthropogenic climate change and winds, climate change may play a weaker role in changes in downslope wind-driven fires than in flammability-limited regimes where increased aridity tied to anthropogenic climate change poses direct implications for future fire regimes (Jones et al., 2022; Pausas & Keeley, 2021).

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The global database for diagnosing downslope winds is available at https://climate.northwestknowledge.net/ACSL/DOWNSLOPEWINDS/. All other datasets used herein are publicly accessible at the following repositories: (a) FPA-FOD: https://www.fs.usda.gov/rds/archive/catalog/RDS-2013-0009.6, (b) MODIS MCS64A1: https://lpdaac.usgs.gov/products/mcd64a1v006/, (c) gridMET: http://thredds.northwestknowledge.net:8080/thredds/reacch_climate_MET_catalog.html, and (d) WRF reanalysis: https://registry.opendata.aws/wrf-cmip6/.

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