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A 30-Year Climatology of Meteorological Conditions Associated with Lightning Days
in the Western United States

by

Dmitri Alexander Kalashnikov

A thesis submitted in partial fulfillment of the
requirements for the degree of

Master of Science
in
Geography

Thesis Committee:
Paul Loikith, Chair
Andrew Martin
Andrés Holz

Portland State University
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Abstract

A 30-year climatology of lightning and associated synoptic meteorological patterns are characterized across the Western United States (WUS), utilizing a comprehensive composite analysis. Results generally show a preferred synoptic meteorological setup with positive 500-hPa geopotential height anomalies to the northeast of the location experiencing a lightning day, and negative sea level pressure anomalies co-located and to the northwest. Variation in preferred anomaly patterns across the western US reflects the divide between those areas affected by the North American monsoon system and areas outside the monsoonal core. Locations in the western Great Basin and northern Rocky Mountains, which are outside the monsoonal core, show preference toward greater amplitude of synoptic circulation fields compared to the interior Southwest. A northwest-to-southeast gradient in magnitude of anomalies of moisture and mid-tropospheric instability is present, with areas northwestward showing preference for greater departures compared to climatological means. These results likely reflect the prevalence of favorable mesoscale dynamics key to lightning during warm season months in locations within the monsoonal core in the interior Southwest, along with the more episodic nature of lightning-conducive features in areas peripheral to this region. Meteorological patterns for select locations are explored in more detail and two case studies of notably active lightning events are presented. This work provides an observation-based foundation for understanding meteorological patterns on lightning days, which may inform operational forecasts for lightning hazards as well as projected changes in lightning activity across the western US from climate model simulations.

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Chapter 1: Introduction and Review of Relevant Literature

1.1: Lightning Detection

Lightning is a natural phenomenon that is observed in many parts of the world. In recent decades, many scholarly attempts have been made to understand lightning, its occurrence, and its relationship with driving meteorological variables. This academic research has been made possible by the availability of lightning data, as well as the computational resources available to process this data. The first large-scale effort to track lightning in the United States was undertaken in the late 1970s, when a network of ground stations was installed across the western states and Alaska. The United States Bureau of Land Management (BLM) originally commissioned the creation of this network in order to detect possible lightning-caused fire starts, in the process creating the first lightning dataset available in the United States (Krider et al. 1980). The original BLM network was eventually assimilated into the National Lightning Detection Network (NLDN), which was formed in 1984 on the East coast and expanded westward over the following years, achieving national coverage by 1988 (Cummins and Murphy 2009).

1.2: Motivation

Lightning serves as a direct indicator for thunderstorm activity, and thunderstorms are a perennial occurrence during warm season months across interior portions of the Western United States (WUS). Cloud-to-ground lightning (hereafter CG flashes) is a major ignition source for summer wildfires across interior portions of WUS (Abatzoglou et al. 2016; Dettinger et al. 1999; Nauslar et al. 2019; Rorig and Ferguson 1999; van

Wagtenonk and Cayan 2008). Improved understanding of lightning activity can be used to help inform outlooks of lightning-related hazards on weather-to-centennial timescales. While previous studies have projected an increase in lightning occurrence under anthropogenic climate change globally (Price 2009) and in the conterminous US (Roms et al. 2014), such conclusions remain uncertain on the regional scale (e.g. Hoogewind et al. 2017; Villarini and Smith 2013). To better inform operational lightning forecasts and projections of possible future changes to lightning climatology, more work is needed to understand the meteorological patterns associated with lightning in the current climate.

1.3: Lightning in Climate Models

While lightning frequency itself has been found to be of secondary importance to spatiotemporal variability of wildfire when compared with climatic and fuel load conditions in many regions (Abatzoglou et al. 2016; Krawchuk et al. 2009), lightning is the dominant source of fire ignitions and burned area in sparsely populated regions of WUS (Balch et al. 2017) in addition to serving as an indicator for other thunderstorm-related impacts such as flash flooding. However, as lightning flashes and therefore thunderstorms are not explicitly simulated by climate models (Magi 2015), understanding how climate change may affect this important feature of the regional summertime climate remains challenging. One way to address this challenge is to evaluate the ability of climate models to simulate the characteristics of atmospheric conditions favorable to lightning, and implement lightning parameterization schemes (Price and Rind 1992; Magi 2015).

1.4: Lightning Studies in the Western US

As a first step, it is necessary to understand the observed seasonality, frequency and spatial distribution of lightning activity across WUS. Following, an observational foundation can be developed of the synoptic-scale weather patterns and meteorological variable indices associated with lightning days in interior portions of this region. As continuous lightning detection in WUS only extends to 1985 (Dettinger et al. 1999), studies focused on this region have utilized shorter lightning datasets, typically between 5 and 20 years in length. Shorter datasets may not fully characterize lightning climatology particularly in areas of infrequent lightning, and no publication to the authors' knowledge has yet been produced characterizing lightning activity on a 30-year baseline in this region.

Previous efforts to describe lightning occurrence in WUS (Abatzoglou and Brown 2009; Adams and Souza 2009; Burrows et al. 2005; Dettinger et al. 1999; Milne 2004; Rorig and Ferguson 1999; Rorig et al. 2007; van Wagtendonk and Cayan 2008) and southwestern Canada (Burrows et al. 2005; Nash and Johnson 1996) have used a suite of dynamic and thermodynamic variables at synoptic to mesoscale resolution, typically focusing on circulation anomalies as well as indices of moisture and instability. In this study, we retain a combination of variables chosen empirically with selection guided by previous works. We utilize a comprehensive and spatially contiguous analysis to describe the synoptic-scale meteorological patterns and a subset of thermodynamic variables found to associate with increased lightning activity in WUS.

Chapter 2: Data and methodology

2.1: Data

We utilize CG flash data from the National Lightning Detection Network (NLDN). The NLDN is a ground-based lightning sensor network spanning the lower 48 states (Cummins and Murphy 2009; Orville 2008), and has served as ground truth in evaluation of other ground-based lightning detection efforts (e.g. Abarca et al. 2010). Although the NLDN is a private network owned and operated by a commercial vendor, daily gridded lightning data is made available to the National Oceanic and Atmospheric Administration's Severe Weather Data Inventory (NOAA-SWDI). This dataset provides daily temporal resolution on a 0.1° latitude-longitude grid. We make use of 30 years of observations, spanning the years 1988 to 2017, in order to provide a climatologically relevant baseline for analysis. Daily meteorological data are obtained from the National Aeronautics and Space Administration's (NASA) Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2; Gelaro et al. 2017). This dataset is on a global domain with spatial resolution of 0.5° latitude by 0.625° longitude.

2.2: Methodology

2.2.1: Spatial and Temporal Subsetting

Analysis is conducted over WUS, defined as the region bounded by latitude 31.5°N - 49°N and between the Pacific Ocean to the west and longitude 105°W to the east, which approximates the Front Range of the Colorado Rocky Mountains. Annual lightning climatology is presented as CG flash density per km^2 , meaning CG flashes per year per

km², obtained by dividing annual averages at that grid cell by latitude-adjusted grid cell area. Composite analysis is conducted over the months from May through September (hereafter, MJJAS), which represents the summertime convective season across the western US (Burrows et al. 2005; Dettinger et al. 1999; Rorig and Ferguson 1999). While impactful lightning events have been known to occur outside of this timeframe in parts of WUS, particularly in the Southwest, we choose to constrain our analysis to warm season climatology in order to minimize interseasonal variation. We define lightning days as those with at least five detected CG flashes in a given 0.1° by 0.1° grid cell. The CG flash threshold is selected to eliminate days in the lower percentiles of lightning activity, while preserving meaningful sample sizes across the study domain. The selection of a relatively low CG flash threshold also minimizes the effects of increasing detection efficiency of the NLDN over time, which has undergone system upgrades during the study period (Cummins and Murphy 2009).

2.2.2: Composite Analysis

The foundation of our results is a composite analysis of dynamic and thermodynamic anomalies present on lightning days over the 30-yr record. To represent synoptic circulation patterns in the mid-troposphere and near the surface, respectively, 500-hPa geopotential height (Z500) and sea level pressure (SLP) are used. Total precipitable water vapor (TQV) provides a vertically integrated snapshot of atmospheric moisture. Instability is represented by the mid-tropospheric lapse rate, defined as the temperature difference between the 700-hPa and 500-hPa pressure levels (L700500). The current

study makes use of deseasonalized anomalies of these variables, which are computed by subtracting the 30-yr daily climatology (1988-2017) from actual daily values. To account for the substantial variability in TQV climatology across the domain, standard deviation departures are utilized to represent daily anomaly values. In addition, 700-hPa wind direction (W700) is included in the analysis to understand lower-tropospheric circulation patterns on lightning days. A summary of analyzed variables is provided in Table 1. For composite analysis, the spatial domain is further constrained to only those grid cells which average at least one lightning day per year as defined above, ensuring a minimum sample size of 30 lightning days at all analyzed grid cells.

2.2.3: Radial Interpolation

To allow for systematic comparison of meteorological variables from different locations, composite patterns are remapped to polar coordinate grids centered on each grid cell, following the methodology employed by Loikith and Broccoli (2012). Radial resolution of 50 km and azimuthal resolution of 1° is selected in order to best approximate the underlying MERRA-2 reanalysis field. This process standardizes coordinates around each grid cell to a unit circle with absolute distances. An example of one such ‘gridcell-relative grid’ is shown in Fig. 1. The outer boundary of the grid is located 2500 km from the central grid cell, a distance chosen empirically such that large-scale circulation patterns would be captured.

Chapter 3: Results and Discussion

3.1: Lightning Climatology

A climatology of CG flash occurrence in WUS is constructed at the grid cell level, utilizing the 0.1° by 0.1° resolution native grid of the NLDN data. Climatological means of total annual CG flashes vary greatly across the domain, with a general northwest to southeast gradient in lightning density (Fig. 2). Areas along the coast, in the western valleys (e.g. Willamette, San Joaquin), and in the Columbia Basin average less than 0.1 CG flashes km^{-2} per year. Annual averages show a rapid increase along the transition from western sections of the Great Basin and interior California into the monsoon-dominated regions further east. Large areas of Arizona and New Mexico average at least one CG flash km^{-2} per year, with substantially higher averages in topographically favored areas. For example, annual flash densities approach five CG flashes km^{-2} at several grid cells, with domainwide maximum annual flash density located on the southern slope of Chiricahua Peak, in southeastern Arizona. General orographic enhancement of CG flash density is apparent throughout the study domain and is consistent with foundational studies (e.g. Reap 1986).

Seasonality of CG flashes shows a sharp contrast between proximate areas to the West Coast and locations further in the interior (Fig. 3). Locations near the coast and in the low-lying valleys, especially in California and to a lesser extent in Oregon and Washington, do not experience a summer peak in lightning activity in contrast to locations further east and at higher elevations. Most interior locations away from the coastal valleys experience peak lightning activity during meteorological summer, mainly

in the months of July and August (Fig. 3a). These two months contribute more than half of all days with at least one CG flash at many grid cells, with areas of southern Arizona exceeding 70% of annual frequency (Fig. 3b).

A map of the total number of lightning days (1988-2017), for all grid cells averaging at least one lightning day per year as defined for this study (≥ 5 CG flashes), is presented in Fig. 4 and serves as the set of grid cells ($N = 24,053$ grid cells) retained for composite analysis. It is inherent in our method and from analysis of Fig. 4 that sample sizes at individual grid cells vary based on the climatological prevalence of lightning days. While the minimum sample size is defined as 30 days, maximum sample size ranges as high as 721 days in southwestern New Mexico, with several grid cells in the region exceeding 700 days. However, composites of key variables are qualitatively insensitive to the choice of sample size or the per day CG flash threshold, as characteristics of meteorological fields show the same fundamental anomaly patterns when lightning is present in any quantity. The spatial variation of lightning day sample sizes in Fig. 4 resembles that of annual CG flash averages in Fig. 2, with masked areas generally corresponding to areas with less than 0.1 CG flash km^{-2} per year in that figure.

3.2: Composite Analysis

3.2.1: Geopotential Heights and Sea Level Pressure

Grand composites of Z500 and SLP anomalies are depicted in Fig. 5. To construct the grand composites, first a grid cell composite is computed for each of the 24,053 grid cells by averaging the Z500 and SLP anomalies for all lightning days at that grid cell. Then,

the 24,053 composite patterns are averaged into one single grand composite, summarizing the average circulation on lightning days across all grid cells. Boxplots are provided to show the distribution of individual grid cell anomalies at the locations of anomaly peaks in the grand composites. A Student's *t*-test is performed in order to test the statistical significance of the grand composite anomaly peaks relative to each other, utilizing the sample size of individual grid cell anomalies at those locations showed by boxplots in Fig. 5c-d. Results indicate a statistically significant difference between the positive and negative anomaly peaks in the grand composites of both variables.

Average lightning days across the domain are characterized by positive Z500 anomalies located to the northeast of the grid cell experiencing lightning, with negative Z500 anomalies located to the southwest (Fig. 5a). A transitional gradient in the large-scale circulation pattern is thus apparent, with an upper-level high pressure ridge downstream and a trough upstream. Negative SLP anomalies are located just north of the grid cell experiencing lightning, suggesting potential for upward vertical motion in the vicinity and areas northward (Fig. 5b). This feature may also be associated with a surface thermal trough, as composite analysis of 2-meter temperature anomalies shows positive departures displaced northward relative to the average grid cell (not shown). The grand composites are consistent with the canonical large-scale weather pattern conducive to lightning outbreaks in the interior WUS, as previous studies have linked this synoptic setup with increased lightning potential and wildfire ignition risk in this region (Abatzoglou and Brown 2009; Chiodi et al. 2016; Dettinger et al. 1999; Rorig and Ferguson 1999; Werth and Ochoa 1993). Likewise, the location of positive Z500

anomalies is in agreement with studies focusing on the core monsoonal region (Higgins et al. 2004; Lorenz and Hartmann 2006), which found a similarly positioned high pressure ridge to the north and northeast of areas experiencing surges of convective activity. North-northeastward displacement of upper-level ridging thus presents a pattern commonality across the latitudinal extent of the interior WUS on lightning days.

To understand regional variation of anomaly patterns and test representativeness of the grand composites across the study domain, spatial statistical metrics are utilized including individual gridcell-based pattern correlations (Pearson's r) and root-mean-square deviations (RMSD) to compare individual grid cell composites with the grand composite. Figure 6 shows Pearson's r values and RMSD statistics, illustrating the closeness of match between the lightning day composite at each grid cell and the grand composites in Fig. 5. Median values of Pearson's r between the grand composite and all of the individual composites are provided as an aggregate metric of the ability of the grand composite to capture common spatial features of the individual composites.

An analysis of Z500 pattern correlations in Fig. 6a reveals generally high levels of similarity between composite patterns at individual grid cells and the grand composite in the western Great Basin and northern Rocky Mountains, with varying levels of similarity in the interior Southwest. However, the preferred north-northeastward displacement of positive Z500 anomalies (exhibited in the grand composite) relative to each grid cell is evident across the study domain (median pattern correlation 0.78). Our results indicate that in the typical interior WUS location, northeastward displacement of mid- and upper-level ridging can lead to lightning activity regardless of latitude. At the surface, SLP

pattern correlations in Fig. 6c show generally high levels of similarity between composite patterns at individual grid cells and the grand composite in areas further north, with lower similarity across the interior Southwest. It is probable that this region lacks the characteristic surface pressure gradients associated with transient synoptic-scale patterns found in locations at higher latitudes.

Corresponding maps of Z500 (Fig. 6b) and SLP (Fig. 6d) RMSD statistics show that highest similarities with the grand composite are displaced further south and east when compared with Pearson r values. Comparatively lower agreement (higher RMSD values) is found in areas of eastern Oregon, northern Idaho, and western Montana, in contrast to the generally high r values in this region. Although some of this increase in RMSD may be attributed to smaller sample sizes introducing noise into the composites, an important factor is the greater synoptic pattern amplitude across these areas on lightning days. An analysis of average pattern amplitude, or the difference between the highest and lowest composite anomaly values relative to each grid cell on lightning days, reveals greater peak-to-peak spread in both Z500 and SLP anomaly fields in the northern and western parts of the domain (not shown). These values are co-located with areas of higher RMSD and can be attributed to locations where midlatitude dynamics play an increased role in thunderstorm formation, compared to regions further south and east where mesoscale dynamics are more influential (Adams and Souza 2009). Areas of lower RMSD are concentrated in the central and southern portions of the domain, indicating weaker synoptic pattern amplitude and closer resemblance to the grand composites.

Regional variability in Z500 pattern progression on days prior to analyzed lightning day is shown in Fig. 7, with correlation coefficients indicating closeness of match between the composite anomaly pattern at each grid cell on lightning days and one, two and three days prior. Southern locations, particularly climatologically active lightning areas in the monsoonal core, show little pattern progression in the three days prior to analyzed lightning day, likely indicating persistent favorable dynamics inherent to this region during monsoon season. In addition, instances of multiple consecutive lightning days across this region, as described in Watson et al. (1994), may mask synoptic pattern transitions between multi-day bursts and breaks in monsoon activity. Areas further west, including the Sierra Nevada, also show little pattern progression possibly reflecting multi-day northward extension of upper-level ridging corresponding to lightning activity. This is in contrast to lower correlation coefficients between days further north, where pattern progression is likely driven by transient upper-level disturbances in the days leading up to lightning activity.

In Fig. 8, mean within-grid cell Z500 pattern correlation coefficients are shown for all lightning days within each grid cell's composite. The correlation coefficients are computed by first correlating Z500 patterns on each lightning day with the composite pattern at that grid cell, then averaging all daily correlation coefficients. This allows for an analysis of composite representativeness of lightning day patterns at that location. Lower values are found in areas southeastward, indicating weaker composite representativeness of lightning days at the grid cell level. Individual composites at grid cells across these areas may mask multiple orientations of synoptic patterns during

lightning outbreaks, as favorable mesoscale dynamics are generally present in these areas during monsoon season. This feature is likely reflected in the Z500 grand composite itself due to the large amount of such grid cells in the domain. Previous studies have found a north-south gradient of increasing complexity in combinations of predictor variables favorable to lightning in western North America (Burrows et al. 2005), indicating climatologically more favorable conditions for lightning occurrence further south and less dependence on rare combinations of variables. Locations on the northern and western periphery in Fig. 8 show higher within-grid cell pattern correlation, likely resulting from increased dependence on certain orientations of preferred synoptic patterns favorable to lightning activity in these areas.

Overall, our results reflect greater amplitude of synoptic patterns typically seen at higher latitudes during boreal summer when compared to the synoptic environment associated with the monsoonal circulation further south. Areas of spatially coincident lower agreement in both r values and RMSD for both Z500 and SLP are evident in parts of the study domain, indicating both lesser amplitude as well as differences in the spatial signature of the sign of anomaly patterns compared to the grand composite. These areas include the Sierra Nevada region as well as some interior basins, such as those containing the Great Salt Lake and the Green River in Utah. While a full analysis of responsible mechanisms for these regional differences is beyond the scope of this study, the influence of topography is speculated to drive most of these regional patterns of preferred lightning conditions.

3.2.2: 700-hPa Wind

To further characterize lower-tropospheric circulation features associated with lightning activity, we explore the 700-hPa wind directions prevalent on lightning days across the region. Dominant mode of W700 direction for each grid cell is presented in Fig. 9a, with wind directions binned into 45-degree increments centered on the eight cardinal and intermediate compass bearings. The frequency of the dominant W700 direction at each grid cell in Fig. 9a is represented as a percentage of all directions in Fig. 9b. Dominant modes of W700 direction follow a general clockwise path along an arc from the low desert regions of Arizona and California (easterly to southeasterly), extending northward through the Great Basin (southerly to southwesterly), and eastward into parts of the central and northern Rocky Mountains (southwesterly to westerly). Areas in central Arizona show weak preference for W700 direction on lightning days (Fig. 9b), likely reflecting the climatological position of the monsoon ridge with weak steering currents in the vicinity, along with the dominant role of mesoscale dynamics in thunderstorm formation across this region regardless of synoptic pattern. As an example, case studies of active lightning periods in Arizona have been associated with both southerly and northerly flow at the 700-hPa level (e.g. in Watson et al. 1994).

Overall, our findings are consistent with the presence of mid- and upper-level ridging across the interior WUS during warm season convective outbreaks, a synoptic feature cited in literature in association with lightning episodes in this region (e.g. Abatzoglou and Brown 2009). Northward extension of upper-level ridging promotes southerly flow in large areas of the interior WUS, specifically in areas north of the low elevation deserts of

the interior Southwest and east of the Sierra Nevada crest. In addition, a southwesterly flow component is introduced by approaching upper-tropospheric troughs and cutoff lows associated with the breakdown of the upper-level ridge, a feature illustrated by the prevalence of southwesterly flow in Fig. 9a. For areas on the southern margin of this flow regime, lightning-conducive 700-hPa flow has been identified as southeasterly in both Arizona and New Mexico (Hales 1977, Higgins et al. 2004), and interior California (van Wagtenonk and Cayan 2008). Similarly, a southeasterly component in 500-hPa flow direction has been identified as conducive to convective precipitation and lightning formation specific to the east slopes of the Oregon Cascades (Chiodi et al. 2016).

3.2.3: Moisture and Vertical Instability

Grand composites for anomalies of moisture (TQV) and instability (L700500) are presented in Fig. 10. Lightning days are characterized by greater positive anomalies across both variables in the vicinity of the grid cell experiencing lightning, with TQV exceeding one standard deviation relative to local climatologies of all 24,053 grid cells (Fig. 10a). Other moisture variables were explored and showed similar positive anomalies in the composite patterns, with 2-meter specific humidity also exceeding one standard deviation relative to local climatology near the grid cell experiencing lightning (not shown).

The grand composite of L700500 shows positive anomalies displaced to the north-northwest of each grid cell (Fig. 10b), indicating greater mid-tropospheric instability and roughly corresponding to the region of negative SLP anomalies in Fig. 5b. Average

positive L700500 anomalies may reflect a combination of cooler air aloft advected by an incoming trough, as well as warmer than average surface temperatures associated with a residual surface thermal trough. When combined with the northeastward upper-level ridge in the grand composite Z500 pattern (Fig. 5a), this configuration strongly resembles the transitional weather pattern described in previous studies as conducive to increased wildfire risk in portions of the interior West (e.g. Werth and Ochoa 1993).

In Fig. 10a-b, dashed contours indicate a 500-km radius used to subset the larger 2500-km radius grand composites of TQV and L700500 for further analysis. This subset radius was chosen after observation of central tendency of anomaly patterns relative to each grid cell, as can be observed from the distribution of elevated values within the larger grand composites. A moving window analysis is performed, aggregating mean values within the 500-km radius at all grid cells. Moving window analysis, also known as focal statistics or neighborhood analysis, is a common geospatial analysis technique that aggregates surrounding values to provide a more robust description of spatial patterns than point values alone. For each variable, all values in a 500-km radius circular window around each grid cell are averaged and then assigned to that grid cell, allowing for a comparison of regional aggregate values relative to the set of lightning days at each grid cell. The resulting focal means quantify regional differences of moisture and instability anomalies not apparent in the grand composites.

Focal means of TQV and L700500 anomalies reflect the divide between areas in the core monsoonal region, and those on the periphery (Fig. 10c-d). Although standardized anomalies of TQV are positive throughout the study domain, departures are only slightly

above daily mean values in parts of Arizona and New Mexico. Departures trend progressively more positive into the western Great Basin, interior California, and the interior Northwest. These findings are in agreement with summertime climatology across this region. Areas in the monsoonal core experience generally moist conditions during this season, which combine with high terrain to produce regularly recurring convective initiation and lightning activity. Lightning days are more frequent in this region, and do not require atmospheric moisture quantities substantially above typical seasonal values. Air mass thunderstorm days across this region may qualify as lightning days as defined in our analysis, further moving local composites toward climatology. This is in contrast with areas further west, which experience generally dry conditions during the summer season and thus require greater positive departures of moisture indices for thunderstorm formation. Our results are consistent with previous studies (e.g. Abatzoglou and Brown 2009) which have associated episodic northward moisture advection, away from typical monsoon areas, with lightning outbreaks across the arid western interior. In addition, studies focused on summertime lightning triggers in California (van Wagtenonk and Cayan 2008) have identified anomalous moisture surges associated with southeasterly flow originating in core monsoon areas. Areas of interior California, in particular, show the greatest positive departures of TQV compared to local climatology in the study domain, likely reflecting the combination of typically dry conditions yielding to substantial moisture advection from proximate monsoonal areas on lightning days.

A regional divide is also observed in anomalies of L700500 (Fig. 10d), with positive departures in excess of 2°C in parts of Oregon and California. Anomalies of L700500 do

not show a meaningful signal in the monsoonal core, with values on either side of zero on lightning days. This regime can also be interpreted in the context of differing summertime climatologies prevalent in these regions. As previously discussed, lightning days in the interior northwestern US are strongly linked with anomalous upper-level ridging as well as incoming troughs during ridge breakdown. Both of these features promote steeper-than-average mid-tropospheric lapse rates through low-level heating and advection of cooler air aloft, respectively. In the monsoonal core, convection is initiated through moisture transport from proximate tropical sources, with lifting provided by surface heating and assisted by steep topography (Adams and Souza 2009). This thunderstorm regime is therefore not dependent on steepened mid-tropospheric lapse rates beyond typical values for this region, and focal means of raw values of 700-500 hPa lapse rates are substantially high on lightning days even in areas of negative departures from daily average values (not shown). It is worth noting, however, that composites of values aggregated to a daily scale may not capture mid-level instability present during actual times of lightning occurrence in parts of this region, especially in valley locations prone to nocturnal thunderstorm maxima (Hales 1977).

3.3: Select Cases

3.3.1: Spatial Case Studies

Regional variability in preferred lightning-conductive meteorological patterns is further illustrated through four select grid cells. Each grid cell is chosen to represent a different region of the study domain. Further, we choose two regions each to represent

the northern and southern half of the study domain, respectively. The regions correspond to Central Oregon (COR), Western Montana (WMT), Eastern Sierra Nevada (ESN), and Central Arizona (CAZ). Within each region, one grid cell is chosen for which composite fields are calculated.

Anomaly patterns of Z500 at the two northern areas (COR and WMT) strongly resemble the grand composite, with a characteristic dipole anomaly arrangement and a transitional gradient apparent around both grid cells (Fig. 11a-b). In addition, the WMT composite strongly resembles the orientation of favorable 700-hPa height anomalies conducive to large lightning days in western Montana presented by Dettinger et al. (1999). COR and WMT composites agree with the pattern correlation maps in Fig. 6a for Z500, as higher r values are shown to concentrate in locations represented by these composites. These local composites therefore reflect the canonical upper-level circulation and surface pressure pattern associated with lightning outbreaks and wildfire ignition risk in the interior northwestern US. Conversely, Z500 anomaly patterns differ at the two southern regions (ESN and CAZ) compared to their northern counterparts (Fig. 11c-d), reflecting generally weaker pattern correlation present in these regions when compared with the grand composite. The southern grid cells do not show substantial negative Z500 anomalies southwestward, indicating that transient upper-level disturbances play a less important role in triggering convection in the southern half of the study domain. However, both locations show positive Z500 anomalies displaced northward in the local composites. While positive Z500 anomaly centers are placed further west when compared to COR and WMT, pattern commonality with grand composite is partially retained as

anomalous geopotential height rises northward relative to these locations appear to favor better convective dynamics.

Anomaly patterns of SLP at COR, WMT, and ESN agree well with the grand composite (Fig. 12), with negative anomalies present around the grid cell experiencing lightning and locations northwestward. The anomaly pattern at EAZ differs from the other three locations and from the grand composite (Fig. 12d), as positive SLP anomalies are found at the grid cell experiencing lightning reflecting the lower SLP pattern correlations found in this region in Fig. 6c. However, the north-northwestward orientation of increasingly negative SLP anomalies likely indicates the presence of south-southeasterly flow at CAZ in addition to COR and ESN on lightning days, suggesting moisture transport from sources located to the south and southeast of these locations.

3.3.2: Event Case Studies

Two select cases of active lightning days are provided in Fig. 13, representing the highest daily totals of CG flash counts over the 30-yr record when aggregated over the western and eastern portions of the domain, respectively. For areas of highest CG flash density in northeastern Oregon (Fig. 13a), arrangement of synoptic circulation anomalies on 5 September 2013 generally resembles the grand composites (Fig. 5a-b). Relative to these locations, a transitional gradient in Z500 anomalies is apparent, with positive anomalies to the northeast and negative anomalies to the southwest, along with negative SLP anomalies placed northwestward into southern British Columbia. The Z500 anomalies represented by this daily snapshot likely capture the optimal position of the

upper-level disturbance for generating convection as it transited the region. Anomalies of Z500 relative to areas of highest CG flash density in Arizona and Utah on 15 August 2003 (Fig. 13b) are explained by both the grand composite (Fig. 5a) and the CAZ composite (Fig. 11d), illustrating individual pattern variability on lightning days. While areas northeastward of these locations agree well with the grand composite in placement of strongest positive Z500 anomalies on 15 August 2003, the CAZ composite better captures this daily pattern in areas westward, where negative Z500 anomalies are absent. The anomaly pattern of SLP relative to these locations resembles the CAZ composite (Fig. 12d) in contrast to the grand composite (Fig. 5b), as positive anomalies are found in areas of highest CG flash density.

Chapter 4: Summary and Conclusions

We present a climatology of lightning seasonality, frequency, and spatial distribution across WUS utilizing a recent 30-year baseline (1988-2017). Further, we characterize the meteorological conditions associated with warm-season lightning days specific to the interior portions of this region. As continuous ground-based lightning detection only extends to the 1980s in WUS (Cummins and Murphy 2009; Dettinger et al. 1999), studies focusing on this region have been constrained to shorter lightning datasets, typically between 5 and 20 years in length. This study benefits from a longer period of available CG flash data, allowing for a more complete characterization of lightning climatology particularly in areas of infrequent lightning. Lightning is mainly a summertime phenomenon in the interior WUS, with annual CG flash density and number of lightning days increasing along a northwest to southeast gradient. General topographic enhancement of CG flash density is apparent throughout the domain, and is consistent with foundational studies which used much shorter available lightning datasets (e.g. Reap 1986).

Lightning days in the interior WUS are generally associated with positive Z500 anomalies displaced to the northeast of the location experiencing a lightning day with negative anomalies to the southwest, placing the lightning location in a transitional gradient on the synoptic scale. Z500 patterns are shown to be more transient preceding lightning activity in areas further north and in parts of the Central Rockies, with little pattern progression on preceding days in parts of the monsoonal core as well as interior California likely reflecting multi-day persistence of lightning activity. Negative SLP

anomalies are co-located and displaced northwest of the lightning location, indicating potential for upward vertical motion in the lower levels. Mid-level instability is also present in the grand composite average, as positive anomalies of L700500 show a similar spatial signature to negative SLP anomalies relative to each grid cell. In the interior WUS, northward displacement of mid- and upper-level ridging generally leads to increased moisture advection and vertical instability during the warm season, allowing for lightning activity regardless of latitude particularly in topographically-favored locations.

Analyzed fields generally reflect the regional divide between those areas under the direct influence of the summertime monsoon circulation, and those on the periphery. Synoptic circulation anomalies (Z500 and SLP) show greater amplitude in western and northern parts of the domain, expressed as higher RMSD values compared to grand composites. These areas also exhibit generally stronger pattern correlation with grand composites, although relatively high Z500 pattern correlation is also found in parts of the Southwest indicating preference for northward-displaced ridging. A north-south divide in SLP pattern correlation is evident across the domain, with lower correlation in the interior Southwest. It is probable that the SLP grand composite captures features more common to midlatitude locations including negative SLP anomalies co-located and extending northwestward of lightning location, features absent in core monsoonal areas (such as the central Arizona example in Figure 12d). On the monsoon periphery, thermodynamic indices experience episodic rises in association with lightning days, as both TQV and L700500 show substantially greater deviations from mean climatological values. In the

monsoonal core, weak L700500 anomalies do not reflect a preference for increased mid-level instability compared to mean climatological values. Likewise, standardized anomalies of TQV are only weakly positive in the monsoonal core when compared to the substantially larger departures from climatology in areas further north and west. W700 fields reflect the preferred regional circulation patterns described above. An easterly component is present across the southern periphery of the study area on lightning days, likely associated with a northward-displaced upper-level high pressure ridge promoting easterly flow in these areas. Locations to the north and west of the low desert regions show a strong preference for south-to-southwesterly flow on lightning days. Favorable dynamics are likely introduced through transient upper-level disturbances displacing ridging northeastward, allowing for increased moisture advection and mid-level instability sufficient for lightning activity in these areas.

While our findings generally reinforce the known mechanisms associated with lightning occurrence across WUS, our results offer a novel composite assessment of all interior WUS grid cells on lightning days. This comprehensive and spatially contiguous analysis helps identify commonalities in anomaly patterns relevant to the entire region such as northward-displaced positive Z500 anomalies, while highlighting regional differences. Aggregate metrics can be derived and applied to future climate model evaluation efforts, helping to understand possible future changes in lightning activity across this region. As metrics would be derived from a 30-year climatology compiled by this study, more confidence can be placed in the evaluation of climate model simulations of future climate baselines. As lightning is a triggering mechanism for wildfire ignition,

such efforts would carry important implications for possible changes to future wildfire regimes, in addition to changes in other thunderstorm-related impacts such as flash flooding.

Locations along transitional gradients of preferred anomaly patterns may be susceptible to changes in future lightning climatology resulting from relatively minor changes in associated meteorological variable fields, further necessitating the application of this work to projections of future climate change. Extension of this work may include compositing of regional anomaly patterns, with the goal of regional climate model evaluation on much finer geographic scales. Additionally, knowledge of preferred synoptic patterns on regional scales can be used to inform operational forecasting efforts to better predict lightning hazards. Both efforts would be especially useful in the context of differing lightning climatologies in areas which are affected by, or are on the periphery of, the summertime monsoon circulation across WUS, as well as locations strongly influenced by local topography.

Variable	Abbreviation	Units
500-hPa geopotential height	Z500	m
Sea level pressure	SLP	hPa
700-hPa wind direction	W700	°
700-500 hPa lapse rate	L700500	°C
<i>Total precipitable water vapor</i>	TQV	kg m ⁻²

Table 1. A summary of variables analyzed on lightning days. Variables represent anomalies relative to daily means, with the exception of W700. Italics denote standard deviation z scores are used.

Figure 1. An illustration of how the gridcell-relative composites are created: (top) map of Z500 anomalies associated with lightning days at the grid cell represented by the green marker. Only data within 2500 km of this grid cell is shaded. (bottom) The above data remapped onto the ‘gridcell-relative grid’ using polar coordinates on a unit circle, with origin set at this grid cell.

Figure 2. Spatial distribution of mean annual CG flash density (flashes $\text{km}^{-2} \text{yr}^{-1}$), for period 1988-2017. Note that values are plotted on logarithmic scale.

Figure 3. Seasonality of CG flash occurrence over WUS displayed as (a) peak month of CG flash density per 0.1° by 0.1° grid cell and (b) annual percentage of all days with at least one CG flash that occur during July - August at each grid cell.

Figure 4. Total number of days with ≥ 5 CG flashes (MJJAS, 1988-2017), per 0.1° by 0.1° grid cell. Only grid cells with at least 30 such days (shaded) in the western US are included in composite analysis. Note that values are plotted on logarithmic scale.

Figure 5. Grand composites of (a) Z500 and (b) SLP anomalies on lightning days for all 24,053 grid cells in the domain, averaged from composites centered on each grid cell (green marker). Contours indicate percentage of all grid cells that feature positive (solid) or negative (dashed) anomalies at those locations relative to each grid cell. Boxplots for (c) Z500 and (d) SLP show distributions of individual grid cell anomalies at the locations of anomaly peaks in the grand composites, with t -test results showing statistically significant difference between grand composite anomaly peaks.

Figure 6. Pearson correlation coefficients (left column) and root-mean-square deviation statistics (right column) between each grid cell's composite and the grand composite (see Fig. 5a-b) for Z500 (top row) and SLP (bottom row). Values to the right of the subtitles in left column represent the median pattern correlation coefficient between the grand composite and all individual grid cell composites in the study domain. In all subplots, values in red indicate high agreement on lightning days between the local grid cell composite pattern and the grand composite in sign (left column) or magnitude (right column).

Figure 7. Correlation coefficients between composite Z500 anomaly pattern on analyzed lightning day and composite anomaly patterns (a) three days, (b) two days and (c) one day prior at each grid cell, with values in red indicating high agreement between days. Values to the right of the subtitles represent the median pattern correlation coefficient across the domain for each two-day pairing.

Figure 8. Mean correlation coefficients of Z500 anomalies on lightning days within each grid cell's sample set, showing representativeness of local grid cell composite anomaly pattern for all grid cells. Value to the right of title represents the median pattern correlation coefficient of all grid cells.

Figure 9. 700-hPa wind direction on lightning days at each grid cell, displayed as (a) the dominant directional mode binned into 45-degree increments centered on the eight cardinal and intermediate compass bearings, and (b) the associated frequency percentages for the dominant mode specific to each grid cell. Gray colors in western Colorado indicate reanalysis grid cells where surface elevation is above the 700-hPa pressure level.

Figure 10. Grand composites of (a) TQV, representing atmospheric moisture content, and (b) L700500, representing mid-tropospheric lapse rate, on lightning days. Note that standard deviation departures are used for TQV. Dashed contours indicate 500-km radius used to subset the grand composites for computation of focal means for (c) TQV and (d) L700500.

Figure 11. Composites of Z500 for the four selected grid cells (green markers), with (a) Central Oregon and (b) Western Montana representing the northern half of the study domain, and (c) Eastern Sierra Nevada and (d) Central Arizona representing the southern half. Sample size of lightning days (n) is provided for each location. Statistically significant anomalies (p -value < 0.05) according to t -test are denoted by black contours.

Figure 12. As in Fig. 11, but for SLP.

Figure 13. Two case studies of active lightning days and associated Z500 (shaded) and SLP (contoured) anomaly patterns on those days. CG flash counts on 5 September 2013 (15 August 2003) were the highest daily totals in the 30-year record when aggregated over the western (eastern) portion of the domain. Note that lightning scales differ between subplots.

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