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High and Low Air Temperatures and Natural Wildfire Ignitions in the Sierra Nevada Region

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Abstract: The Sierra Nevada region has experienced substantial wildfire impacts. Uncertainty pertaining to fire risk may be reduced by better understanding how air temperature (Ta: °C) influences wildfire ignitions independently of other factors. We linked lightning-ignited wildfires to Ta patterns across the region from 1992 to 2015 and compared monthly high- and low-air-temperature patterns between ignition and non-ignition locations at local scales (4 km). Regionally, more ignitions occurred in springs with a greater number of high-Ta months and fewer cool Ta months (analyzed separately) and in summers with fewer cool Ta months. Locally, summer ignition locations experienced warmer summer months on a normalized scale than non-ignition locations. The probability of a wildfire ignition was positively associated with a greater number of high-Ta months during and prior to fire seasons. Regionally, springs with a greater number of high-Ta months had more wildfire ignitions. Locally, as individual locations in the region experienced a greater number of high-Ta months preceding and including the fire season, they exhibited substantial increases in spring (+1446%), summer (+365%), and fall (+248%) ignitions. Thus, the frequent occurrence of high-Ta months is positively associated with lightning-ignited wildfires in the Sierra Nevada region.

Keywords: fire risk; forest; climate; California; Nevada

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1. Introduction

Measures of wildfire activity, including the number of large wildfires, burned area extent, and wildfire severity, have been increasing in many locations across the western United States since the 1980s [1–4]. These increases have largely been attributed to the interactive effects of climate warming and the legacy of human wildfire and forest management [1,3]. The average annual burned area in the western US increased at a rate of 355 km^2 per year from 1984 to 2011 [5], and wildfires have caused considerable damage to ecosystems, human health, and human communities in the wildland–urban interface [6,7]. As conditions supporting wildfire—and especially very large wildfires—increase across the western US as a result of climate change, wildfire affected areas are expected to also increase considerably within this region [8–11]. The Sierra Nevada region of California and Nevada is one of the largest wildfire-affected areas of the western US and has experienced a greater than six-fold increase in average annual burned area since 1972 [2,12]. Yet, while wildfire increases are anticipated, fire risk assessments remain difficult to quantify across the diverse causative agents—human actions, climates, landscape and topographic conditions, and over- and understory characteristics of ecosystems—that comprise the Sierra Nevada region [13–16].

Many wildfire ignitions in the western US—including the Sierra Nevada region—are initiated by lightning strikes (e.g., natural wildfire ignitions; Short [17]). The fire risk associated with lightning-ignited wildfires is influenced by multiple factors. Short-term weather patterns influence the frequency and timing of lightning strikes, and lightning strikes vary geographically and topographically [18–21]. At seasonal to interannual timescales, precipitation and temperature influence the ignition probability component of fire risk through their interactive effects on understory vegetation and fuel moisture [19,22], and wildfire has been found to coincide with dry periods and lightning strikes [23]. In the Sierra Nevada region, vegetation composition and structure vary at fine spatial scales, and over interannual to decadal time periods [24,25]. Thus, the components of natural fire risk—lightning occurrence and ignition probability—may often exhibit considerable spatial and temporal variation, and their interaction may in some instances enhance risk and in other instances lessen it [19]. Considerable research suggests that climate change will increase lightning occurrence and ignition probability [8,26,27], although Finney et al. [28] suggest that global lightning density may actually decline in coming decades. Increasing temperatures and earlier spring snowmelt are already lengthening and intensifying ecosystem drying and wildfire activity periods [29,30], and the associated occurrence of extreme climate events, including drought and heat waves, have been linked to regional patterns of wildfire extent and severity [31,32]. These studies point to a future where enhanced lightning occurrence and ignition probability could lead to enhanced fire risk across both space and time.

Wildfire characteristics—ignition, extent, and severity, for example—are enhanced by hot and dry conditions [20] but through different pathways. Once hot and dry conditions have been realized, wildfire ignition is strongly influenced by weather patterns and the favorability of ignition agents [19,27], wildfire severity is strongly influenced by topography, vegetation composition, and vegetation structural characteristics [33,34], and wildfire extent is strongly influenced by wind speed, topography, and the occurrence of precipitation [22,33,35]. Complex and interactive processes such as these may be simplified—if not fully resolved—by compartmentalizing their components independently. To this end, we propose that air temperature (Ta: °C) may have utility for quantifying fire risk. Ta is positively associated with lightning strikes, heat waves, and meteorological drought, such that warmer temperatures may capture variation in both lightning occurrence and ignition probability [20,26]. Recent research suggests that properties of extreme events may capture conditions exceeding normal environmental variation and help to identify changes in fire risk [32]. We therefore postulate that Ta may indirectly capture ignition probability through its strong negative association with fuel moisture (indicating enhanced ignition probability; Abatzoglou and Kolden [36], Flannigan et al. [37]) and through its positive association with dry atmospheric events and meteorological conditions supporting lightning strikes [20,26]. That is, Ta variation—and especially the occurrence of high-Ta periods—is associated with the meteorological and environmental conditions supporting natural wildfire ignition and may be a useful way to compartmentalize and simplify one component of fire risk.

Although considerable research has linked Ta to lightning strikes and wildfire ignitions, it is not clear if analyses of Ta can be used to quantify change to fire risk and at what spatial and temporal scales these changes may be anticipated. If Ta patterns are related to the probability of wildfire ignition, this determination can help to identify how ignition probabilities will change in a warming regional climate and indicate locations where management interventions should be prioritized. In this study, we explored relationships between Ta change, the properties of high (warm) and low (cool) Ta months, and the occurrence of lightning-ignited wildfires in the Sierra Nevada region from 1992 to 2015. During a similar timeframe (1992–2012), this region experienced the most lightning-ignited wildfires in the contiguous US [38]. The objectives of this research were to: (1) determine if regional temperature patterns from 1992 to 2015 in the Sierra Nevada region were related to the number of regional wildfire ignitions in spring, summer, and fall fire seasons; (2) contrast the frequency of occurrence and magnitude of high- and low-Ta months in spring, summer, and fall fire seasons between locations that experienced a wildfire ignition and locations that did not (fire ignition vs. non-ignition locations); and (3) explore to what degree the frequency of high- and low-Ta months prior to spring, summer, and fall fire seasons are related to ignition probability. Our analyses explore Ta–ignition relationships averaged across the region and for individual locations through time. Our analyses also evaluate the magnitude and occurrence of high- and low-Ta months within individual wildfire seasons and also evaluate high- and low-Ta months in preceding seasons, which may indicate sustained conditions (or lack thereof) that amplify wildfire ignition probability. Because wildfires have been strongly tied to hot and dry conditions in this region [14,32], we hypothesized that regional analyses focusing on high Ta would show a greater association with wildfire ignition compared to analyses of low Ta. Similarly, we hypothesized that the magnitude of high-Ta months would have a greater association with wildfire ignitions (due to their general indication of drier conditions and favorable weather for lightning strikes) compared to the frequency of high-Ta months.

2. Site Description

The Sierra Nevada region encompasses an area of 64,544 km^2 ([39]; Figure 1a). This ecologically diverse region is comprised of forest, woodland, and shrubland vegetation, with a plant species composition that is influenced by the surrounding ecoregions: the Cascade–Sierra Mountains to the north, the Great Basin to the east, the Mojave Desert to the south, and the Central Valley to the west [24]. The Sierra Nevada has a Mediterranean climate, with the majority of annual precipitation (∼500–2030 mm total) falling between fall and spring, and with dry summers [24]. Average daily temperatures vary across seasons, topography, and elevation (∼100–3900 m; United States Forest Service [24], PRISM Climate Group [40]). Vegetation composition also varies across topography and elevation, often at relatively fine spatial scales [14,41]. Frequent, small fires that maintained ecosystem health and structure in this region were reduced due to human fire suppression in the 20th century, which resulted in increasing fuels and vegetation density and contributed to the occurrence of large wildfires over the past 40 years [42]. Vegetation mortality and die-offs are also increasing across the region due to the interplay of and altered fire regime, drought, and pathogen outbreaks, which portend to an uncertain future for the region's ecosystems and the services they provide [21,32].

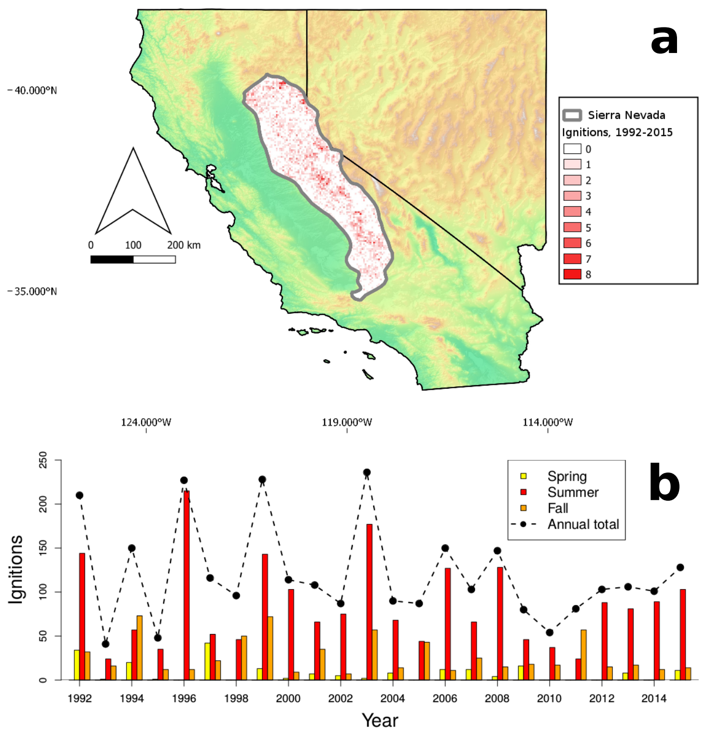

Figure 1. Study area map of the Sierra Nevada region, including the number of fire ignitions in each 4 km grid cell from 1992 to 2015 (Panel **a**), and a barplot illustrating the timeseries of wildfire ignitions in spring, summer, and fall from 1992 to 2015 (Panel **b**). The black line in Panel (**b**) illustrates total wildfire ignitions in each year.

3. Methods

3.1. Weather Estimates and Spatial Wildfire Data

We obtained daily maximum (Ta_{max}) and minimum (Ta_{min}) air temperature estimates at 4 km resolution from 1990 to 2016 from the Parameter-elevation Regressions on Independent Slopes Model (PRISM; PRISM Climate Group [40]), which has been used in other, recent wildfire-focused research [43,44]. We clipped PRISM raster files to the Sierra Nevada region (4034 total 4 km resolution cells). Weather estimates, including PRISM, may experience autocorrelation due to both naturally occurring patterns as well as interpolation procedures, and we found a moderate degree of autocorrelation of Ta_{max} and Ta_{min} for our study area (Figure S1). Fortin and Dale [45] recommend the use of small blocks when autocorrelation is present, and we minimized potential autocorrelation effects by analyzing Ta in each grid cell independently of surrounding cells. We conducted spatial data harmonization using QGIS [46], and we compiled and analyzed all data using R [47].

We obtained point-based wildfire ignition data for the Sierra Nevada region from 1992 to 2015 from the Fire Program Analysis Fire-Occurrence Database [17]. Our analyses included only lightning-ignited wildfires and included fire size classes from >0.10 to ≥2023.43 ha (Class B to Class G), the characteristics of which are provided in the attribute data of the Fire Program Analysis Fire-Occurrence Database [17,48]. We did not include fires ≤ 0.10 ha (Class A; 7897 of 10,788 total fires; 73%), which may occur following lightning strikes even when ignition agents are unfavorable for wildfire spread. These small fires may include ignitions with greater wildfire potential that were quickly contained and suppressed, and there is therefore some uncertainty in whether the fires removed from our analysis were of lower or higher risk.

We assigned point-based wildfire occurrence data to the centroid of the nearest 4 km cell. In our analyses, we compared ignition and non-ignition cells, evaluated seasonally at discrete time steps. For example, a single 4 km cell was designated to be an ignition location in any season when it experienced a wildfire ignition (summer 2010, for example) and was designated a non-ignition location in seasons when it did not. We evaluated 3 fire seasons (spring: March–May; summer: June–August; fall: September–November). Only 10 ignitions during winter met the Class B to Class G criteria of this study, and we therefore did not analyze winter ignitions.

3.2. High- and Low-Temperature Months

We used a peak-over-threshold approach from Coelho et al. [49] to calculate the occurrence and properties of high- and low-Ta months. This is a nonstationary approach that is used to identify anomalous and extreme values at the monthly time step from the distribution of daily values, across a moving time window. This technique is especially useful for identifying unique features in climatic data that have a positive or negative trend in their mean or variance through time (due to climate change, for example). Using this technique, analysis can focus on the properties of daily values occurring above a time-varying threshold, or on variation in the threshold values (see Petrie et al. [50] for an example using temperature simulations and a focus on statistically extreme events). For each 4 km cell in each month, our analyses focused on determining the temperature threshold value designating a high- or low-Ta month. On average, 20–30% of all months in our analyses were high- or low-Ta months. Our reported high- and low-Ta months are therefore best understood as the occurrence and magnitude of the top 20–30% of warm or cool months, instead of extreme events in the top 5% of all values.

To determine the occurrence and threshold magnitude of high-Ta months, we first calculated a 3-year floating mean of daily Ta_{max} values in each month. For example, the 3-year floating mean for a single cell in August 1995 was the mean of 93 daily Ta_{max} values from August, 1994, 1995, and 1996. In this analysis, we found that window length had minimal influence on monthly floating mean values and chose a 3-year window length to maximize the number of observations. After calculating the 3-year floating mean, we then determined the daily Ta_{max} values in the analysis month (August, 1995, in this example) that were greater than the 3-year floating mean value and ranked these daily values from the highest daily value to the lowest. A month with ≥20 daily Ta_{max} values in this category therefore experienced at least 1 day with a Ta_{max} value that exceeded the top 5% of days and was therefore a statistical extreme event for daily values. The observed daily Ta_{max} value ranked sequentially below the top 5% of values (e.g., 1–2 values below the highest daily value) was the threshold value, which designated the boundary air temperature between extreme and non-extreme daily values. Although this threshold value indicates a month with an extreme Ta day, we clarify that this is best viewed as a month located in the top 27% of observed daily temperature values. We calculated high- and low-Ta months separately. To determine the occurrence of low-Ta months, we used the same procedure but evaluated daily values of Ta_{min} below the 3-year floating mean.

Because the distribution of average Ta differed among the cells in our study region, we normalized the magnitude of high- and low-Ta months as an anomaly ((observed–long-term mean)/standard deviation of long-term mean). To allow for analysis of these anomaly values across cells with significant and insignificant trends in Ta magnitude, we detrended the magnitude of high and low Ta for cells that experienced a statistically significant linear trend in the threshold value over the 1991–2015 study period (at least 7 high- or low-Ta months observed; $p < 0.05$).

3.3. Analysis

Our regional analyses explored relationships between temperatures and wildfire ignitions from 1991 to 2015 and relationships between the frequency of occurrence and the magnitude of high- and low-Ta months and the occurrence of wildfire ignitions. Our analyses of individual locations (e.g., 4 km cells) focused on contrasting the frequency of occurrence and the magnitude of high- and low-Ta months between ignition locations and non-ignition locations in spring, summer, and fall fire seasons. We determined significant relationships between the number of high- and low-Ta months and wildfire ignitions using linear correlations (R^2 coefficient of determination; $p < 0.05$), and we determined significant differences in the average magnitude of high- and low-Ta months between ignition and non-ignition locations using ANOVA and Tukey's honest significant differences ($p < 0.05$).

We determined to what degree the occurrence and magnitude of high- and low-Ta months in seasons preceding the fire season were related to differences between ignition and non-ignition locations. To determine if ignition locations experienced a differing magnitude of high- or low-Ta months compared to non-ignition locations, we contrasted the magnitude of high- and low-Ta months between ignition and non-ignition locations in the seasons preceding each fire season, as well as in spring, summer, and fall fire seasons. To determine if ignition locations experienced a greater frequency of high- and low-Ta months compared to non-ignition locations, we counted the total number of high- or low-Ta months (separate analyses for high versus low) in seasons preceding each fire season. Our counts included the 3 seasons prior to each fire season (0 months minimum, 9 months maximum) as well as the 3 prior seasons up to and including spring, summer, and fall fire seasons (0 months minimum, 12 months maximum). We interpreted a positive relationship between the proportion of locations experiencing a wildfire ignition and a higher number of Ta months (either high or low) as evidence that Ta and wildfire ignitions were positively associated. To evaluate these relationships, we grouped all locations experiencing the same number of high- or low-Ta months into discrete categories (0 months, 1 month, 2 months, etc.) and calculated the ignition proportion of each category independently from the number of locations experiencing a wildfire ignition divided by the number not experiencing an ignition. We required at least 8 locations in each category, and we combined observations when necessary (for example, combining 9 and 10 month locations to reach the required number of 8 observations, resulting in a 9–10 category).

4. Results

4.1. Regional Change from 1992 to 2015

The number of wildfire ignitions was lower in the later third of our 1992–2015 study period (2008–2015) compared to the first two-thirds (1992–2007), and summer and fall accounted for 87.8% of the total ignitions (Figure 1b, Table 1b). The magnitude of the high-Ta months was generally lower in the first 8 years of our 24-year study period (1992–1999) compared to the last 16 years, but significant differences between study period intervals were inconsistent and were strongly influenced by a large number of observations (Table 1a, Figure 2). The magnitude of high-Ta months was generally greater in the last 8 years of our study period (2008–2015) compared to the first 16 years (ANOVA and Tukey's honest significant differences, $p < 0.05$; Table 1b). We observed a slight decline in the frequency of high-Ta months in spring and summer in the later third of our 1992–2015 study period (2008–2015) compared to the first two-thirds (1992–2007; Table 1a).

Table 1. Seasonal air temperature (Ta: °C) differences between 8-year time periods from 1992 to 2015 in the Sierra Nevada region. Ta differences were analyzed for high-Ta months (Section **a**) and locations with high-Ta months that experienced a concurrent wildfire ignition (Section **b**). The number of observations in each category is indicated in the table, and significance is indicated by differing letters (determined at $p < 0.05$).

(a) High-Ta months.								
Time Period	Spring		Summer		Fall		Winter	
	# obs.	(°C)	# obs.	(°C)	# obs.	(°C)	# obs.	(°C)
1992:1999	29,541	22.8 ^{c}	33,485	31.6 ^{b}	27,878	24.9 ^{c}	20,147	17.1 ^{b}
2000:2007	32,926	24.1 ^{a}	29,990	31.1 ^{c}	29,625	25.6 ^{b}	19,751	17.2 ^{a}
2008:2015	18,027	23.7 ^{b}	19,826	32.5 ^{a}	27,667	28.1 ^{a}	20,828	16.7 ^{c}
(b) High-Ta months, fire ignition locations.								
Time period	Spring		Summer		Fall		Winter	
	# obs.	(°C)	# obs.	(°C)	# obs.	(°C)	# obs.	(°C)
1992:1999	83	25.6 ^{b}	318	31.9 ^{ab}	89	28.5 ^{ab}	5	21.4
2000:2007	23	27.6 ^{a}	213	31.2 ^{b}	84	27.4 ^{b}	5	18.4
2008:2015	15	29.3 ^{a}	175	32.1 ^{a}	58	29.9 ^{a}	0	-

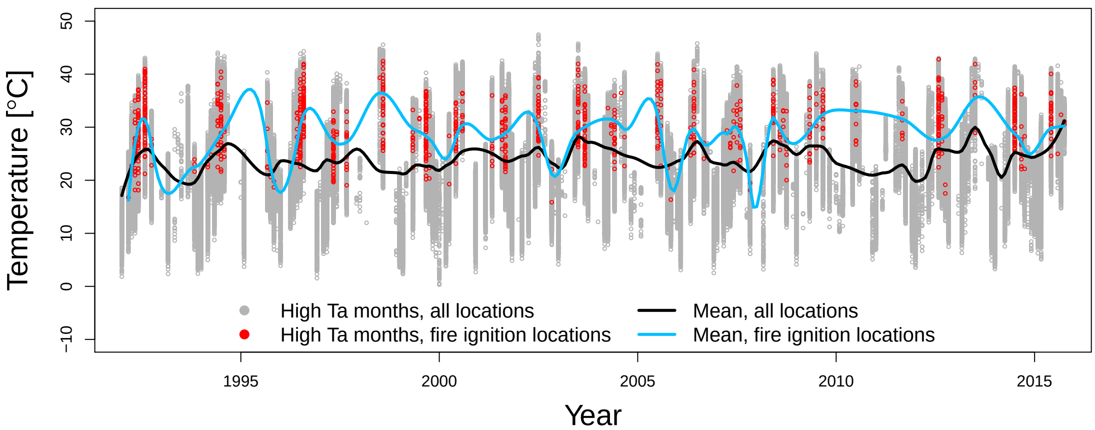

Figure 2. Timeseries of the magnitude of high-air-temperature months (Ta: °C) across the Sierra Nevada region from 1992 to 2015, and the magnitude of high-Ta months for fire ignition locations in the month when ignition occurred. Lines were loess smoothed for illustration.

4.2. The Magnitude of High and Low Temperatures and Wildfire Ignitions

Across the Sierra Nevada region, there was no relationship between the normalized magnitude of high- or low-Ta months and the percentage of locations that experienced a wildfire ignition in the spring, summer, or fall fire seasons (Figures 3a and S2a). At local scales, the ignition locations in summer experienced (on a normalized scale) warmer high-Ta summer months (Figure 4b), and the ignition locations in fall experienced less cool low-Ta fall months (Figure S3c). The differences in the magnitude of high and low Ta in months preceding the fire seasons were inconclusive (Figures 3 and S2).

4.3. The Frequency of High- and Low-Temperature Months and Wildfire Ignitions

Regionally, a greater number of ignitions occurred in springs that experienced a greater proportion of locations experiencing one or more high-Ta months (0.003% ignition percentage at a proportion of 0.0% of locations; 0.4% ignition percentage at 100% of locations; Figure 3b), a lower proportion of the locations experiencing one or more low-Ta months (0.0% ignition percentage at a proportion of 100% of locations; 0.4% ignition percentage at 0.0% of locations; Figure S2b), and in summers with a lower proportion of locations experiencing one or more low-Ta months (1.3% ignition percentage at a proportion of 100% of locations; 3.0% ignition percentage at 0.0% of locations; Figure S2b). At local scales, the ignition locations in spring, summer, and fall experienced a greater number of high-Ta months, both in the fire season and in the previous seasons (Figure 5). In spring and summer, the ignition locations generally experienced fewer low-Ta months (Figure S4).

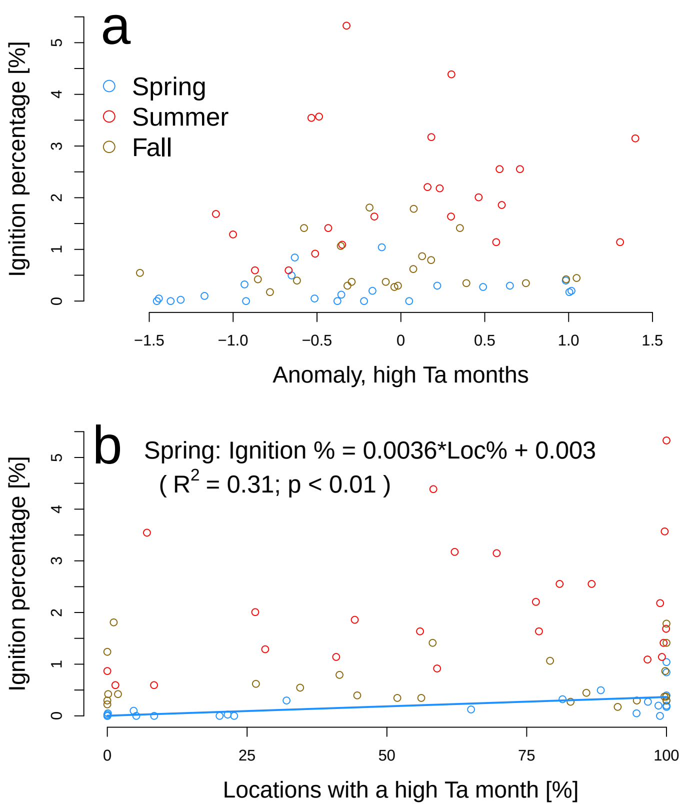

Figure 3. Relationships between the average anomaly of high-air-temperature months (anomaly = observed − long-term mean/standard deviation of long-term mean) and the percentage of locations in the Sierra Nevada region experiencing a wildfire ignition in spring, summer, and fall seasons (Panel **a**), and relationships between the percentage of locations in the Sierra Nevada region experiencing a high-air-temperature month and the percentage of locations in the Sierra Nevada region experiencing a wildfire ignition in spring, summer, and fall seasons (Panel **b**). Significant relationships are shown in each panel (R^2 coefficient of determination; $p < 0.05$).

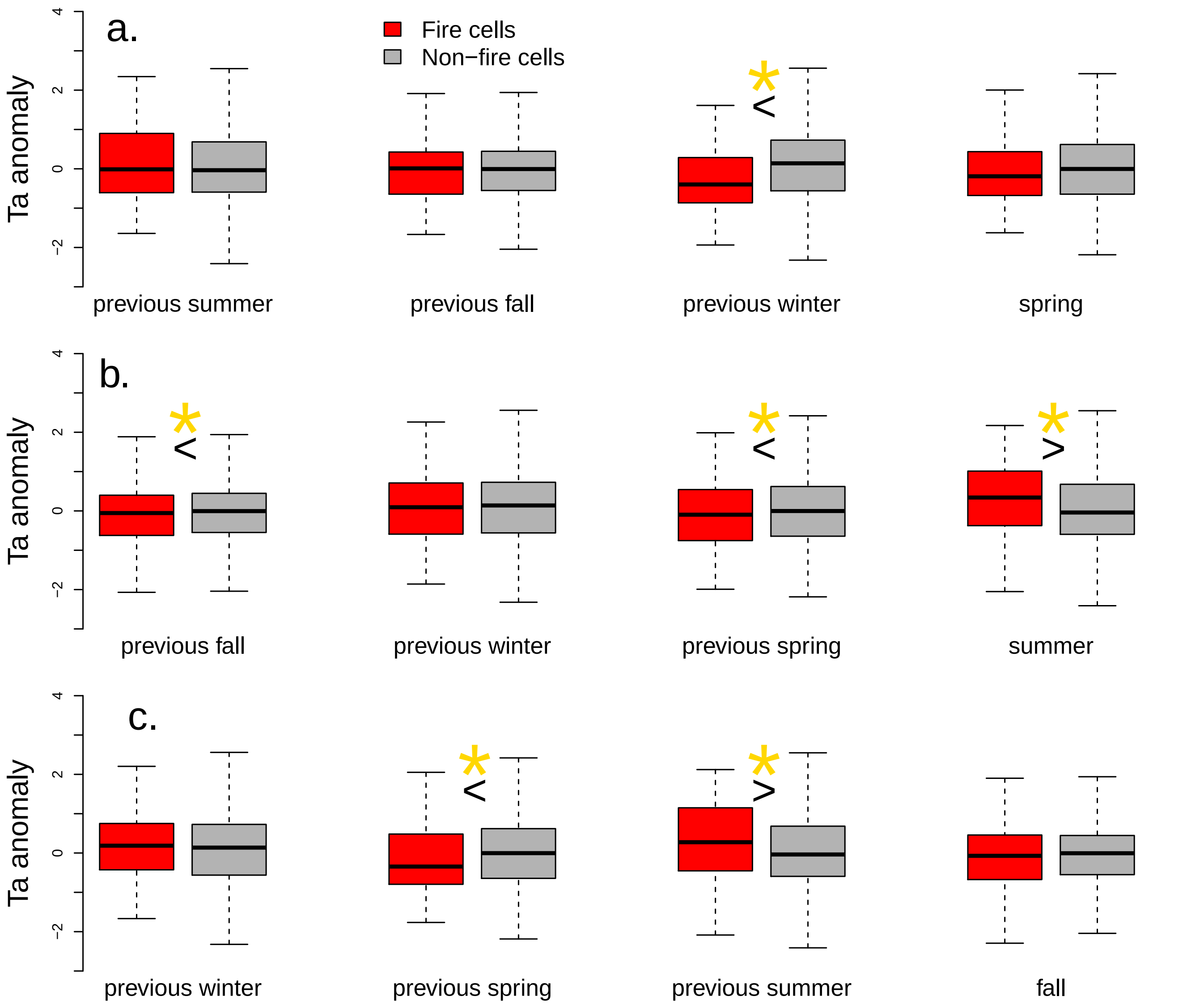

Figure 4. Boxplots illustrating differences in the anomaly of high-air-temperature months (anomaly = observed − long-term mean/standard deviation of long-term mean) between ignition (red) and non-ignition (gray) locations in the 3 seasons previous to and including the spring (Panel **a**), summer (Panel **b**), and fall (Panel **c**) fire seasons. Significant differences and the direction of difference are indicated for each boxplot pair (one-tailed *t*-tests; $p < 0.05$).

The number of high-Ta months occurring prior to and during fire seasons was positively correlated to the percentage of locations experiencing a wildfire ignition (Figure 6). In spring, wildfire ignitions occurred in ∼0.08% of the locations that did not experience a high-Ta month, and increased to ∼0.5% for the locations experiencing 5–6 of these months in the prior three seasons (of nine possible; Figure 6c), and to ∼0.9% of the locations experiencing 7–8 of these months in the prior 3 seasons plus the spring fire season (of 12 possible; Figure 6b). In summer, wildfire ignitions occurred in ∼1.2% of the locations that did not experience a high-Ta month, and increased to ∼4.2% for locations experiencing 7–8 of these months in the prior three seasons (of nine possible; Figure 6c), and to ∼4.4% for locations experiencing 9–10 of these months in the prior 3 seasons plus the summer fire season (of 12 possible; Figure 6d). In fall, wildfire ignitions occurred in ∼0.7% of the locations that did not experience a high-Ta month, and increased to ∼1.5% for the locations experiencing seven of these months in the prior three seasons (of nine possible), and to

~1.7% for locations experiencing 8 of these months in the prior 3 seasons plus the fall fire season (of 12 possible; Figure 6e,f). We were not able to assess ignition increases for the three preceding seasons in spring due to too few observations (Figure 6a). We did not observe significant relationships between the number of low-Ta months and the percentage of locations experiencing a wildfire ignition (not shown).

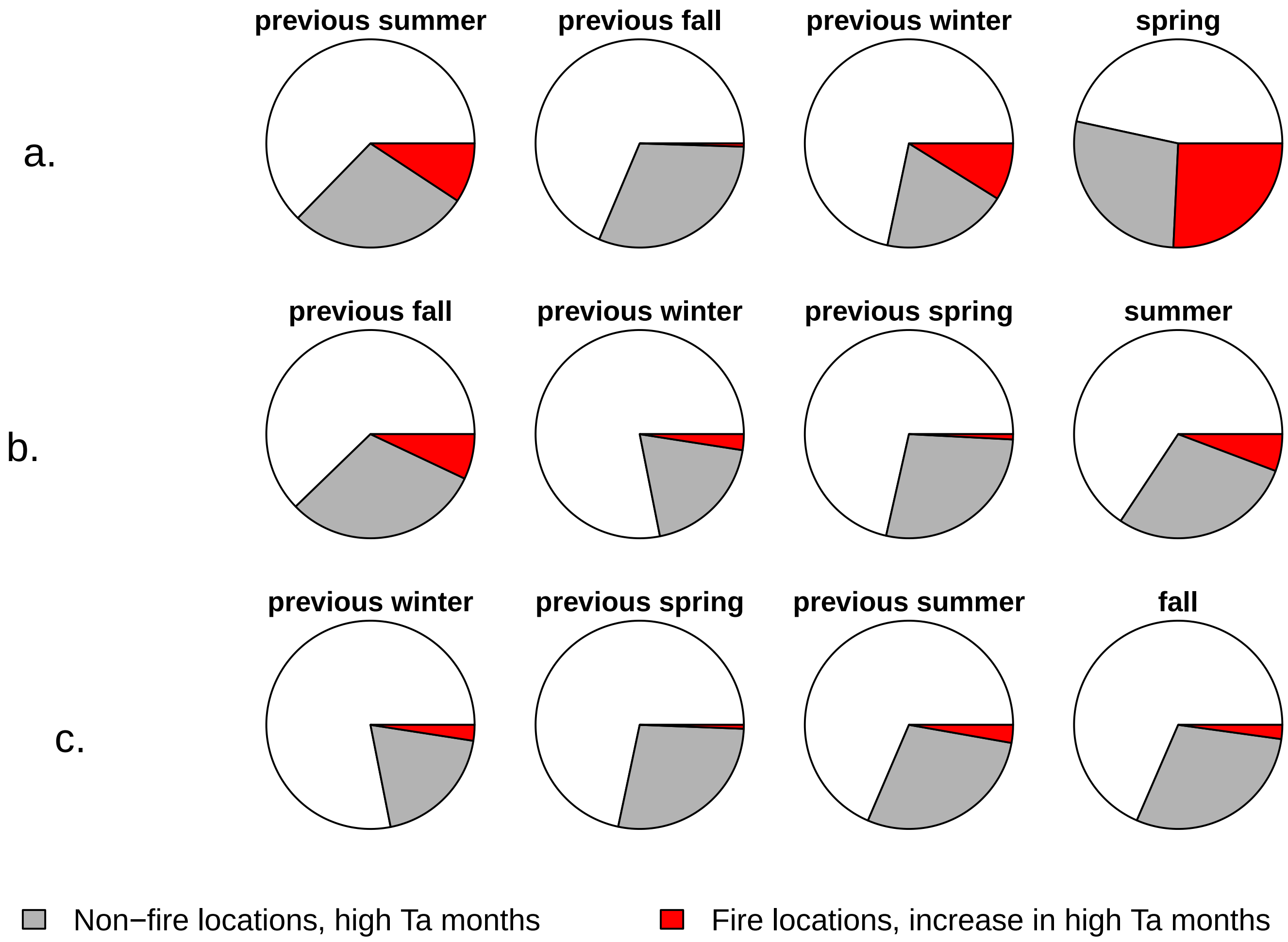

Figure 5. Pie charts illustrating differences in the proportion of ignition and non-ignition locations experiencing a high-air-temperature month in the 3 seasons previous to and including the spring (Panel **a**), summer (Panel **b**), and fall (Panel **c**) fire seasons. The average proportion of non-ignition locations experiencing a high-Ta month in each season is illustrated in gray, and the proportional increase in ignition locations experiencing a high-Ta month in each season is shown in red.

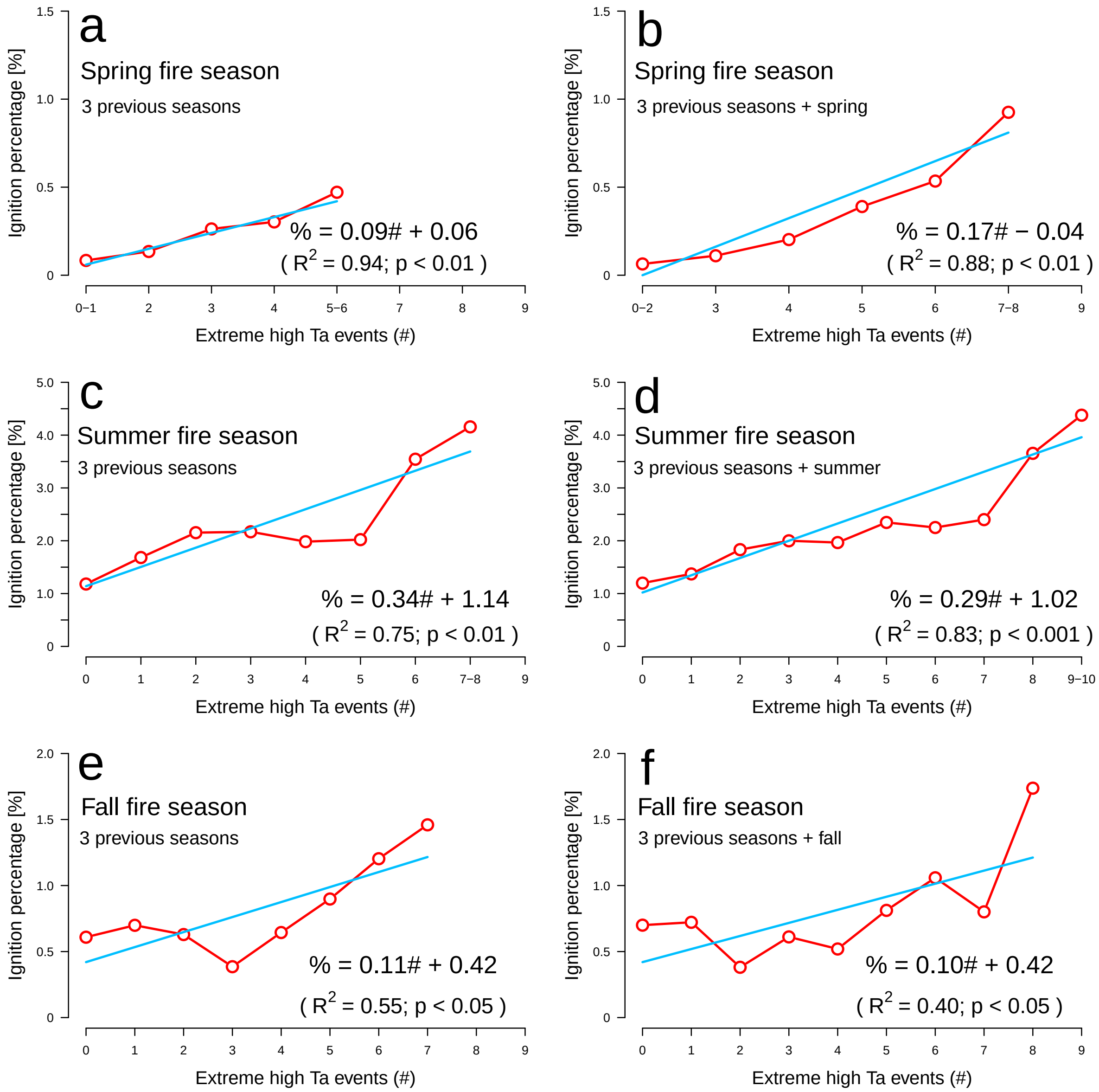

Figure 6. Fire ignition probability for locations experiencing differing numbers of high-air-temperature months during and prior to the fire season, summarized across 1992–2015. Panels (**a**,**c**,**e**) illustrate fire ignition probability in the spring (Panel **a**), summer (Panel **c**), and fall (Panel **e**) fire season in response to high-Ta month occurrence during the 3 prior seasons (3 seasons, 9 months maximum). Panels (**b**,**d**,**f**) illustrate fire ignition probability in the spring (Panel **b**), summer (Panel **d**), and fall (Panel **f**) fire season in response to high-Ta month occurrence during the 3 prior seasons and also the fire season (4 seasons, 12 months maximum). In cases where too few events were observed in a single category, these events were merged with the next lowest category. Because multiple observations were combined in some categories, linear correlations were developed for category number instead of observation number (Panel (**a**) example: 0 observations = category 0; 5–6 observations = category 4).

5. Discussion

The slightly increasing magnitude of Ta across the Sierra Nevada region did not correspond to increased wildfire ignitions, which have been declining across the western US in recent decades [51]. In refutation of our first hypothesis, we did not find associations between the magnitude of high- and/or low-Ta months with wildfire ignitions at the regional scale. That is, the Sierra Nevada region as a whole did not experience variation in wildfire ignitions that can be tied to regionally warmer or cooler months. At the 4 km local scale, however, ignition locations in summer had relatively warmer high-Ta months compared to non-ignition locations, and ignition locations in fall had less cool low-Ta months. This corroborates other work linking high air temperatures to the dry environmental and high-pressure systems that support lightning strikes and wildfire ignition [20,52].

In refutation of our second hypothesis, we found that the frequency of high- and low-Ta months was closely associated with wildfire ignitions. Regionally, more ignitions occurred in springs with a greater number of high and fewer cool Ta months, and in summers with fewer cool Ta months. Locally, ignition locations consistently experienced a greater number of high-Ta months in fire seasons and in the three preceding seasons. As the number of high-Ta months increased from 0 to a maximum of ∼7–10, we found a 1446% increase in spring ignitions, a 365% increase in summer ignitions, and a 248% increase in fall ignitions. This considerable increase in wildfire ignition probability suggests that fire risk in the Sierra Nevada region is enhanced by the more frequent occurrence of warm temperatures over multiple months. In summer and fall, an observation of high-Ta months prior to the fire season suggested ignition percentages that were similar to percentages observed in analyses that included observations during the fire season (summer: 4.2% prior, 4.4% prior + fire season; fall: 1.5%, 1.7%). This suggests that the variation in the probability of fire ignitions in summer and fall may in many cases be strongly influenced by the legacy effects of prior seasons.

Spring ignitions were notably emergent under a greater frequency of warm conditions and were enhanced by additional high-Ta months in spring (0.5% prior, 0.9% prior + fire season). Spring ignition locations experienced a greater number of high-Ta months and fewer low-Ta months in the spring and preceding winter, which corroborates previous research linking winter weather to spring temperatures, moisture patterns, and fire activity [29,30]. A higher Ta also decreases snowpack, resulting in more lightning strikes reaching surface fuels [53]. Although our analyses of spring ignitions were limited by relatively low ignition occurrence, our results suggest that consistent movement toward warmer and less cool winter conditions—and not change to episodic periods of the very coldest or warmest winter temperatures—may support the emergence of spring wildfire ignitions in this region.

5.1. How Broadly Is Air Temperature Associated with Wildfire?

Ta patterns have been previously linked to wildfire ignition [54,55], and our results show that observation of the frequency of high-Ta months has utility for the assessment of fire risk. It remains unclear, however, if Ta variation can help to understand wildfire extent and severity, which are underrepresented components of wildfire that differ from more commonly focused on components, such as fire risk and fire hazard [19]. Ta variation may capture conditions shaping wildfire severity and extent due to the influence of weather on wildfire activity [56] and climate on vegetation characteristics [27,57]. Understory fuel moisture influences both wildfire ignition and wildfire spread, and periods of low humidity associated with higher temperatures can increase dry fuel loads [37]. Thus, wildfire extent and severity may in some cases be associated with Ta, but these components are influenced more directly by over- and understory vegetation characteristics, such as tree stand health and density [34,36]. Additionally, Ta variation may have indirect effects on wildfire through other physical processes, including the potential for relatively cool and wet periods to increase wildfire severity by supporting the growth of understory vegetation [41]. Thus, although our results point to one pathway by which high temperatures may be associated with an increase in wildfire ignitions, there are many factors and mechanisms shaping ignitions and other wildfire components, especially over multiyear and decadal timescales.

We note a few caveats associated with the datasets we used in our study that should be considered when evaluating our reported Ta–ignition relationships. First, the accuracy of wildfire ignition coordinates may differ from the actual ignition location [58]. Second, spatial datasets such as PRISM provide an estimate of Ta patterns and do not fully resolve Ta in heterogeneous mountain landscapes [59]. Third, our analyses did not account for multiple ignitions in the same month or season in a single location, for the effect of previous fires on future ignitions [60], and our study area includes locations with limited causative agents (such as low vegetation cover) that may limit ignition.

5.2. Managing for Wildfire

Climate change is increasing the occurrence and extent of large wildfires, and over 4 million hectares of burned area in the western US has been linked to Ta-associated increases in vapor-pressure deficit in recent decades [43]. The frequency and magnitude of high-Ta months will likely increase throughout the western US in coming decades [50]. When vapor-pressure deficit is high, sustained high Ta enables the drying of fuels and may be associated with weeks to months of severe fire weather, and these conditions may often be clustered spatially [23,37]. In our analyses, we used a nonstationary method to calculate high- and low-Ta months, which minimizes the effect of changing mean temperatures through time [49], and we detrended their magnitude when appropriate. It follows that the methodology we employed could provide consistent indication of wildfire ignition probability in a warmer future climate, but we caution that climate change may alter some or many of the physical processes that influence wildfire in ways that do not have a contemporary analog. It is not yet fully clear if the associations between Ta and wildfire ignition that we observed over a 24-year period in the Sierra Nevada region will be consistent in a changing climate and to what degree they may be extended to other semiarid regions that differ in regional climate, topography, and ecosystem characteristics.

The use of Ta in wildfire research is bolstered by the variable's accessibility and predictability, and relationships between Ta and wildfire ignitions can provide practical utility for fire season planning. Specifically, consistent observations of high monthly temperatures preceding spring, summer, and fall fire seasons indicate elevated wildfire ignition probability for locations in the Sierra Nevada region. Future work could improve these results by determining to what degree spatial clustering of high Ta may indicate higher ignition probabilities (see Podschwit and Cullen [23] for a similar focus over very broad spatial areas), although the determination of natural versus artificial spatial autocorrelation across topographically complex areas may complicate this determination. We recommend that the findings of the present study can help land managers efficiently deploy actions that minimize the potential for wildfire ignitions and spread, including vegetation thinning and using natural fires to reduce fuels [61,62]. Specifically, locations that are regularly experiencing high-Ta months and also have high vegetation density and/or high understory fuels should be prioritized for thinning and fuel reduction treatments, especially when these locations are experiencing abnormal high summer temperatures. Locations experiencing an increase in high-Ta months and/or a decline in low-Ta months in spring may be more likely to experience an emergence of spring wildfire ignitions. That is, better anticipation of ignitions can be achieved through analyses of Ta and can be a useful tool to direct resources that help to protect regional ecosystems.

6. Conclusions

In this work, we sought to improve the understanding and anticipation of fire risk in the Sierra Nevada region, USA, by linking wildfire ignitions at regional and local scales to high and low air temperatures (Ta: °C) and the properties of high and low Ta evaluated at the monthly time step. Regionally, more ignitions occurred in springs with a greater number of high-Ta months and fewer low-Ta months, and in summers with fewer low-Ta months. We found that wildfire ignitions were most strongly associated with the frequency of high-Ta months, and wildfire ignition probability increased substantially when a greater number of these months occurred both prior to and during the fire season. Summer ignitions experienced the highest percentage increases (up to 4.4% of the locations) and were enhanced by both the frequency and the magnitude of high-Ta months in summer. Spring ignitions became emergent when they experienced an increase in the occurrence of high-Ta months or a decline in low-Ta months. Thus, the more frequent occurrence of high-

Ta months is positively associated with lightning-ignited wildfires in the Sierra Nevada region. Although there remains some uncertainty pertaining to the physical mechanisms and pathways that underlie these findings, Ta increases have the potential to enhance fire risk by increasing ignition probability and possibly by increasing lightning occurrence. The identification of change to the properties of Ta can help to identify locations and time periods experiencing enhanced fire risk and prioritize management interventions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/environments9080096/s1, Figure S1: Spatial autocorrelation results; Figure S2: Regional relationships between ignitions and low Ta months; Figure S3: Low Ta month anomaly between ignition and non-ignition locations; Figure S4: Differences in the proportion of ignition and non-ignition locations experiencing a low Ta month.

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