Distribution of Lightning Across the Western United States and its Relationship to Wildfire

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Abstract:
Lightning is a common source of wildfire ignition and an improved understanding of the spatial and temporal dynamics of lightning will lead to the development of more accurate wildfire hazard models. This study explored the spatio-temporal distribution of lightning strikes between 1987 and 2021 across the western United States using the NOAA National Lightning Detection Network (NLDN). The correlation between lightning frequency and wildfire occurrence was accomplished using data provided in the Historic Fires Database (HFD). The resulting database contained over 97 million records of lightning strikes and over 36,000 documented wildfires. Analysis was completed in ArcGIS Pro using Getis-Ord Gi* hot spot analysis and geographically weighted regression (GWR). The results of these analyses indicate both lightning and wildfires are not uniformly distributed over time and space. Instead, lightning shows a strong southeast (hot spot) to northwest (cold spot) spatial trend across the study area. Furthermore, while wildfire occurrence is not well correlated with lightning frequency ($R^2 = 0.009$), wildfire events do exhibit some spatial clustering. In addition, El Niño events appear to depress wildfire occurrence relative to La Niña and neutral Oceanic Niño Index (ONI) years ($P < 0.05$). An interesting bidecadal temporal pattern of wildfire frequency may exist but additional research is necessary to more fully assess this trend.

Keywords: *Lightning, wildfire, NLDN, National Lightning Detection Network, Historic Fires Database, HFD, Geographically Weighted Regression*

Introduction:
Lightning is a common source of wildfire ignition across the western United States and indeed, much of the world (Read et al. 2018). Because of this, it is of interest to learn if a relationship exists between wildfire occurrence and lightning strike frequency. Initially, it may be assumed that a strong relationship must exist, but this assumption may not be well founded. To better understand this, the reader should recall the fundamental fire triangle. That is, a fire can only exist when oxygen, heat, and fuel are all sufficiently available. In the case of wildland fires, oxygen is typically always sufficiently available. Fuel on the other hand, is not always abundant or available in sufficient quantity. Vegetation biomass (the primary source of fuel in wildland fires) can be too rare to carry a fire across the landscape (i.e., lack of fuel continuity) or too wet to combust. For these reasons, wildfires tend to occur in late summer when vegetation has senesced and, in the case of annual grasses like cheatgrass (*Bromus tectorum*), transformed from live vegetation to fine fuels.

Lightning can provide the third component of the fire triangle (i.e., heat or ignition). However, if a lightning strike is accompanied by rainfall a wildfire may be extinguished just as quickly as it is ignited (Hall 2007). In many parts of the United States (e.g., the Midwest), dry thunderstorms are practically unheard of. Yet in other areas, such as the western US, late summer dry thunderstorms are the norm.

Based upon this premise, a study was conducted to map and explore the spatial and temporal distributions of lightning across the western United States and develop a better understanding of wildfire. To accomplish this, lightning strike, wildfire frequency, weather condition, and El Niño Southern Oscillation (ENSO) data were examined to complete this study.

Methods:

Study Area

The western United States (**Figure 1**) was selected as the study area for this research as fire frequency and area burned is well documented by the Historic Fires Database (HFD) (Weber 2023). It is also an area known to experience a large number of wildfires annually.

Figure 1. The study area focused on the western United States, contained the states of Arizona, California, Colorado, Idaho, Montana, Oregon, Nevada, New Mexico, Utah, Washington, and Wyoming.

Data Acquisition and Preparation

Two spatial datasets were required to complete this study; (1) the location of wildfires and (2) the location of lightning strikes. Wildfire data was provided by the HFD. This polygon feature class contained attributes describing the year of the fire as well as the spatial extent of each wildfire greater than one acre in size (prescribed fires are not included in the HFD). It is noted that the HFD does not attribute the cause of the fire. These data were downloaded as a file geodatabase and were effectively analysis ready.

To facilitate raster data analysis, fire frequency layers were created for each year of this study (1987-2021). These raster layers were stored as TIFF files with 30-meter cell size. All pixels where a fire occurred in a given year was given a value of one (1) and all other pixels were given a value of zero. Pixels outside the study area were assigned *No Data*. By summing all annual fire frequency raster layers, a final fire frequency TIFF file was created describing the frequency of wildfires across the western United States between 1987 and 2021.

Lightning strike data was acquired through the National Lightning Detection Network (NLDN) (NOAA NCDC 2023a) as annual comma-separated values (CSV) files. The structure of the CSV files contained a date column (ZDAY), gridded location columns (CENTERLON and CENTERLAT), and a lightning frequency column (TOTAL_COUNT). The polarity of each lightning strikes was not provided (positive, long-continuing current strikes are generally considered more likely to cause wildfire ignition (Pérez-Invernón et al. 2021, Pineda et al 2014, and Larjavaara et al. 2005)) nor was attribution of whether the lightning was in-cloud (IC) or a cloud-to-ground (CG) strike. The spatial resolution of these data was relatively coarse and mapped to 0.1° or approximately 10 km. This resolution followed a regular grid pattern across the United States which resulted in highly uniform data across all years (**Figure 2**). The TOTAL_COUNT column contained a count of all lightning strikes recorded by the NLDN and included both in-cloud and cloud-to-ground lightning. There is no method available to separate these two types of lightning within the NLDN data and as a result this study used TOTAL_COUNT throughout the analysis. This is a recognized potential error in the study as in-cloud (IC) lightning is not a source of wildfire ignition. However, Schultz et al. (2011) demonstrated that total lightning count is a better indicator of severe weather than cloud-to-ground (CG) strikes only. This is because IC lightning frequently occurs prior to CG strikes as storm fronts move across a landscape and should not be considered mutually exclusive types of storm events. Furthermore, there is a general positive correlation between IC and CG lightning strikes (Boccippio et al 2001) suggesting the use of all lightning strikes –as in this study-- does not necessarily result in an error of analysis or an error in the inferences drawn as a result of the analyses.

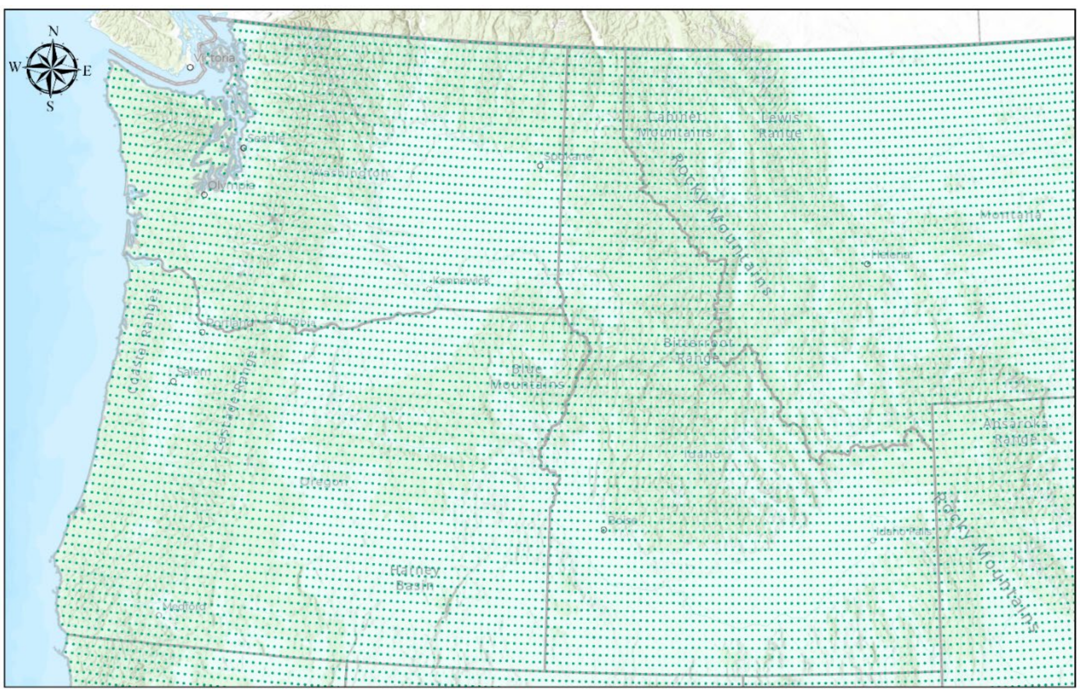

Figure 2.The regular grid pattern used by the National Lightning Detection Network (NLDN). Each point represents a collection of lightning strikes detected within 0.1° area centered over the point (points are separated by approximately 10km).

Each annual CSV file was imported into an ArcGIS file geodatabase as a point feature class. This was repeated for each year (1987-2021). The annual point feature class layers were then merged into a single point feature class. Because the source data was from an ASCII text file, the ZDAY field was not recognized as a DATE data type. To enable querying this feature class by year, month, and/or day, three additional short integer fields (Year, Month, and Day, respectively) were created and populated with the appropriate date data. The resulting point feature class contained 97,935,467 lightning strike records from January 1st 1987 through December 31st 2021.

Spatial and Statistical Analysis

To better analyze these data and visualize broad patterns of lightning strike frequency across both space and time, a hex bin polygon feature class was created for the study area (n = 5,112 polygon features). Each hex bin polygon had a distance of 25 km between its east-west perimeter lines and a resulting area of 625km^2. On average, six NLDN point features were contained within each hex bin polygon for each year of this study.

The Summarize Within geoprocessing tool was used in ArcGIS Pro to calculate lightning strike frequency (i.e., the sum of the TOTAL_COUNT field) within each hex bin polygon. This analysis was completed for all lightning strikes occurring throughout the year and repeated for lightning strikes occurring during the months of July and August only. The latter analysis was conducted as data from NOAA's National Centers for Environmental Information (NOAA NCEI 2021) indicates 35% of wildfires occurred during the months of July and August in 2021.

The Getis-Ord Gi* hot spot analysis tool was used in ArcGIS Pro to identify statistically significant hot spots/cold spots using the hex bin polygon feature classes created above. The sum of TOTAL_COUNT field was used and a false discovery rate correction was applied (Benjamini and Hotchberg 1995). This analysis identifies those areas where lightning strikes occur with very high frequency (a hot spot) or with very low frequency (a cold spot). Further, hot spots and cold spots are quantified following standard confidence intervals.

The same hex bin polygon feature class was also used to calculate zonal statistics for the sum of fire frequency pixels within each hex bin polygon. This approach was used to ensure the spatial basis for analysis between fire frequency and lightning strike frequency was identical. A Getis-Ord Gi* hot spot analysis was similarly computed for fire frequency.

Results and Discussion:

In total, 97,935,451 lightning strikes occurred across the western United States between 1987 and 2021 (**Figure 3**) (Note: 2020 was considered a lightning drought year (Vaisala 2021)). Of these, 61,367,802 strikes occurred during the months of July and August (63%). Based upon both annual and monthly summarizations of these data, we conclude lightning strikes are not uniformly distributed over time. Instead, lightning strike occurrence across the western United States increases during the late summer months which also tend to exhibit hotter and drier atmospheric conditions. This observation is supported by the Global Summary of the Month/Year Dataset (GSOM/GSOY) (NOAA 2023b) which shows July has the highest mean and median temperature and lowest mean and median percent humidity across the study area (**Table 1**) (Durre et al., 2010; NCEI 2019).

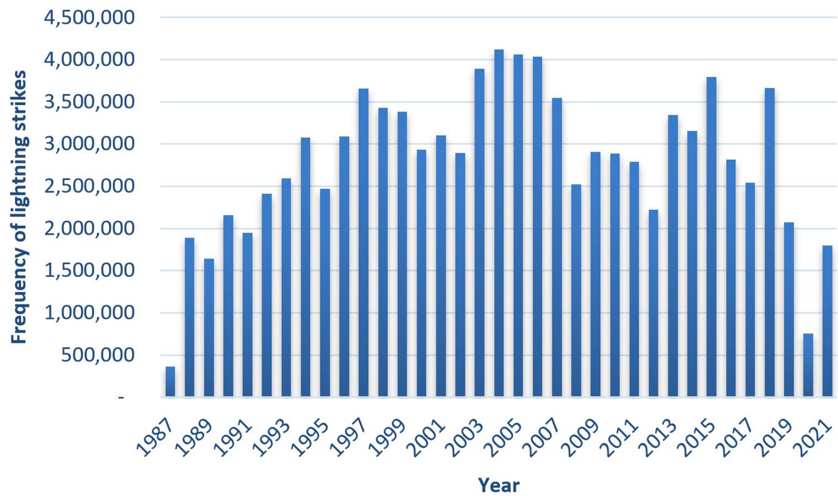

Figure 3. Annual frequency of lightning strikes between 1987 and 2021 across the western United States. Note, 1987 was the first year when NLDN data were available and may not represent a complete record. The year 2020 also exhibited anomalously low lightning frequency and was considered a lightning drought year. Even with these anomalies, the distribution curve follows a roughly convex shape.

Table 1. Mean and median ambient temperature (T) and percent humidity (RH) across the study area for the period of 1987 through 2021. Note July has both the hottest and driest records.

	June		July		August		September	
	T (° C)	RH (%)	T (° C)	RH (%)	T (° C)	RH (%)	T (° C)	RH (%)
Mean	25.1	22.3	28.9	21.7	28.1	22.0	24.0	24.9
Median	23.6	22.4	28.0	21.7	27.3	22.8	23.4	25.9

The spatial distribution of lightning strikes is not uniformly distributed (**Figure 4**). Rather, lightning strikes demonstrate a clustered distribution in the southwestern United States with 29% of all hex bin polygons considered hot spots (99% CI). A nearly opposite phenomenon exists along with west coast and northwestern United States where 46% of hex bin polygons are considered cold spots (99% CI) (**Figure 5**).

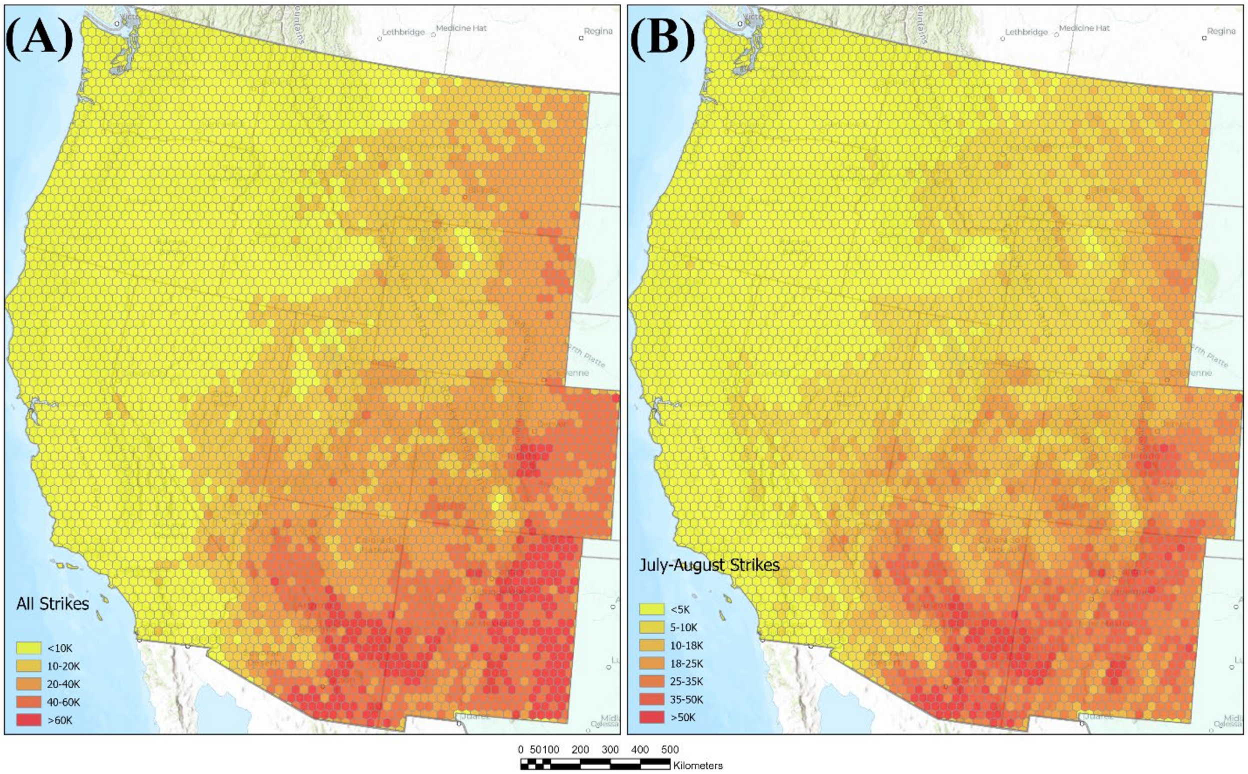

Figure 4.Distribution of lightning strikes throughout the year (A) and for the months of July and August only (B) within hex bin polygons. Note the clustered pattern in the southwest United States.

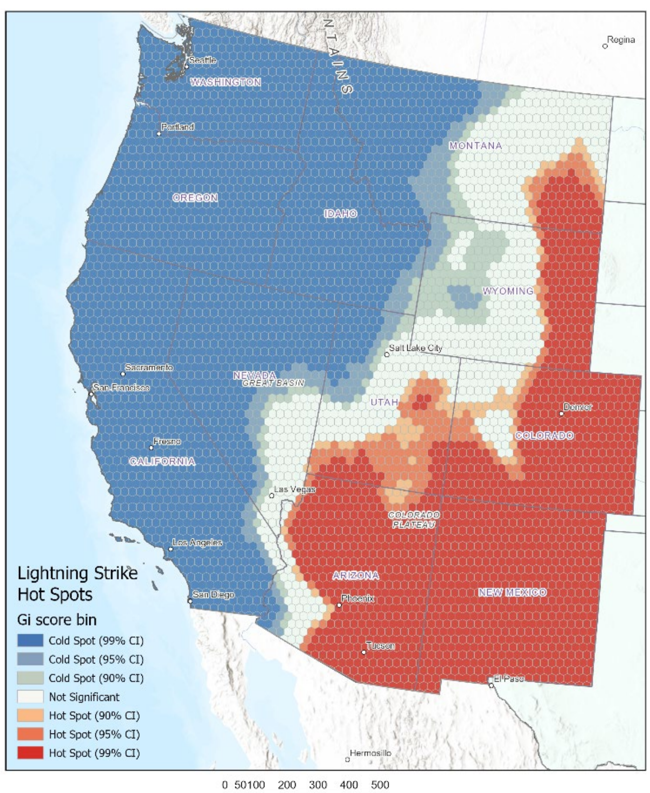

Figure 5. Hot spot and cold spot areas of lightning strike frequency based upon Getis-Ord analysis.

It is interesting that the effect of various geographic features can be seen in these data (**Figure 4**). For instance, higher frequencies of lightning strikes tend to be associated with pronounced mountain ranges such as the Sierra Nevada range (California), Absaroka range (Montana-Wyoming), Front range (Colorado), and Gila Mountains/San Francisco plateau (Arizona). The latter area is considered a meteorological region of systematic deep convection (Adams and Comrie 1997). In most of these cases, the increase in lightning strikes occurred to the west of the mountain range save for that seen in Arizona which showed an increase in lightning strikes north of the Gila Mountains. In contrast, the effect of the Upper Snake River Plain (Idaho) is also visible and associated with a decrease in lightning frequency. The decreased lightning frequency seen across the Snake River Plain is a result of the influence of terrain on thunderstorm development. Lightning is much more common in the surrounding mountains/highlands where elevated terrain serves as a constant source of forcing to trigger thunderstorms. In the flat landscape of the Snake River Plain, orographic forcing is absent necessitating an upper-level low pressure system or similar event to trigger the storms and lightning in this area.

The high incidence of lightning strikes in the southwest United States – particularly in Arizona and New Mexico- can be explained at least in part, by the pattern of the North American Monsoon which delivers more than 50% of annual precipitation to these states in July and August (Adams and Comrie 1997). The timing of monsoonal moisture (and lightning) is of interest relative to wildfires as large amounts of rainfall will normally extinguish fires ignited by lightning strikes (Hall 2007).

In total 36,825 wildfires occurred across the western United States between 1987 and 2021 (**Figure 6**). No strong temporal pattern or statistical trend was identified in these data although repeating peaks and troughs can be seen throughout the 35-year study period. Based purely upon data visualization, there appears to be a primary bidecadal pattern (approximately 1987-2006 and 2007-2021) within which smaller, secondary variations can be seen (e.g., the years 1999-2001). Additional research is merited to determine if a bidecadal pattern can be quantified.

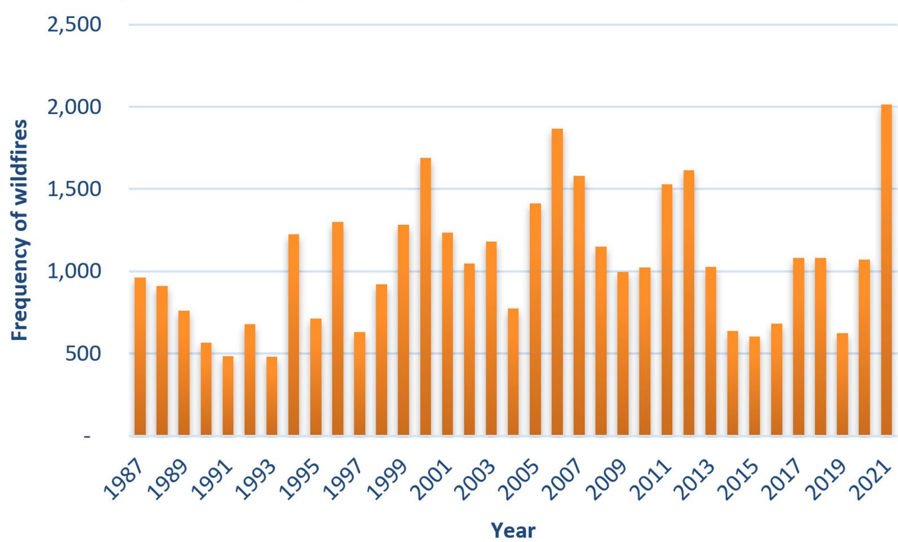

Figure 6. Annual frequency of wildfires between 1987 and 2021 across the western United States. Note, the bimodal or bidecadal pattern that appears to exist in these data.

The spatial distribution of wildfires, like the distribution of lightning strikes, is not uniformly distributed (**Figure 7**). Wildfires exhibited a clustered or semi-clustered distribution with only 6% of hex bins considered statistically significant hot spots (≥ 90% CI), while no hex bins were considered a cold spot. The hot spots identified using Getis-Ord Gi* analysis did not correlate well with lightning strike hot spots and if anything, correlated better with lightning strike cold spots although no significant relationship was observed.

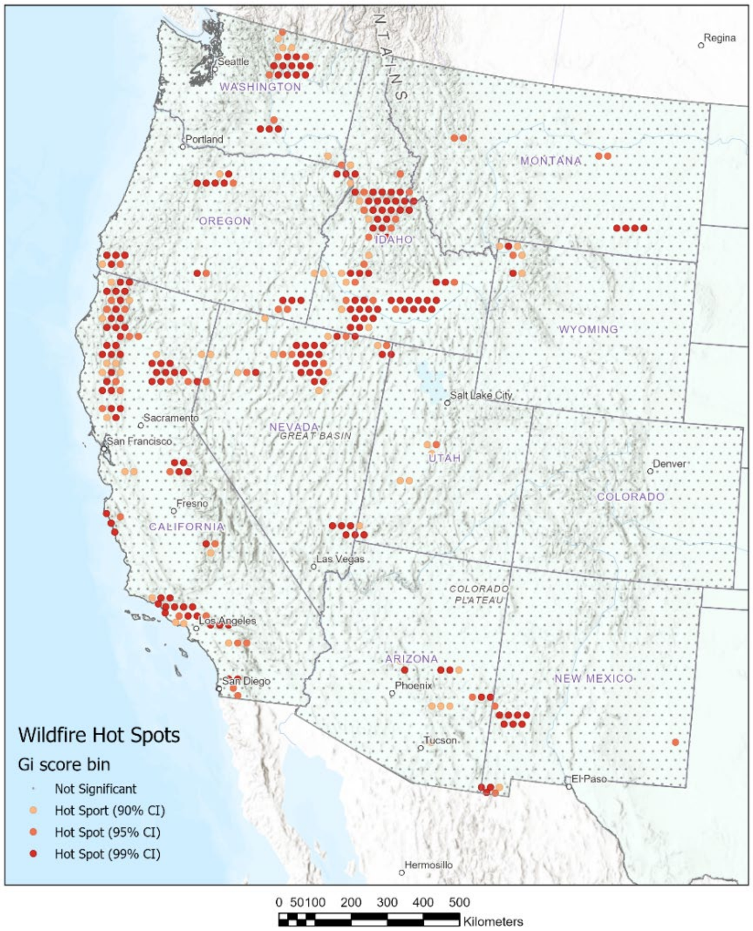

Figure 7. Hot spot areas for wildfire frequency based upon Getis-Ord Gi analysis.*

To explore the relationship between lightning frequency and wildfire frequency, Geographically Weighted Regression (GWR) was used in ArcGIS Pro. For this analysis, lightning frequency for July and August was selected as the independent or explanatory variable and fire frequency was set as the dependent variable (both variables were based on the hex bin layers described earlier). The results of this analysis indicate a very weak and almost non-existent relationship exists ($R^2 = 0.009$). This is not to say that lightning cannot start wildfires but rather, while lightning is a substantial source of fire ignition, it is just one stage in the sequence of events leading up to a wildfire. Moreover, for a wildfire to occur requires combustible fuel (e.g., biomass that is sufficiently dry to burn), sufficient fuel continuity to carry the fire, adequate ambient conditions (i.e., sufficiently warm air and low humidity), and an ignition source. Lightning is a viable ignition source but if all other precursors are not met, a wildfire will not occur. In fact, based on the recorded number of lightning strikes, wildfire starts due to lightning could be considered a rare event as over 97 million lightning strikes resulted in only 36,825 wildfires. The author notes the cause of the wildfires examined in this study are not known and are being not attributed wholly to lightning. However, it is well documented that across the western United States approximately 70% of all wildfires are caused by lightning (Brey et al. 2018).

To better understand the long-term, multi-decadal pattern of lightning and wildfire frequency, El Niño and La Niña event years were incorporated into this study for the same 35-year time period (1987 through 2021). Using the Oceanic Niño Index (ONI) (one measure of ENSO), six moderate or greater (ONI $\geq$ 1.0) El Niño events were identified; 1987, 1991, 1992, 1997, 2009, and 2015. In contrast, nine years (1988, 1989, 1999, 2007, 2008, 2010, 2011, 2020, and 2021) were considered periods of moderate or greater (ONI ≤ -1.0) La Niña events, while the remaining 20 years were considered neutral ONI event years. Using analysis of variance (ANOVA) no effect of ONI on lightning frequency was identified (P = 0.08). However, El Niño years appear to depress wildfire events relative to La Niña and neutral years (P = 0.03) (**Table 2**). However, since only six years (17%) were considered El Niño years, this conclusion is not definitive and requires additional research.

Table 2. The frequency of lightning and wildfire events during El Niño (ONI > 1.0), La Niña (ONI < -1.0), and neutral ONI years. El Niño appears to depress wildfire frequency (P = 0.03).

	Lightning strike frequency			Wildfire frequency		
	El Niño	La Niña	Neutral	El Niño	La Niña	Neutral
Mean	2,514,369	2,355,188	3,082,628	725	1,258	1,058
Median	2,659,145	2,519,842	3,081,810	655	1,151	1,065
SD	1,268,931	906,768	640,221	207	391	392

Conclusions:

This study examined over 97 million lightning strikes occurring between 1987 and 2021 across the western United States. The results indicate lightning strikes are not temporally or spatially random occurrences. Rather, 63% of all lightning strikes occurred during the late summer months of July and August with no discernible effects due to the ENSO. Spatially, lightning showed a strong southeast (hot spot) to northwest (cold spot) trend across the western United States study area.

Wildfire trends did not follow the same spatial pattern as lightning with very few significant hot spots observed. Moreover, wildfires are not randomly or uniformly distributed temporally or spatially. However, the El Niño Southern Oscillation (ENSO) appears to depress wildfire frequency relative to La Niña and neutral years ($P < 0.05$). Additional research on the effect of ENSO is merited and should be explore this phenomenon using latitudinal gradients across the western United States. Lightning accounts for approximately 70% of wildfire ignitions across the western United States and is projected to increase by as much as 50% over this century (Romps et al. 2014). If this trend is realized, an increase in wildfire frequency needs to be anticipated.

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