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Human-related ignitions concurrent with high winds promote large wildfires across the USA

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Abstract. Large wildfires (>40 ha) account for the majority of burned area across the contiguous United States (US) and appropriate substantial suppression resources. A variety of environmental and social factors influence wildfire growth and whether a fire overcomes initial attack efforts and becomes a large wildfire. However, little is known about how these factors differ between lightning-caused and human-caused wildfires. This study examines differences in temperature, vapour pressure deficit, fuel moisture and wind speed for large and small lightning- and human-caused wildfires during the initial days of fire activity at ecoregion scales across the US. Large fires of both human and lightning origin occurred coincident with above-normal temperature and vapour pressure deficit and below-normal 100-hour dead fuel moisture compared with small fires. Large human-caused wildfires occurred, on average, coincident with higher wind speeds than small human-caused wildfires and large lightning-caused wildfires. These results suggest the importance of winds in driving rapid fire growth that can allow fires to overcome many of the factors that typically inhibit large human-caused fires. Additionally, such findings highlight the interplay between human activity and meteorological conditions and the importance of incorporating winds in modelling large-fire risk in human-dominated landscapes.

Additional keywords: fire regimes, lightning, weather.

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Introduction

Large wildfires are a native component of many ecosystems, yet can also have immediate and residual detrimental impacts to local communities, and degrade air quality across broader geographic regions (Keane *et al.* 2008). Bottom–up factors of vegetation, land use and anthropogenic features, as well as top–down atmospheric factors of climate and weather have been implicated in the occurrence of large wildfires (Meyn *et al.* 2007). Climate and vegetation collectively enable wildfire by preconditioning fuel abundance and aridity contingent on the limiting landscape factors for carrying fire. Wildfire occurrence and the resultant area burned in an individual wildfire are driven by numerous factors including fuel connectivity, human factors (including suppression efforts) and weather conditions (Cardille *et al.* 2001; Syphard *et al.* 2008; Abatzoglou and Kolden 2011). Weather conditions interact with human factors, facilitating greater suppression success when conditions are cool and wet. Conversely, fire weather conditions such as sustained strong winds can overwhelm suppression efforts and promote rapid fire growth (Moritz 2003).

The risk of large fires has been modelled over broad geographic scales using both top–down and bottom–up environmental factors (Westerling and Bryant 2008; Finney *et al.* 2011; Parisien *et al.* 2012, 2016; Hawbaker *et al.* 2013). Bottom–up controls on large wildfire occurrence consider several static or slowly changing factors such as topographic features (Stambaugh and Guyette 2008), as well as the abundance, composition (Marchal *et al.* 2017) and connectivity of fuels (Ager *et al.* 2007; Parks *et al.* 2012). Anthropogenic activity constitutes another bottom–up factor in the occurrence of large fires through the introduction of ignitions, land-use change and fire suppression (e.g. Syphard *et al.* 2008; Finney *et al.* 2011). Although the influence of anthropogenic land use on fire activity varies geographically (Fusco *et al.* 2016), most estimates suggest that higher population density and human land use decrease the occurrence of large fires (Parisien *et al.* 2012, 2016).

By contrast, top–down atmospheric controls on large fire occurrence are temporally dynamic, and understanding their influence requires considering both spatial and temporal aspects of large fire events. Top–down atmospheric controls include the influence of antecedent climate conditions on fuel abundance in fuel-limited systems and on fuel aridity in flammability-limited systems (Stocks *et al.* 2002; Westerling *et al.* 2003; Barbero *et al.* 2014). In addition, shorter-duration top–down weather drivers have been tied to the development and progression of large fires. Shorter-duration weather drivers include elevated temperature and dewpoint depression (Potter 1996), prolonged periods of dry conditions that allow fuel moistures to remain critically low (Johnson and Wowchuk 1993; Flannigan *et al.* 2000; Abatzoglou and Kolden 2011) and strong sustained winds that encourage fire spread (Moritz *et al.* 2010) and crown fire initiation (Bessie and Johnson 1995). Most efforts to evaluate the risk of large wildfire have used a pyrogeographic approach to understand geographic controls of vegetation, climate and human factors, without explicitly accounting for the temporal influence of weather in driving large fire growth. For example, Parisien *et al.* (2012) modelled the spatial occurrence of large fires with predictor variables including temperature, precipitation and wind speed, and found that wind speed had little influence in the model. However, their analysis included only the spatial aspect (e.g. strongest wind speed in the driest month for a given pixel) rather than winds temporally coincident with large fire events.

In addition to the need for more consideration of the temporal component of fire weather in risk assessments, environmental conditions that facilitate large fires may also differ between human- and lightning-ignited fires. Humans are responsible for a majority of reported wildfire starts in the United States (Balch *et al.* 2017), but human-caused wildfires are generally smaller and have higher rates of suppression success during initial attack, which is generally defined as the first 24 h after discovery, than their lightning-caused counterparts (Arienti *et al.* 2006). Nonetheless, human ignitions are responsible for 44% of overall burned area within the continental US (Balch *et al.* 2017). Human ignitions also have expanded the temporal niche of fire to encompass the spring and fall (autumn) (Balch *et al.* 2017), when fuel moisture and fire weather are likely to differ considerably from the lightning-dominated summer months. Despite the likely differences in the climatology of human- vs lightning-ignited large fires, studies that have analysed the two types of fires separately are rare (Abatzoglou *et al.* 2016; Marchal *et al.* 2017) and have not thoroughly examined the influence of weather conditions coincident with ignitions.

Lightning is most prevalent during summer months across most mid-to-high latitude land masses (Christian *et al.* 2003), coinciding with the time of the year when wind speeds and the frequency of strong winds are reduced owing to lower pressure gradients (e.g. Klink 1999). The prevalence of human-caused wildfires outside the summer months coinciding with stronger wind speeds in the mid-latitudes may allow winds to play a more prominent role as a top–down driver of large fire occurrence in spring and fall as long as fuels remain available and receptive to carrying fire, but this has not yet been explored. Regional fire outbreaks have been associated with synoptic to mesoscale weather patterns that promote strong and sustained winds and facilitate rapid fire spread (Cheney and Gould 1995; Crimmin 2006; Moritz *et al.* 2010; Cruz *et al.* 2012; Billmire *et al.* 2014). Yet, although many studies have linked wildfire activity to primary climate variables and drought (Westerling *et al.* 2003; Abatzoglou and Kolden 2013; Littell *et al.* 2016), fewer studies have explicitly examined the influence of winds on the development of large fires across broader scales (Jin *et al.* 2014; Krueger *et al.* 2015).

The present study focuses on the role of weather drivers of large fire events across the contiguous US separately for human-caused and lightning-caused wildfires. We aim to complement previous studies of large fire risk by explicitly examining differences in characteristics of short-term atmospheric contributors to the fire environment between large and small fires of human and lightning origin. We specifically focus on weather conditions encompassing the 24 hour initial attack suppression period, which include the date of fire discovery and 1 day following to allow for the wide variability of ignition times over the course of a given day.

Materials and methods

We used the Fire Program Analysis (FPA) fire occurrence database, which included more than 1.8 million individual fire events from 1992 to 2015 (Short 2014) that required an agency response (e.g. suppression). Agricultural burns and prescribed fires were not included in the database unless they escaped and became wildfires. These data were quality-controlled and georeferenced in an effort to reduce redundant fire reports issued by different reporting units. We used information on fire location, date of fire discovery, final burned area (minimum fire size reported was 0.04 ha) and fire cause. Wildfires that had a missing fire cause and those that occurred outside the contiguous US (CONUS) were removed from subsequent analyses. We separated lightning-caused fires from human-caused fires following Abatzoglou *et al.* (2016) and Balch *et al.* (2017).

Large fires were defined as those that burned at least 40 ha following previous studies (Finney *et al.* 2009; Miller *et al.* 2009), although studies have acknowledged geographic differences in what constitutes a large fire across the US (Nagy *et al.* 2018). Small fires were defined as those that burned less than 40 ha. Using this threshold and the distinction between human-caused and lightning-caused wildfires, we considered four wildfire classes, hereafter referred to as large human-caused fires (LHF), large lightning-caused fires (LLF), small human-caused fires (SHF) and small lightning-caused fires (SLF). Large fires comprised 2.7% of the fires and 92.4% of the burned area from 1992 to 2015 (Table 1). Fig. 1 shows the geographic and seasonal distribution of large fires across the US. Approximately 31% of large fires were lightning-caused. A vast majority (82%) of large lightning-caused fires occurred from June to August, with most of these occurring in the western US. By contrast, large human-caused fires were well distributed geographically and seasonally across the US, similarly shown by Balch *et al.* (2017).

Daily maximum temperature, mean wind velocity, vapour pressure deficit (VPD) and 100-h dead fuel moisture (FM100) calculated using the US National Fire Danger Rating System (Cohen and Deeming 1985) were acquired from the surface gridded meteorological dataset of Abatzoglou (2013). Data were extracted from the 1/24° (~4 km) pixel co-located with the reported point of fire origin. These four variables include several aspects of the fire environment that change over sub-monthly (i.e. 100-h fuel moisture) to sub-weekly (wind speed)

Table 1. Total number and burned area extent (millions of hectares, Mha) for the four fire classes considered: large lightning-caused fire, large human-caused fire, small lightning-caused fire and small human-caused fire across contiguous United States from the Fire Program Analysis (FPA) dataset covering the period 1992–2015

The percentage of total fires and burned area for each fire class are provided in parentheses

Fire class	Number	Burned area (Mha)
Large lightning-caused	14 343 (0.8%)	22.56 (56%)
Large human-caused	32 122 (1.9%)	14.68 (36.4%)
Small lightning-caused	260 005 (15.3%)	0.38 (0.9%)
Small human-caused	1 394 917 (82%)	2.67 (6.6%)
Totals	1 701 387	40.3

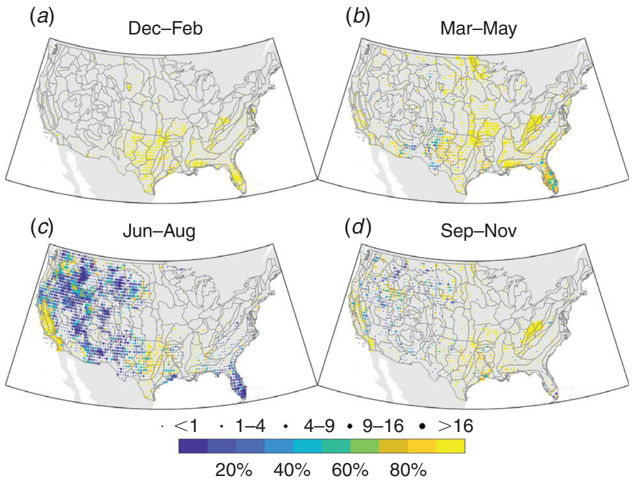

Fig. 1. Area-weighted counts of the number of large (>40 ha) wildfires binned using a 0.5° grid from 1992 to 2015 for (*a*) winter, Dec–Feb; (*b*) spring, Mar–May; (*c*) summer, Jun–Aug; and (*d*) autumn, Sep–Nov from the Fire Program Analysis (FPA) dataset. The symbol size corresponds to the large fire density (average number of fires per 10 000 km^2 per season) and the colours show the proportion of large fires that were human-caused. Polygons show the boundaries for Bailey's ecoprovinces used in subsequent analysis.

timescales and encompass aspects of fuel aridity and potential rates of spread that primarily vary on short timescales, including those that are often used in fire outlooks and daily fire weather briefings. This is not an exhaustive list of top–down atmospheric variables that influence the fire environment but covers many of the near-surface variables for assessing fire risk at large geographic scales. Furthermore, whereas some fire danger indices combine measures of fuel moisture and wind, we intentionally chose not to include these in an effort to better discern the independent influences of wind and fuel aridity. We additionally extracted the monthly Palmer Drought Severity Index (PDSI) from these same data concurrent with the month of fire discovery to assess longer-term moisture anomalies.

We constrained our focus to weather conditions during the fire suppression initial attack period, defined as the first 24 h of a suppression response following the fire being reported (after the first 24 h, the fire requires an extended attack suppression response and different tactics are utilised). It is important to note that fire discovery times are not equivalent to fire ignition times, particularly for fires occurring before modern detection capabilities and widespread Global Positioning Systems availability. It is not uncommon for hours or even days to pass before a fire becomes large enough to be observed and reported, and even then, the suppression response can be delayed if limited suppression resources are available or if the fire is not initially suppressed and instead managed to meet natural resource objectives. As discovery and initial attack may occur throughout the day, assessing conditions for a 2-day window defined by the discovery date and following day conservatively encompasses that entire 24-h period, and describes the conditions under which initial attack either succeeded or failed. We acknowledge that wildfires may reach large-fire (>40 ha) status 2 or more days after the discovery date. Although it is not tractable to reconstruct daily growth rates for the fires in our analysis, reported dates of containment were available for over half of the fires from the FPA dataset. Approximately 83% (46%) of all large human-caused fires (large lightning-caused fires) were contained within 1 day of the fire discovery date, which provides credibility for examining meteorological conditions over this period. Hereafter, unless otherwise stated, we used the 2-day average value of surface weather variables for the discovery date and following day.

Our analyses focused on relationships between weather drivers and fire occurrence at the geographic scale of Bailey ecoprovinces. Ecoprovinces were chosen in an effort to balance preserving vegetation-specific climate–fire relationships (Littell *et al.* 2009) while maintaining a large enough sample size of fires to run statistical analyses. Analyses were only conducted where ecoprovinces had at least 30 fires ignited by either lightning or humans. For illustrative purposes, we also examined relationships by pooling fires regardless of geographic location.

Daily surface weather variables and fuel moisture were examined across different fire types as well as contrasted between fire types (i.e. LHF and SHF, LLF and SLF, and LHF and LLF) using composite analysis. This was done to better elucidate how weather conditions coincident with fire discovery facilitate large fires at ecoprovince levels, and the degree to which these factors vary differ between human- and lightning-ignited fires. Comparisons were done using both raw values of maximum temperature, mean wind speed, mean VPD and FM100 and anomalies defined as daily averages for the 1992–2015 period. Analysing weather anomalies reduces the influence of differences in seasonality and geography within an ecoprovince. We quantified significant differences in the means for composite analyses using a student *t*-test at $P < 0.05$.

Second, we asked how the probability of different fire classes varies across a range of ambient meteorological conditions. Complementary to the composite analysis outlined in the previous paragraph, this analysis attempts to delineate the relative odds of fire classes (given an ignition occurs) across gradients of increasing wind speeds, VPD and drought. This was accomplished by tabulating fire occurrences for weather conditions exceeding a range of thresholds for wind speed (e.g. number of large human-caused fires where wind speed >5 m s^{-1}), VPD and PDSI. Counts were further normalised by the total number of fires for a given fire class within an

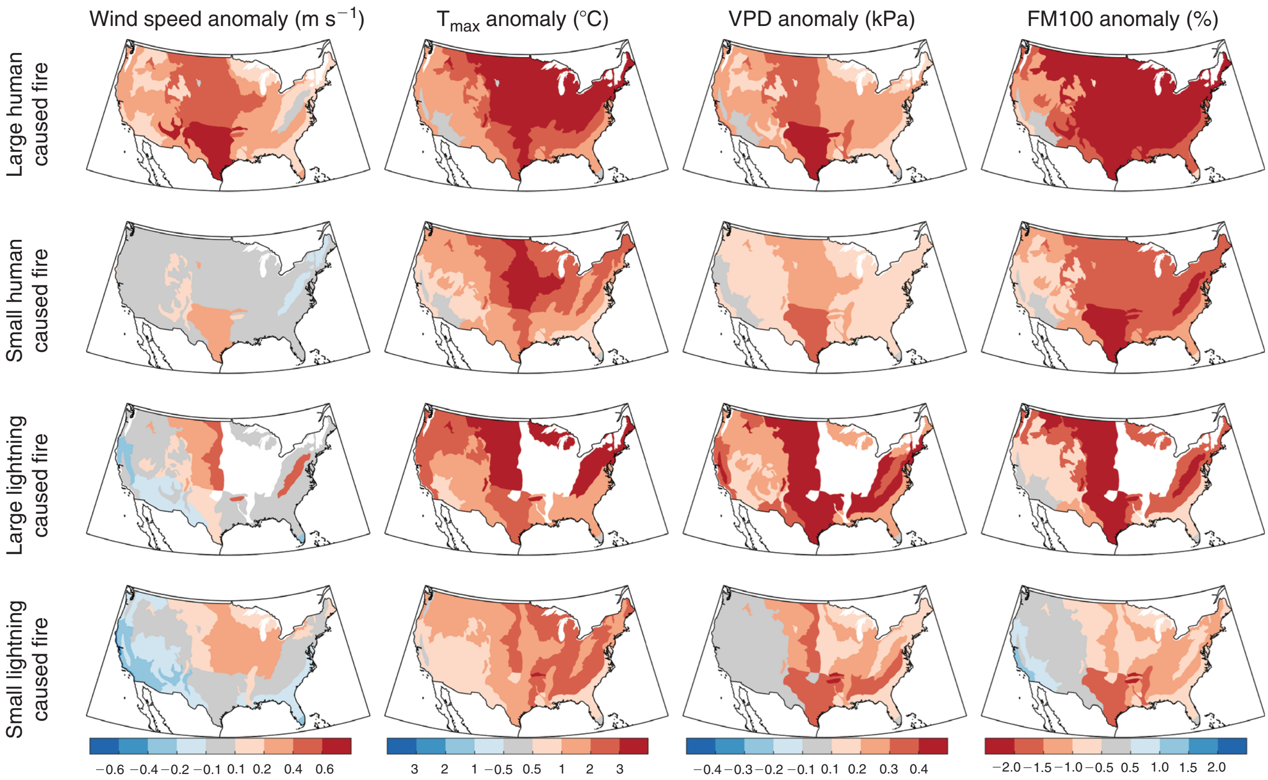

Fig. 2. Composite anomalies of (left to right): daily mean wind speed, daily maximum temperature (Tmax), daily mean vapour pressure deficit (VPD), and 100-hour dead fuel moisture (FM100) averaged over the date of fire discovery and the following day for (top to bottom): large human-caused fires, small human-caused fires, large lightning-caused fires, and small lightning-caused fires. Non-statistically significant anomalies are shaded grey, and ecoregions with fewer than 30 fires of a given type are omitted (white).

ecoregion. We then examined how these probabilities varied between fire classes (e.g. relative occurrence of large human-caused fires vs small human-caused fires when winds >5 m s^{-1}), hereafter referred to as normalised fire ratios. Normalised large-fire ratios provide an estimate of the occurrence of fire events relative to the background ratio or expected value of 1 defined within each ecoregion. We identify statistically significant normalised fire ratios where there were at least 10 fires of each type (e.g. ≥10 LHF and ≥10 LLF to calculate the LHF : LLF ratio) and the chi-square test was $P < 0.05$.

Results

Wildfires commonly occurred coincident with above-normal temperature and VPD, and below-normal FM100 over most ecoregions of the US for all fire classes (Fig. 2). The primary exception was across the western US where small lightning-caused fires occurred coincident with near-climatological normal VPD and FM100, on average. A distinctly different pattern was seen for wind speeds, which were near or below normal across most of the western US for both small lightning-caused fires and large lightning-caused fires, as well as small human-caused fires. Above-normal wind speeds were associated with large lightning-caused fires across much of the Great Plains, Midwestern US and Appalachians. In contrast, above-normal wind speeds were associated with large human-caused fires across nearly all ecoregions.

Large fires, both human and lightning-caused, coincided with more favourable environmental conditions for landscape flammability and fire spread than smaller fires as seen by higher wind speeds, temperatures and VPD, and lower FM100 (Fig. 3). The environmental influences of anomalies in temperature, VPD and FM100 on large fires were particularly evident for western ecoregions, regardless of ignition source. Similar results were found for faster-reacting 10-h dead fuel moisture (not shown). However, large human-caused fires occurred coincident with anomalously higher winds speeds than large lightning-caused fires, particularly across the southern tier of the US and much of the western US. By contrast, larger VPD anomalies were seen for large lightning-caused fires vs large human-caused fires in central US ecoprovinces.

A comparison of the raw data further supports these differences in meteorological and fuel conditions coincident with fire discovery (Fig. 4). Significantly higher wind speeds were seen for large fires compared with small fires, most notably for human-ignited fires. Mean wind speeds coincident with large human-caused fires were ~10% higher than for small human-caused fires, and 25 and 30% higher than for large lightning-caused and small lightning-caused fires respectively. Higher temperatures and VPD and lower FM100 were found for large fires vs small fires across the western US. Finally, although large human-caused fires occurred with higher wind speeds than large lightning-caused fires across most ecoregions, they also

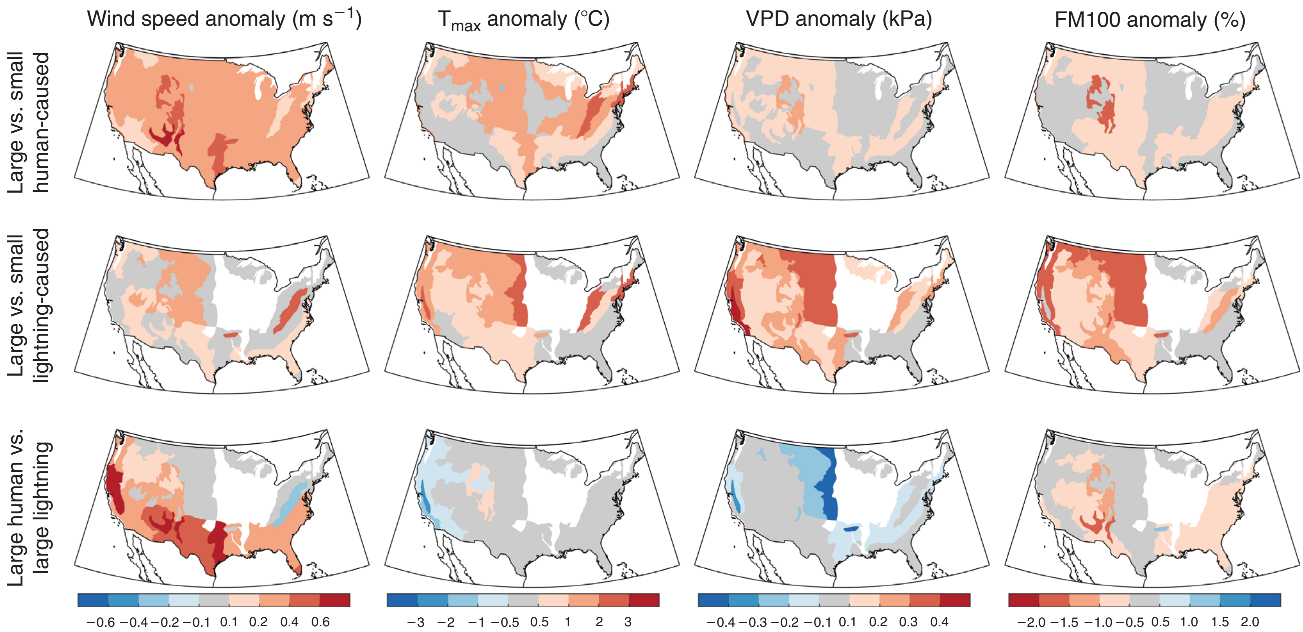

Fig. 3. Composite of differences in anomalies in (left to right), daily mean wind speed, daily maximum temperature (Tmax), vapour pressure deficit (VPD), and 100-h fuel moisture (FM100), between (top to bottom): large human-caused and small human-caused fires, large lightning-caused and small lightning-caused fires, and large lightning-caused and large human-caused fires. Non-statistically significant anomalies are shaded grey, and ecoregions with fewer than 30 fires of a given fire class being compared are omitted (white).

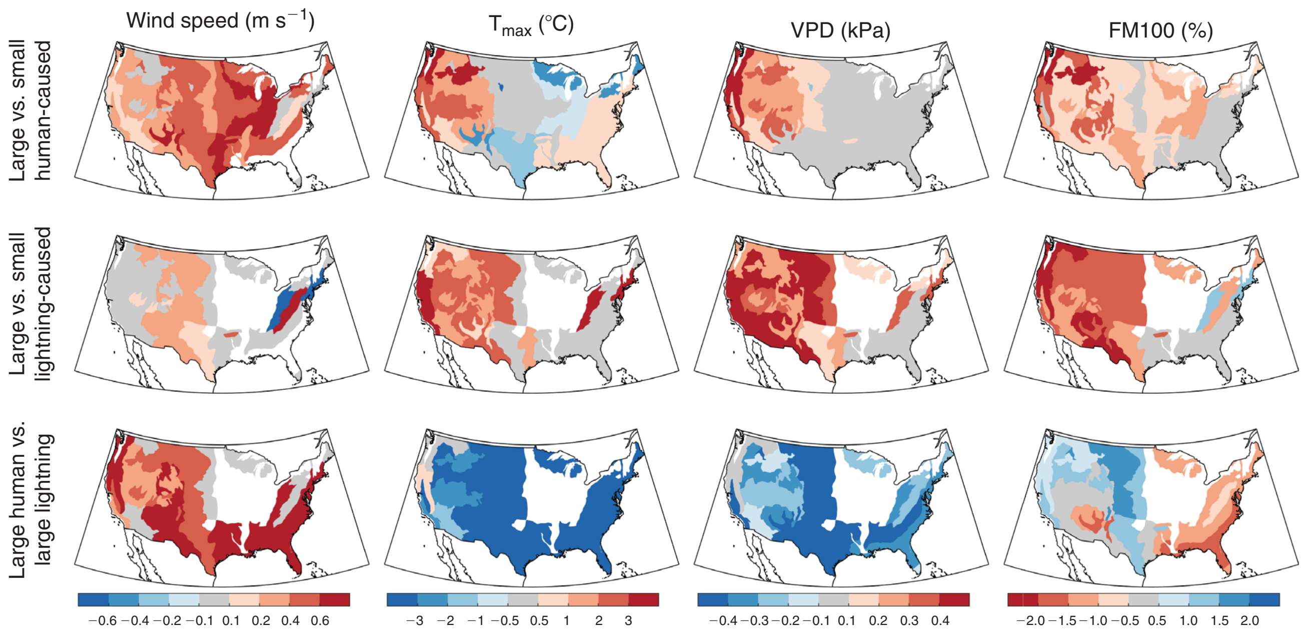

Fig. 4. As in Fig. 3 but comparing observed raw data rather than anomalies.

occurred during periods of lower temperature and VPD, consistent with differences in the seasonality of large fires (e.g. Fig. 1).

The normalised fire ratio for wind speed, VPD and PDSI exceeding various thresholds using fires pooled across CONUS is shown in Fig. 5*a–c*. Large fires were relatively more frequent with higher wind and VPD. For example, 31% of all large human-caused fires occurred with wind speeds >5 m s^{-1}, compared with 20% for all small human-caused fires. This resulted in a normalised ratio of large human-caused to small human-caused fires of 1.55, meaning that human-caused fires >40 ha were 55% more probable relative to their background proportion when sustained strong winds (>5 m s^{-1}) occurred

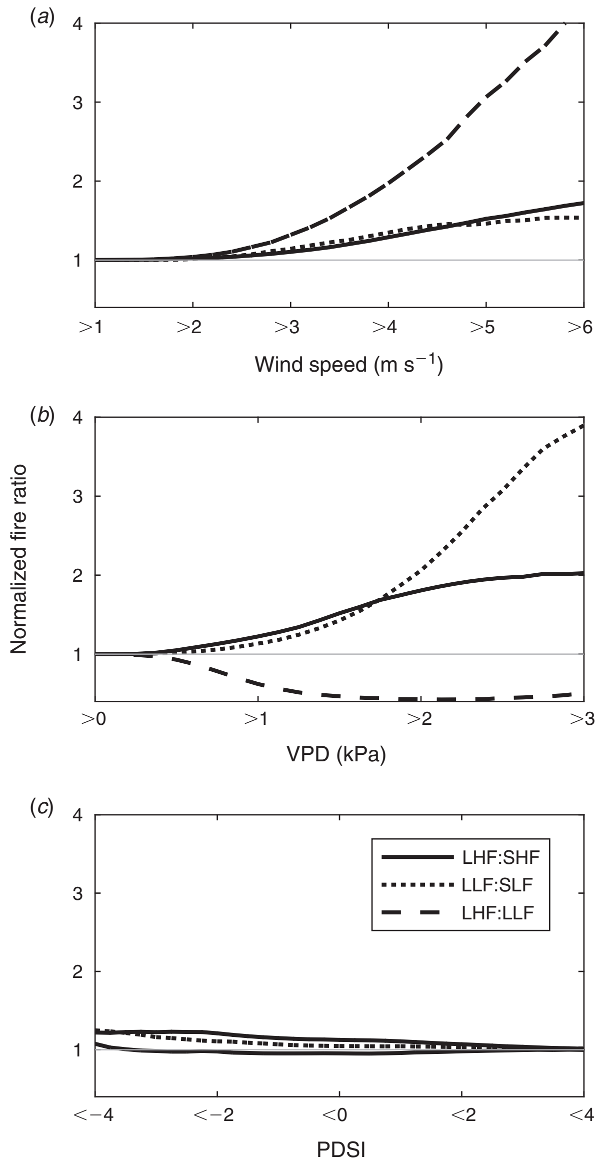

Fig. 5. Normalised fire ratios using data pooled over the US for (*a*) wind speed; (*b*) vapour pressure deficit (VPD); and (*c*) drought severity exceeding given values. The black, blue and red lines show ratios between large and small human-caused fires (LHF : SHF), large and small lightning-caused fires (LLF : SHF), and large human and lightning fires (LHF : LLF) respectively. For example, panel (*a*) shows that proportion of large human-caused fires is twice that of large lightning-caused fires when mean winds speed were >4 m s^{-1} over the first 2 days of fire discovery. The normalised fire ratio for (*c*) considered counts of fire classes contingent on Palmer Drought Severity Index (PDSI) below the values stated, whereas exceedances for wind speed and VPD are above the stated values.

coincident with fire discovery. Likewise, the normalised ratio of large lightning-caused to small lightning-caused fires was 2.4 when daily mean VPD >2 kPa, meaning that lightning-caused fires exceeding 40 ha were 140% more probable with elevated VPD levels. During longer-term drought (PDSI < –2), human-caused and lightning-caused fires were 25 and 15% more likely to exceed 40 ha respectively. The relative occurrence of large human-caused fires (31%) was substantially higher than large lightning-caused fires (10%) coincident with strong winds (>5 m s^{-1}). By contrast, nearly half of all large lightning-caused fires occurred coincident with elevated VPD (>2 kPa) compared with 21% of all large human-caused fires. Finally, long-term drought did not differentiate the normalised ratio of large human-caused and lightning-caused fires at the geographic scale analysed.

Fig. 6 shows the normalised fire ratios mapped at ecoprovince levels for daily mean wind speeds >5 m s^{-1} and VPD >2 kPa. Regional relationships were broadly consistent with those seen at the national level, with normalised ratios of large human-caused to small human-caused fires of 1.2–2.0 for wind speed >5 m s^{-1} over a majority of the ecoprovinces (Fig. 6*a*). Large lightning-caused fires were relatively more probable with wind speeds >5 m s^{-1} across several ecoprovinces but lacked widespread significance across ecoregions as seen for large human-caused fires (Fig. 6*b*). Large fires of both human and lightning origin occurred at a higher ratio across much of the western US with elevated VPD >2 kPa (Fig. 6*d*–*e*). Similarly to that seen in the national-scale analysis, the normalised ratio of large human-caused and lightning-caused fires exceeded 2 for wind speeds >5 m s^{-1} for most ecoprovinces across the western US and southern tier of the US whereas the opposite was seen for VPD >2 kPa.

Discussion and conclusion

Large fires generally occurred coincident with anomalously high daytime maximum temperatures and VPD and low fuel moistures across the contiguous US, consistent with other studies that have documented short-term top–down factors that enable and drive large wildfires (e.g. Koutsias *et al.* 2012; Riley *et al.* 2013; Barbero *et al.* 2014; Stavros *et al.* 2014). We further demonstrate that measures of atmospheric and fuel aridity coincident with the first 24 h following fire discovery commonly differentiated large from small fires for both human-and lightning-caused fires across much of the western US. These results are complementary to Abatzoglou *et al.* (2016) who showed similar interannual climate–fire relationships for human-caused and lightning-caused fires across ecoregions of the western US.

Unique to the present study is the finding that large human-caused fires were more likely to occur coincident with higher wind speeds than large lightning-caused fires, and both types of large fires occur with stronger winds than small fires. Our analysis suggests that the human expansion of the fire niche (Balch *et al.* 2017) also includes an expansion of ignitions into regions and seasons where wind speeds are climatologically higher, which facilitates the growth of large human-caused fires. Some human-caused fires may also be intentionally set during high wind events if arsonists recognise the growth potential. Assuming fuels are available, strong winds would facilitate larger wildfires by accelerating the flame front, desiccating fuels and increasing available oxygen for combustion (Fendell and Wolff 2001). Stronger winds may also allow fires to propagate across sparser fuels (e.g. Hargrove *et al.* 2000; Moritz 2003), thereby overcoming bottom–up barriers for fire growth such as the lack of continuity typically associated with human land use. Moreover, stronger winds may also inhibit the efficacy of initial attack suppression

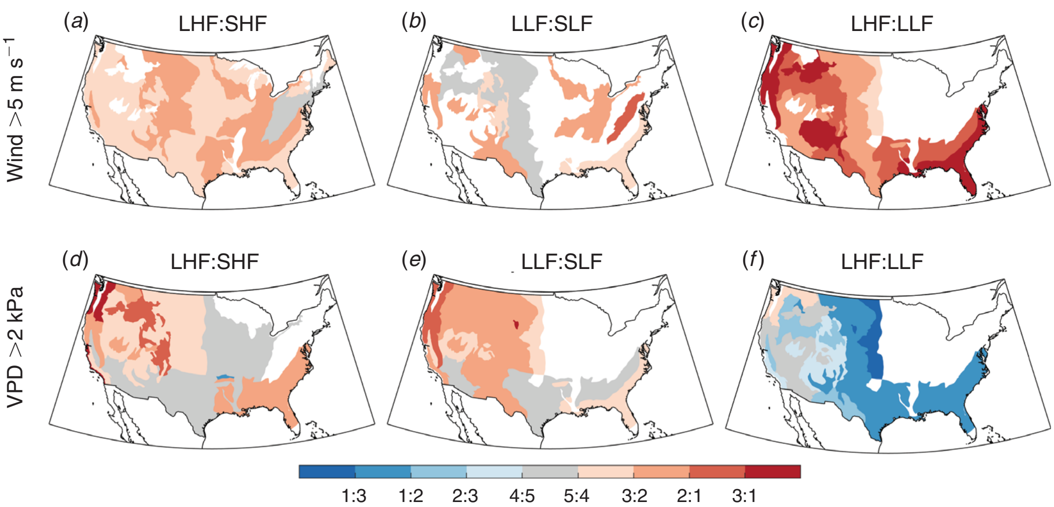

Fig. 6. Normalised fire ratios for ecoprovinces for (*a–c*) wind speeds exceeding 5 m s^{-1}; and (*d–f*) vapour pressure deficit (VPD) exceeding 2 kPa. Non-statistically significant ratios are shaded grey, and ecoregions with fewer than 10 fires of a given class being compared or where ratios were not statistically significant are omitted (white).

efforts as the active fire perimeter grows. Case studies and modelling efforts have shown the importance of winds in facilitating large fire growth (Linn and Cunningham 2005; Cruz *et al.* 2012), but have not effectively demonstrated the importance of wind speeds across a broader region. By contrast, previous studies in lightning-dominated fire regimes in boreal systems have shown that sustained strong winds are not a significant contributor to the occurrence of large fires or burned areas (e.g. Flannigan and Harrington 1988; Abatzoglou and Kolden 2011).

Rapid fire spread and extreme fire behaviour common to wind-driven fires are a major detriment to initial attack success for several key reasons. First, although there is no hard limit for aerial fire suppression operations with regards to wind, winds >10 m s^{-1} usually reduce tactical capabilities for retardant drops, and winds >15 m s^{-1} will often ground aircraft entirely, depending on the terrain complexity and type of aircraft (NWCG 2014). Second, higher wind speeds produce longer flame lengths, which determine what resource types are capable of direct attack on the flaming front vs indirect attack (away from the flaming front) (NWCG 2013). With longer flame lengths (generally longer than 3.4 m; NWCG 2006), suppression crews often use indirect attack, which by definition enlarges the fire size, as it requires suppression forces to build fire containment lines at a distance from the head of the active fire and utilise burnouts and other types of fuel removal to contain fire spread. Third, higher wind speeds are conducive to increased spotting, wherein firebrands and other flaming material are carried by the wind ahead of the primary flaming front, starting new fires that are ultimately consumed by the main fire (Koo *et al.* 2010). Finally, higher winds speed can support convective pre-heating and volatilisation of biomass ahead of the active combustion occurring along the flaming front, particularly in steeper terrain when winds are aligned with slope; these conditions have been identified in several case study fires where a 'firestorm' erupted, including fatality events (Pagni 1993).

Previous studies have demonstrated that fire weather indices that include wind speed are useful for predicting wildfire containment efficacy (e.g. Arienti *et al.* 2006). Our findings suggest winds may be particularly important for human-caused fires that often occur in areas where bottom–up factors such as suppression resources, response times and greater landscape fragmentation would otherwise tend to reduce large fire potential (Parisien *et al.* 2012). In addition to promoting fire propagation, strong winds can also facilitate human-caused ignitions as in the case of fallen powerlines (Mitchell 2013; Collins *et al.* 2016), which account for a large proportion of the overall burned area in some regions where winds have been implicated in fire activity (Syphard and Keeley 2015).

Seasonal and geographic differences in where the occurrence of strong winds aligns with the seasonal nadir in fuel moisture content likely contribute to the pyrogeography of large human-caused fires in the mid-latitudes. The poleward contraction and weakening of the jet stream during the boreal summer months accompanied by weakened sea-level pressure gradients reduces the frequency of synoptically forced strong near-surface winds and frontal systems across much of the US (Klink 1999; Berry *et al.* 2011). Cold fronts can occur during the summer months across portions of the interior western US during the fire season (e.g. Shafer and Steenburgh 2008) and constitute a critical fire weather pattern due to their potential to initiate both lightning and strong winds (both synoptically forced and downdrafts from thunderstorms). The frequency of synoptically forced strong winds increases in the shoulder seasons as lightning frequency wanes. Human ignitions have the potential to add to the large fire burden by imposing ignitions coincident with available fuels and increased winds. This concept is well established with Santa Ana wind-driven wildfires that occur predominantly during the autumn months across south-western California before the onset of the wet season (Westerling *et al.* 2004; Moritz *et al.* 2010). The frequency and strength of Santa Ana winds increase throughout the fall coincident with the development of the Great Basin thermal high and peaks during the winter (Abatzoglou *et al.* 2013). Hence, delayed arrival of cool-season precipitation across south-western California poses a particularly important risk for large human-caused fires as fuels remain receptive to carrying fire and the probability of Santa Ana wind events increase. Capstone wind events that occur near the climatological end of the fire season when fuel moistures are critically low can be particular important drivers of very large fires and associated wildfire hazards (Keeley *et al.* 2009; Koutsias *et al.* 2012).

Although we demonstrate the importance of winds as a top–down factor of large human fires, the dataset on winds that we used has several caveats that are worth noting. First, the gridded meteorological dataset of Abatzoglou (2013) interpolates winds from the North American Regional Reanalysis, which has a native resolution of 32 km. This resolution is appropriate for capturing synoptic-scale wind patterns but is inadequate for many mesoscale features including terrain-driven flows. Second, we focused on daily-mean wind speeds, which may overlook short-lived periods of intense winds, including those associated with outflow from dry thunderstorms or passage of a frontal boundary that may contribute to rapid fire spread. Third, estimates of wind speed do not account for dynamics, including winds, created by the fire itself. Improved estimates of wind speed across landscapes at high temporal resolutions that capture these factors may help further uncover the interactions between wind speed and human ignition that facilitate large human-caused fires. In addition, we did not attempt to discriminate the roles of low-frequency climate factors that enable fire activity from short-term weather drivers. For example, large fires may be more probable with weaker winds following wet years that promote fine fuel accumulation in fuel-limited fire regimes (Balch *et al.* 2013). Finally, bottom–up factors such as topography and fuel continuity, as well as priority, availability and accessibility for fire suppression resources are important factors that interact with top–down factors examined in the present study to help shape whether an ignition becomes a large fire.

As shown by Balch *et al.* (2017), human-caused fires occupy an environmental niche characterised by lower lightning-frequency and higher fuel moisture than lightning-caused fires. The present work complements those findings by demonstrating the likelihood of human ignitions evolving into large fires when facilitated by strong winds. Most models of fire risk do not explicitly incorporate winds or differentiate the co-occurrence of winds with human-ignition agents (e.g. roads, powerlines). Future efforts may be able to better integrate information on winds into fire risk models by explicitly highlighting geographic areas and times of the year when human-caused ignitions prominently contribute to the fire burden.

Conflicts of interest

The authors declare no conflicts of interest.

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