Research Article

Temporal and Spatial Distribution of Lightning Strikes in California in Relation to Large-Scale Weather Patterns

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ABSTRACT

The temporal and spatial distribution of lightning strikes varies across California and has a differential effect on lightning fire ignitions. We analyzed 16 years of lightning strike data obtained from the National Lightning Detection Network to determine how the distribution of lightning strikes was affected by geography, topography, and large-scale weather patterns. Although there were significant differences in the number and density of strikes among bioregions, the annual, monthly, and hourly patterns were similar. The number of strikes increased with elevation. Strike polarity varied by month, and mean peak positive current, mean peak negative current, and number of return strokes per strike varied by bioregion. Weather patterns associated with lightning included strengthened high pressure cells stationed over the western United States that deploy moist monsoon-like air masses and promote rising motions, especially over mountain features. Understanding the variation in lightning strike distributions provides insight into the role of fire in different bioregions of the state and aids in the prediction of wildland fire occurrence.

Keywords: California, lightning strikes, weather patterns, wildland fires

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INTRODUCTION

The role fire plays in an ecosystem is dependent on the simultaneous occurrence of an ignition source, sufficient fuel to carry the fire, and weather conditions conducive for burning. Lightning strikes are an important source of ignition for wildland fires in California and throughout the western US. Although lightning strikes are pervasive, their temporal and spatial distributions vary across the state and have differential effects on lightning fire ignitions. In addition, lightning strike characteristics such as polarity, maximum peak current, and number of return strokes vary over time and space.

These variations are influenced by geography, topography, and large-scale weather patterns. Information about the temporal and spatial distributions of lightning and the factors that affect those distributions is critical for predicting the occurrence of wildland fires and for understanding fire regimes.

Fire ecologists use fire regimes to describe the complex pattern of fire effects over long time periods, multiple fire events, and numerous ecosystem properties (Sugihara *et al*. 2006). A fire regime is defined according to attributes such as seasonality, fire return interval, size, spatial complexity, intensity, severity, and fire type. The timing and location of lightning has a direct effect on seasonality and an indirect effect on fire return interval, as less frequent lightning ignitions result in longer intervals between fires. Long return intervals lead to fuel accumulations that burn with greater intensity and produce more severe effects. Weather conditions compound the interaction between lightning ignitions and fuels, not only by producing different patterns of lightning occurrence but also by affecting fire behavior should an ignition occur.

California is a very diverse state geographically, topographically, and climatically. As a result, there are equally diverse vegetation types, weather patterns, and fire regimes. These variations are captured by bioregions, which are derived from the ecological sections and subsections described by Miles and Goudey (1997) (Figure 1). Part of the variation in fire regimes among bioregions might be attributed to differing patterns of lightning strikes.

Fires ignited by lightning have been a part of California's bioregions for millennia. For example, early evidence of the presence of fire in the Sierra Nevada can be seen in lake sediments over 16 000 years old in Yosemite National Park (Smith and Anderson 1992). Ignitions by Native Americans were also a source of fires, possibly as early as 9000 years ago (Hull and Moratto 1999). Although it is currently not possible to distinguish charcoal deposits or fire scars caused by lightning fires from those ignited by Native Americans, it is reasonable to assume that ignitions by Native Americans were significant but varied over the spectrum of inhabited landscapes (Vale 2002).

The 1910 fires that swept the western United States spurred an interest in lightning as a cause of forest fires. Plummer (1912) was one of the first to study the effects of lightning strikes on trees in the US. He concluded that trees do not differ in their susceptibility to lightning but do in their flammability, with only two percent of trees that were struck being ignited. In a study of thunderstorms and lightning fires in California, Palmer (1917) found that the number of lightning fires varied across the state, with the mountainous regions receiving more than the coastal regions. He attributed the difference to the prevalence of summer convection thunderstorms in the mountains as opposed to winter cyclonic

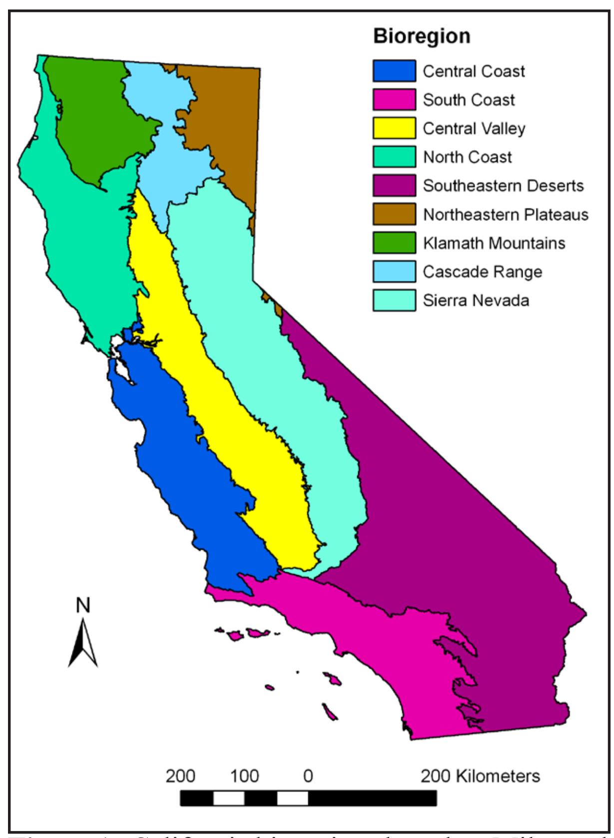

Figure 1. California bioregions based on Miles and Goudey (1997).

storms along the coast. Show and Kotok (1923) delineated lightning fire zones in California but only included areas where lightning had started fires that required action by Forest Service crews. The relationship between thunderstorm days and lightning fires was investigated by the Forest Service in the northwest and the Rocky Mountains (Morris 1934, Barrows 1954). Thunderstorm days include all days during which thunder from all strikes, not just cloud-to-ground strikes, occurs. Court (1960) conducted similar studies in California and found that weather station reports of thunderstorm activity were not a reliable index of the number of fires caused by lightning, with more fires relative to storms during the summer months.

Lightning strikes have several characteristics that affect their potential to start fires. Virtually all lightning comes from thunderstorms, which have a negative charge at the lower part of the cloud and a positive charge in the upper part (Fuquay 1980). Discharges occur within the cloud, between clouds, in the air, and between the cloud and the ground. Both negative and positive charges reach the ground and can start fires. Lightning strikes have discrete discharges called return strokes that consist of current surges that last only a few microseconds. Negative strikes can have one to several return strokes, while positive strikes usually have only one. Arnold (1964) reported that some surges had long continuing currents that lasted up to 1800 µs. Uman (1987) summarized our knowledge of lightning characteristics by stating that 90 % of all lightning strikes are negative and 10 % positive; that the average number of strokes is 3 to 4 per negative strike and 1 per positive strike; and that 20 % to 40 % of the negative strikes have long continuing currents as opposed to 50 % to 100 % for positive strikes.

In order to determine why all lightning strikes do not result in fire, Fuquay *et al.* (1967) and Fuquay *et al.* (1972) investigated the characteristics of 16 documented lightning discharges. Eleven of the discharges started fires, and each had a long continuing current phase of at least 400 µs. Although they were not able to determine the polarity of the 11 discharges, subsequent research indicated that positive strikes in summer thunderstorms were likely fire starters (Fuquay 1982). The mechanism for ignition of fuels by lightning was explored by Taylor (1974). He hypothesized that the relatively long electrical charge ignited a mixture of volatile extractives and fine debris into a fire ball or column, which then ignites the fine fuels. Fuquay (1980) concluded that the probability of igniting fuels was a function of current duration and independent of the current magnitude of the current flow. Latham and Schlieter (1989) simulated lightning discharges using an electrical arc source and determined that a long continuing current was the most important variable associated with igniting fuel samples.

Beginning in 1976, the Bureau of Land Management (BLM) operated a network of magnetic direction finding stations in the western US including Alaska (Krider *et al.* 1980, Graham *et al.* 1997). Fire managers received lightning data in near real time on the date, time, and location of all strikes detected by the stations. Nimchuk (1989) tested the accuracy of the system by comparing 350 observations of lightning that actually struck lookouts with the reported locations of those strikes. He determined that there was a detection efficiency of 79 % and a mean location error of 9.8 km and found that location error decreased as station density increased.

The National Lightning Detection Network (NLDN) began in 1987 when several regional networks were combined into a national system operated by a commercial vendor (Orville 2008). In 1997, the BLM system was integrated into an upgraded NLDN that combined magnetic direction-finding sensors with time-of-arrival technology throughout the US (Graham *et al.* 1997). In addition to date, time, and location, the combined system provided polarity, mean peak current in kiloamps (kA), and number of return strokes. Data from the national network were summarized for the United States by Orville (1991), Orville and Silver (1997), Orville and Huffines (1999), Orville *et al.* (2002), Zajac and Rutledge (2001), and Orville (2008). The availability of lightning detection technology created interest in lightning research in many countries around the world including Germany (Finke 1999), Finland (Larjavaara *et al.* 2005), Canada (Wierzchowski *et al.* 2002), Austria (Schulz *et al.* 2005), and Brazil (Saba *et al.* 2006).

In California, the original direction-finding system was used by van Wagtendonk (1991, 1993) to analyze spatial and temporal patterns of lightning strikes and fires in Yosemite National Park. The density of strikes was positively correlated to elevation, with the greatest percent of lightning strikes occurring between 2700 m and 3000 m elevation. However, the largest proportion of fires was ignited between 2100 m and 2400 m. He attributed this fact to a lack of fuels and poor burning conditions at the higher elevations. Wells and McKinsey (1995) found a similar correlation with elevation in San Diego County, California.

Many researchers took advantage of the new lightning detection technology to relate lightning occurrence to topography and weather patterns. In northeastern Colorado and central Florida, Lopez and Holle (1986) found that underlying topography and the associated diurnal circulations affected the time and place of lightning ground strikes. Reap (1986) analyzed over two million lightning strike locations in the western United States and determined that the hour of maximum lightning frequency was directly related to elevation and that maps of daily lightning activity were in agreement with thunderstorm climatologies. In Florida, Reap (1994) associated the temporal and spatial distribution of lightning activity with specific synoptic regimes of low-level wind flow using 18 h and 30 h sea level pressure forecasts. Lyons *et al.* (1998) used data from the NLDN to investigate the spatial distribution of large peak current cloud-to-ground lightning strikes and found that large positive strikes were most common in the high plains and upper midwest, while large negative strikes were most prevalent along the Gulf Coast and the southeastern United States. They attributed the presence of large peak current positive strikes to transient luminous events in the stratosphere.

There have been only a few studies relating lightning strikes to fire starts (Fuquay *et al.* 1972, Wierzchowski *et al*. 2002, Larjavaara *et al*. 2005). Rorig and Ferguson (1999) used thunderstorm occurrence, precipitation observations, and lightning strikes in the Pacific northwest to classify convective days as either dry or wet. Based on the classification and upper-air sounding data, they were able to determine that increased low-level moisture (e.g., dew point at 850 hPa) and higher instability (e.g., temperature difference between 850 hPa and 500 hPa) would indicate days that were more conducive for lightning-ignited fires. They used the same criteria during the 2000 fire season in the Pacific northwest and the northern Rockies and found that the number of lightning-caused fires corresponded more closely to high instability and high dew point than the total number of lightning strikes (Rorig and Ferguson 2002).

The role of lightning-caused fires could change under different climate change scenarios. For example, Price and Rind (1991) analyzed a global climate model that was run under doubled pre-industrial CO_2 levels and found that, in association with increased global air temperatures of 4 ºC, global mean lightning activity increased by 26 %. Coupled with the increased temperatures, Price and Rind (1994) estimated that these lightning strikes would ignite 44 % more fires and burn 78 % more area than under current conditions. Recent observational evidence indicates that, since the mid-1980s, warmer spring and summer temperatures have caused earlier snowmelt and drier landscapes and thus have allowed wildfires to start earlier, last longer, and become larger in middle elevation forests of the western United States (Westerling *et al*. 2006). Understanding the current distribution of lightning in California should provide a basis for predicting future wildland fire occurrence and behavior.

In this study, we examined data for cloud-to-ground lightning strikes occurring in California during the years from 1985 through 2000. Our objective was to determine the effect of geography, topography, and large-scale weather patterns on the temporal and spatial distribution of lightning strikes and lightning strike characteristics.

METHODS

Study Area

The bioregions of California have diverse topography, vegetation types, weather patterns, and fire regimes (Figure 1). The North Coast bioregion has numerous valleys and steep coastal and interior mountains, which contain large circulation and moisture gradients in response to numerous winter and infrequent summer storms. Although fire is infrequent in the North Coast bioregion, particularly in the moist coastal conifer forests, nearly annual burning by Native Americans occurred historically in grasslands and oak woodlands (Stuart and Stephens 2006). The Klamath Mountains bioregion comprises a complex group of mountain ranges and a diverse flora. Fires in the Klamath Mountains were frequent and of low to moderate intensity (Skinner *et al*. 2006). Tall volcanoes and extensive lava flows characterize the Southern Cascades and Northeastern Plateau bioregions. The fire regimes of the Southern Cascades consist of frequent low to moderate intensity surface fires (Skinner and Taylor 2006). Within the Northeastern Plateaus bioregion, fire regimes vary with vegetation; frequent low intensity fires in pine stands and less frequent moderate intensity fires in sage shrub steppe (Riegel *et al*. 2006). Immediately south of the Cascades is the Sierra Nevada bioregion, which rises to over 4400 m and extends nearly half the length of the state. This gradient of elevation and latitude is manifested in a variety of vegetation types and fire regimes from recurrent fires in foothill woodlands and montane forests to return intervals of over 1000 yr in subalpine forests (van Wagtendonk and Fites-Kaufman 2006).

The Sacramento and San Joaquin rivers flow through broad interior valleys with extensive, nearly flat alluvial floors that constitute the Central Valley bioregion. The flat terrain, abundant dry grasses, and high densities of Native Americans indicate that fires could have burned every one to three years historically (Wills 2006). Coastal valleys and mountains and interior mountains are also typical of the Central Coast bioregion. Burning by Native Americans along the central coast shortened fire return intervals in grasslands and adjacent forests (Davis and Borchert 2006). Southern California, with its coastal valleys and the prominent Transverse and Peninsular ranges, are included in the South Coast bioregion. Before human occupancy, shrublands in the bioregion burned when occasional late summer lightning fires persisted into the fall and were spread by foehn winds, while montane forests burned more frequently (Keeley 2006). The vast southeast corner of California constitutes the Southeastern Desert bioregion. Fires were infrequent in the deserts because fuels were discontinuous and sparse (Brooks and Minnich 2006).

Lightning Data

We obtained the lightning data for the years 1985 through 2000 from the National Lightning Detection Network and reformatted them for use in a geographic information system (GIS). The 1985-1996 data were from the original BLM system and included date, time, and location. The 1997-2000 data came from the new sensors of the NLDN and, in addition, included polarity, mean peak current, and number of return strokes. The locations of the NLDN sensors that detect lightning strikes in California are shown in Figure 2. The new system achieved detection efficiencies of 80 % to 90 % and location accuracies of 0.5 km over most of the United States. In addition, the new sensors achieved maximum network-relative detection efficiency, defined as the ratio of the number of strokes detected by a sensor to the total number of strokes detected by the network, when sensors were located from 275 km to 325 km apart (Cummins *et al.* 1998). The network-relative detection efficiency for locations in California is shown in Figure 2. We used the bioregion map to remove the strikes that did not occur within California before summarizing the total number of strikes

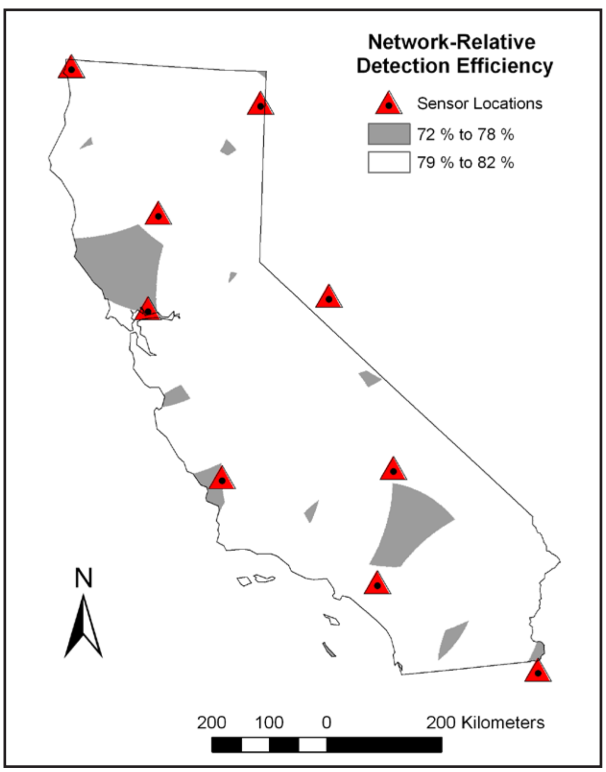

Figure 2. Sensor locations and network-relative detection efficiency, defined as the ratio of the number of strokes detected by a sensor to the total number of strokes detected by the network, in California.

by bioregion, year, month, and hour. For the spatial analyses, we summarized the total number of strikes that occurred within 600 m elevation bands and subsections as defined by Miles and Goudey (1997). We calculated density using a cell size of 5 km and a search radius of 33 km, and we expressed the densities in terms of number of strikes per year per 100 square kilometers. We summarized lightning characteristics by month and bioregion.

Weather Data

To explore how the variation in lightning strikes was influenced by large scale weather patterns, we examined atmospheric circulation over the North Pacific and western North America during months having relatively high or relatively low numbers of strikes. We narrowed our analysis to the four subsections that represented a selection of the diverse regional landscapes and geographic range of California: the high elevation East Franciscan mountain portion of the North Coast, Markleeville in the eastern Sierra Nevada, Ivanpah Valley in the Southeastern Deserts, and the San Jacinto Mountains in the South Coast bioregions (Miles and Goudey 1997). We averaged the 700 hPa height anomaly patterns from each of the 16 summer (June, July, August and September) months within the 1985 through 2000 period having the highest number of strikes and, analogously, from the 16 summer months within this period having the lowest number of strikes in those subsections. The number of strikes during the later period of new lightning sensors (after 1996) was adjusted by a scale factor to normalize the increase in the number of strikes during this period compared to the number in the early (1985-1996) period of the original lightning detectors. The scale factor was set to the number, per year, of strikes in the early period divided by the number of strikes in the later, post-1996 period. The specific anomalies we examined during high lightning episodes were geopotential height, vertical velocity, and precipitable water. Geopotential height is the distance in meters from sea-level to a given pressure surface in the atmosphere. The 700 hPa height anomaly was used here as an indicator of where high and low pressure systems are occurring and also describes the atmospheric flow pattern in the lower troposphere at an altitude of approximately 3000 m. Because vertical velocity is difficult to measure directly, it is diagnosed from the spatial structure of the geopotential height patterns, via the omega equation (Holton 1972). Precipitable water is the total atmospheric water vapor contained in a vertical column of unit cross-sectional area extending from the surface to the top of the atmosphere, expressed as the height to which that water vapor would stand if completely condensed and collected over same unit cross section (Huschke 1989). Because most of the atmospheric water vapor occurs within the first 3 km or so of the surface, a positive anomaly of precipitable water generally is indicative of enhanced moisture in the lower atmosphere.

RESULTS

Over one million lightning strikes were detected during the 16 years of the study; 656 384 from 1985 through 1996 and 349 847 from 1997 through 2000. We will first present the temporal and spatial distribution of those strikes and their characteristics, and then the corresponding weather patterns.

Temporal Distribution

The annual number of lightning strikes in California for the 16 yr period ranged from 31 650 in 1985 to 115 573 in 1998 (Table 1). However, detection efficiencies before 1997 were less because the sensors had only

Table 1. Number of lightning strikes by year and bioregion in California, 1985 through 2000.

Year	North Coast	Klamath Mountains	Cascade Range	Northeast Plateaus	Sierra Nevada	Central Valley	Central Coast	South Coast	Southeast Deserts	Total
1985	327	3 800	1 070	2 345	8 323	832	274	1 270	13 409	31 650
1986	412	1 972	3 609	5 554	10 438	1 504	332	2 317	27 352	53 490
1987	539	1 550	2 788	4 241	12 963	2 705	645	4 551	26 880	56 862
1988	517	1 692	4 326	7 432	24 435	3 863	3 993	4 610	56 739	107 607
1989	3 049	2 080	3 095	2 622	16 554	6 355	845	1 286	23 169	59 055
1990	2 193	5 331	6 586	6 445	21 594	2 405	2 110	4 405	33 563	84 632
1991	578	4 069	5 680	6 736	14 262	1 589	1 670	4 676	27 476	66 736
1992	1 237	5 944	6 206	5 614	15 585	1 385	698	6 999	35 912	79 580
1993	350	1 437	1 796	2 715	3 431	1 184	195	1 575	8 985	21 668
1994	471	2 341	2 901	4 064	6 407	1 550	703	2 577	13 439	34 453
1995	614	2 626	2 566	1 985	6 399	1 048	221	1 691	9 094	26 244
1996	287	2 759	3 486	4 936	9 668	880	241	1 424	10 726	34 407
1997	1 175	2 663	5 744	5 375	13 186	2 413	1 452	4 373	33 155	69 536
1998	1 761	3 311	4 897	7 848	19 465	3 771	1 814	10 553	62 153	115 573
1999	1 546	1 782	2 236	3 025	13 029	2 281	2 815	9 512	62 674	98 900
2000	474	2 830	1 574	2 250	14 538	1 423	256	6 546	35 947	65 838
Total	15 530	46 187	58 560	73 187	210 277	35 188	18 264	68 365	480 673	1 006 231

direction finding capability. The annual pattern among bioregions was relatively consistent, although the Klamath Mountains showed a decrease between 1985 and 1987 while other bioregions showed increases (Figure 3). The Central Valley had less annual variation than the other bioregions.

Statewide, most lightning occurred during August with the least lightning occurring during December (Table 2). There was variation among the bioregions, with the monthly peak occurring in July in the Klamath Mountains, Cascade Range, and Northeastern Plateaus. September was the peak month in the Central Valley and Central Coast bioregions. All bioregions followed the same general monthly pattern with the exception of the Central Coast and Central Valley. They had a decrease in the number of lightning strikes during July and August (Figure 4).

The peak hour for lightning strikes statewide was between 1600 PST and 1700 PST, while the lowest was between midnight and 0100 PST (Table 3). The earliest peak was in the South Coast bioregion at 1400 PST and the latest was in the Cascade Range bioregion at 1800 PST. All bioregions followed the same pattern with low lightning occurrence during the morning hours, afternoon peaks, and evening subsidence (Figure 5).

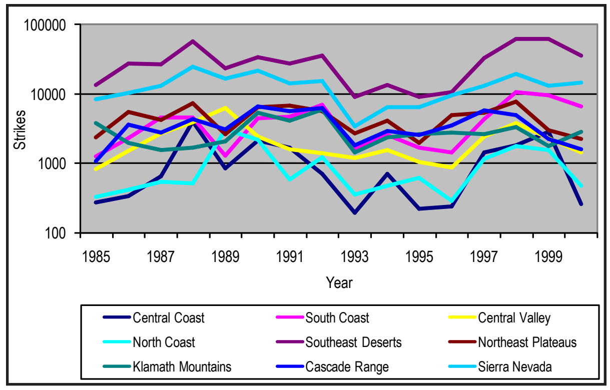

Figure 3. Number of lightning strikes by year and bioregion in California, 1985 through 2000. There is substantial year-to-year variation in the number of lightning strikes.

Spatial Distribution

Although the Southeastern Deserts bioregion received the greatest number of

Table 2. Number of lightning strikes by month and bioregion in California, 1985 through 2000.

Month	North Coast	Klamath Mountains	Cascade Range	Northeast Plateaus	Sierra Nevada	Central Valley	Central Coast	South Coast	Southeast Deserts	Total
January	436	184	213	18	729	469	169	496	218	2 932
February	446	296	203	47	836	880	432	1 650	3 220	8 010
March	424	788	697	382	2 778	2 708	946	1 682	7 317	17 722
April	389	2 460	2 114	1 812	4 034	1 333	292	1 376	5 152	18 962
May	691	3 896	6 034	6 535	18 683	3 126	964	4 649	29 074	73 652
June	3 121	10 178	13 451	17 119	33 275	7 059	4 166	1 685	33 069	123 123
July	2 633	15 676	15 591	22 618	58 132	3 409	1 099	15 303	109 430	243 891
August	2 774	6 941	11 715	18 284	56 124	4 495	1 055	21 188	186 021	308 597
September	3 554	4 942	7 173	5 785	25 564	7 589	8 356	15 960	80 725	159 648
October	412	595	1 150	548	7 902	2 879	437	3 319	21 257	38 499
November	297	138	190	24	2 005	1 016	202	745	4 774	9 391
December	353	93	29	15	215	225	146	312	416	1 804
Total	15 530	46 187	58 560	73 187	210 277	35 188	18 264	68 365	480 673	1 006 231

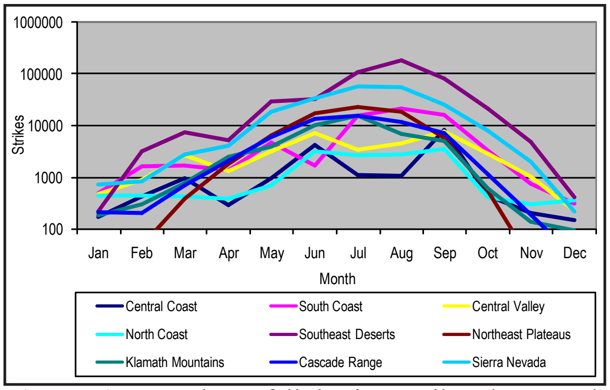

Figure 4. Number of lightning strikes by month and bioregion in California, 1985 through 2000. The monthly pattern is consistent with more strikes occurring during the summer months than during the winter months.

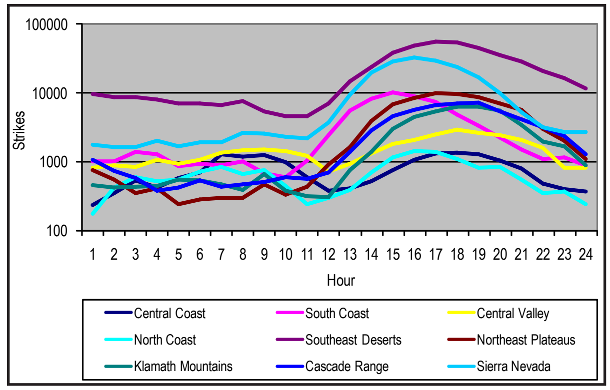

Figure 5. Number of lightning strikes by hour and bioregion in California, 1985 through 2000. The number of strikes peaked in all bioregions from mid to late afternoon. Hour denotes Pacific Standard Time.

Table 3. Number of lightning strikes by hour and bioregion in California, 1985 through 2000.

Hour	North Coast	Klamath Mountains	Cascade Range	Northeast Plateaus	Sierra Nevada	Central Valley	Central Coast	South Coast	Southeast Deserts	Total
0000-0059	174	457	1 054	759	1 752	822	234	999	9 663	15 914
0100-0159	423	416	741	553	1 609	891	350	1 021	8 669	14 673
0200-0259	597	426	573	345	1 642	834	539	1 379	8 630	14 965
0300-0359	523	438	377	406	2 000	1 060	417	1 265	8 086	14 572
0400-0459	552	550	416	238	1 687	941	571	853	6 990	12 798
0500-0559	722	530	527	285	1 885	1 078	701	937	7 030	13 695
0600-0659	836	473	426	296	1 884	1 343	1 287	881	6 717	14 143
0700-0759	659	390	468	295	2 636	1 446	1 196	1 009	7 667	15 766
0800-0859	761	655	504	466	2 571	1 499	1 256	682	5 421	13 815
0900-0959	438	376	595	328	2 299	1 442	993	586	4 625	11 682
1000-1059	239	314	555	428	2 202	1 224	599	1 038	4 622	11 221
1100-1159	297	302	700	908	3 662	723	376	2 429	6 999	16 396
1200-1259	390	763	1 394	1 636	9 403	930	413	5 525	14 803	35 257
1300-1359	697	1 393	2 825	3 879	19 585	1 313	519	8 218	23 984	62 413
1400-1459	1 146	2 961	4 559	6 779	28 992	1 800	749	10 090	38 167	95 243
1500-1559	1 440	4 456	5 684	8 499	32 332	2 088	1 055	8 956	48 825	113 335
1600-1659	1 373	5 343	6 610	9 910	29 577	2 520	1 307	7 398	56 423	120 461
1700-1759	1 093	6 272	7 098	9 730	24 075	2 913	1 350	4 865	54 455	111 851
1800-1859	824	6 265	7 141	8 728	16 766	2 640	1 284	3 361	45 578	92 587
1900-1959	836	5 524	5 408	6 951	9 891	2 431	1 038	2 248	35 753	70 080
2000-2059	552	3 413	4 096	5 604	5 308	2 044	796	1 509	28 653	51 975
2100-2159	352	1 938	3 202	3 033	3 145	1 579	475	1 088	20 885	35 697
2200-2259	363	1 654	2 330	2 029	2 677	822	395	1 148	16 519	27 937
2300-2359	243	878	1 277	1 102	2 697	805	364	880	11 509	19 755
Total	15 530	46 187	58 560	73 187	210 277	35 188	18 264	68 365	480 673	1 006 231

lightning strikes, it is also the largest bioregion, resulting in a density of 27.34 strikes yr^{-1} 100^{-1} km^{-2}. The Central Coast and the North Coast had the lowest densities with 2.96 and 2.97 strikes yr^{-1} 100^{-1} km^{-2}, respectively. The spatial distribution of lightning strike density across the state is shown in Figure 6. Within the Southeastern Deserts bioregion, the highest densities occurred near its boundaries with Nevada and Arizona, reaching to nearly 40 strikes yr^{-1} 100^{-1} km^{-2}. The Sierra Nevada and Northeastern Plateaus bioregions have areas with similarly high densities. Coastal bioregions and the Central Valley generally had densities below 5 strikes yr^{-1} 100^{-1} km^{-2}.

The density of lightning strikes increased with elevation up to a point before decreasing slightly in all bioregions (Table 4). The elevation zone in which the maximum strike density occurred varied by bioregion. For most bioregions, there was a significant drop-off in strike density above 1800 m. In the Northeastern Plateaus bioregion, the drop-off occurred above 2400 m and in the Sierra Nevada bioregion above 3000 m.

The two most heavily struck subsections in each bioregion are listed in Table 5. Within

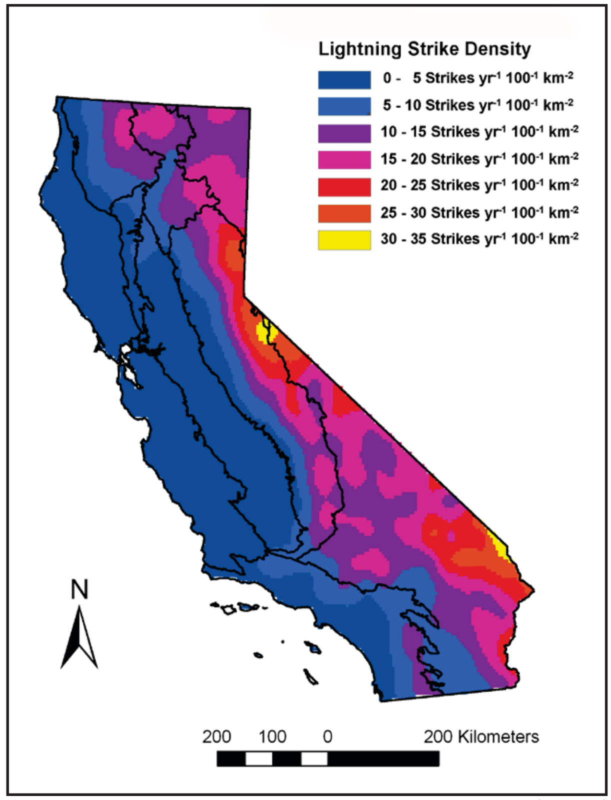

Figure 6. Lightning strike density (strikes yr^{-1} 100^{-1} km^{-2}) in California, 1985 through 2000. Lightning density increased from coastal and valley bioregions to the mountains and deserts.

Table 4. Number of lightning strikes by 600 m elevation zones and bioregion in California, 1985 through 2000.

Elevation (m)	North Coast	Klamath Mountains	Cascade Range	Northeast Plateaus	Sierra Nevada	Central Valley	Central Coast	South Coast	Southeast Deserts	Total
-86 to -1	0	0	0	0	0	0	0	0	8 739	8 739
0 to 599	5 829	2 353	2 845	0	7 092	32 043	8 697	12 274	100 254	171 387
600 to 1 199	5 698	19 300	9 698	0	17 542	3 095	8 632	20 013	213 966	298 807
1 200 to 1 799	3 231	18 247	28 206	863	41 280	50	934	24 011	97 358	264 844
1 800 to 2 399	772	6 109	17 123	51 527	64 544	0	1	9 012	37 386	154 813
2 400 to 2 999	0	178	543	19 866	48 872	0	0	2 756	18 511	71 789
3 000 to 3 599	0	0	107	929	25 965	0	0	299	3 729	30 102
3 600 to 4 199	0	0	35	2	4 958	0	0	0	720	5 713
4 200 to 4 418	0	0	3	0	24	0	0	0	10	27
Total	15 530	46 187	58 560	73 187	210 277	35 188	18 264	68 365	480 673	1 006 231

Table 5. Number of lightning strikes, area, and strike density for two most heavily struck subsections (Miles and Goudey 1997) within each bioregion in California, 1985 through 2000.

Bioregion Subsection	Area	Strikes	Density
	km^2	no.	# yr^{-1} 100^{-1} km^{-2}
North Coast			
Eastern Franciscan	5 070.45	4 919	6
Central Franciscan	491.82	422	5
Klamath Mountains			
Duzel Rock	786.67	3 589	29
Scott Valley	313.73	1 041	21
Cascade Range			
Blacks Mountain	1 796.33	7 666	27
Butte Valley	304.45	1 157	24
Northeastern Plateaus			
Pine Nut Mountains	216.34	1 570	45
Antelope – Mason V.	81.72	580	44
Sierra Nevada			
Markleeville	779.95	6 211	50
Glaciated Batholith	1 838.13	13 018	44
Central Valley			
Northern East Terraces	320.43	661	13
Tehama Terraces	2 956.63	4 262	9
Central Coast			
Caliente Range	1 452.32	1 309	6
Santa Lucia Range	4 976.46	2 991	4
South Coast			
San Gorgonio Mts.	933.82	4 299	29
San Jacinto Mts.	756.07	3 386	28
Southeastern Deserts			
Ivanpah Valley	1 632.37	10 424	54
Sweetwater Mts.	1 763.30	7 040	49

the North Coast bioregion, the subsections of the northern Coast Ranges received the greatest amount of lightning, while the central core of the Klamath Mountains bioregion had the highest density. A mountain valley and a volcanic mountain plateau were the most heavily hit subsections in the Cascade Range, as were two valleys and a mountain range near the Nevada boundary in the Northeastern Plateaus bioregion. Subsections just north of Lake Tahoe and along and immediately east of the crest of the Sierra Nevada had some of the highest lightning densities in the state. Within the Central Valley, the northern end of the valley and the terraces to the west and east had two to three times as many strikes per area than the rest of the bioregion. The interior mountains and valleys were struck most often in the Central Coast bioregion, which had the least lightning in the state. The Transverse Ranges had the highest lightning density in the South Coast bioregion; up to five times as much as the coastal subsections. The Southeastern Deserts bioregion received more lightning than any other part of the state, and two valleys in the Mojave Desert had the highest densities in the bioregion.

Strike Characteristics

Lightning strike characteristics for the years from 1997 through 2000 varied by month and by bioregion. Negative strikes comprised 93.4 % of the total and were most prevalent during August. The number of positive strikes reached their peak during September, but the greatest proportion of positive to negative strikes occurred in November. The mean peak current for positive strikes was greater during the winter months, while the mean peak current for negative strikes remained relatively constant throughout the year. The average number of return strokes for positive strikes during the 4 yr period was 1.08, and there was little variation among months. Over 93 % of the positive strikes had only one return stroke, and the maximum number was 10 (Table 6). Negative strikes averaged 1.63 strokes per strike and varied from 1.26 strokes in January to 1.94 strokes in July. Single return strokes comprised 57.2 % of the negative strikes, and the maximum number of negative return strokes was 15.

Table 6. Number of strokes per strike and percent of strikes by polarity in California, 1997 through 2000.

Strokes	Positive Strikes	Positive %	Negative Strikes	Negative %
1	21 541	93.5	187 073	57.2
2	1 232	5.3	71 394	21.8
3	177	0.8	33 859	10.4
4	48	0.2	16 980	5.2
5	24	0.1	8 614	2.6
6	6	0.0	4 560	1.4
7	5	0.0	2 315	0.7
8	2	0.0	1 189	0.4
9	0	0.0	618	0.2
10	1	0.0	91	0.0
11	0	0.0	61	0.0
12	0	0.0	26	0.0
13	0	0.0	16	0.0
14	0	0.0	7	0.0
15	0	0.0	6	0.0
Total	23 036	100.0	326 811	100.0

The Sierra Nevada had the greatest proportion of positive strikes averaging 2.37 strikes yr^{-1} 100^{-1} km^{-2} (Table 7). Negative strikes were most prevalent in the Southeastern Deserts with 42.57 strikes yr^{-1} 100^{-1} km^{-2}, more than twice the density of any other bioregion. The spatial distribution of mean peak currents varied across the state. Mean peak positive currents were highest in the coastal and valley bioregions and were lowest in the mountain and desert bioregions. The North Coast had the highest and the Southeastern Deserts had the lowest mean maximum peak positive currents. This pattern repeats for mean maximum peak negative currents, but with a greater preponderance of low currents. The North Coast and the Southeastern Deserts had the highest and the lowest peak negative currents. There was no apparent pattern to the spatial distribution of the number of return strokes for negative strikes, although the mountain and desert bioregions had conspicuously more return strokes than the coastal and valley bioregions. The mean number of positive return strokes ranged from 1.05 for the North Coast bioregion to 1.93 for the Sierra Nevada.

Weather Patterns

Within the four subsections we examined for weather patterns, lightning strike occurrence varied significantly from year to year. The summer total number of lightning strikes has ranged by more than a factor of ten across

Table 7. Total number of strikes, percent of strikes, and number of strikes per year per 100 km^2 by polarity and bioregion in California, 1997 through 2000.

Bioregion	Positive Strikes	Positive %	Positive # yr^{-1} 100^{-1} km^{-2}	Positive Strokes	Negative Strikes	Negative %	Negative # yr^{-1} 100^{-1} km^{-2}	Negative Strokes	Total strikes
North Coast	847	17.1	0.65	1.05	4 109	82.9	3.15	1.67	4 956
Klamath Mts.	1 118	10.6	1.24	1.08	9 468	89.4	10.50	1.63	10 586
Cascade Range	1 460	10.1	1.88	1.08	12 991	89.9	16.69	1.69	14 451
NE Plateaus	1 466	8.2	1.80	1.06	16 487	91.8	20.26	1.78	17 953
Sierra Nevada	6 369	10.6	2.37	1.09	53 849	89.4	20.07	1.92	60 218
Central Valley	2 044	10.7	0.90	1.11	7 844	79.3	3.47	1.71	9 888
Central Coast	773	11.4	0.50	1.10	6 025	88.6	3.91	1.76	6 798
South Coast	1 615	5.3	0.96	1.07	28 908	94.7	17.20	1.75	30 523
SE Deserts	7 344	3.8	1.67	1.08	187 130	96.2	42.57	1.88	194 474
Total	23 036	6.6	1.41	1.08	326 811	93.4	19.97	1.85	349 847

the 16 yr of the analysis. The range was even greater during monthly intervals within the summer, with some months having essentially zero strikes and some having several hundred. Year to year variability was very similar across the four subsections, especially between the subsections in the Sierra Nevada and the Mojave Desert. The same patterns of high and low occurrence exist to some extent among all four subsections.

The 700 hPa geopotential height pattern corresponding to high summer lightning strike months, shown in Figure 7a, illustrates the strong influence of west-to-east flow into California from the North Pacific. In addition, there is a tendency for air to flow from the southeast, south, and southwest around the periphery of the high pressure system stationed over the southern tier of the United States. The patterns from the south and southeast are monsoon or monsoon-like flow patterns. The associated mean precipitable water pattern for these months, shown in Figure 7b, illustrates the low moisture levels within the region and the adjacent eastern North Pacific. Substantial moisture levels, and likely sources of moisture that support lightning strikes, are found to the south and to the east of California.

The 700 hPa height and precipitable water patterns shown in Figure 7 are the mean of monthly patterns. Because lightning occurs infrequently, these do not differ too much from the overall average geopotential and precipitable water fields. However, there are important differences that are brought out in the composite anomaly maps. The anomaly composite patterns for 700 hPa geopotential height are shown in Figure 8, wherein locations having anomalies that depart significantly from the null hypothesis of a two-tailed t-test at the 0.05 % level are indicated by the stippled area. In general, these patterns reveal that anomalously high or low lightning activity within each of the four subsections is set up by super-regional circulation patterns that extend well beyond California. In comparing the anomalous flow for each of the subsections, some striking differences and some strong similarities emerge. The 700 hPa geopotential height anomalies associated with summer months having high numbers of lightning strikes in the North Coast bioregion features a broad negative anomaly center to the south and positive anomalies to the north of the region, which would produce anomalous flow from the south and east. As shown by the precipitable

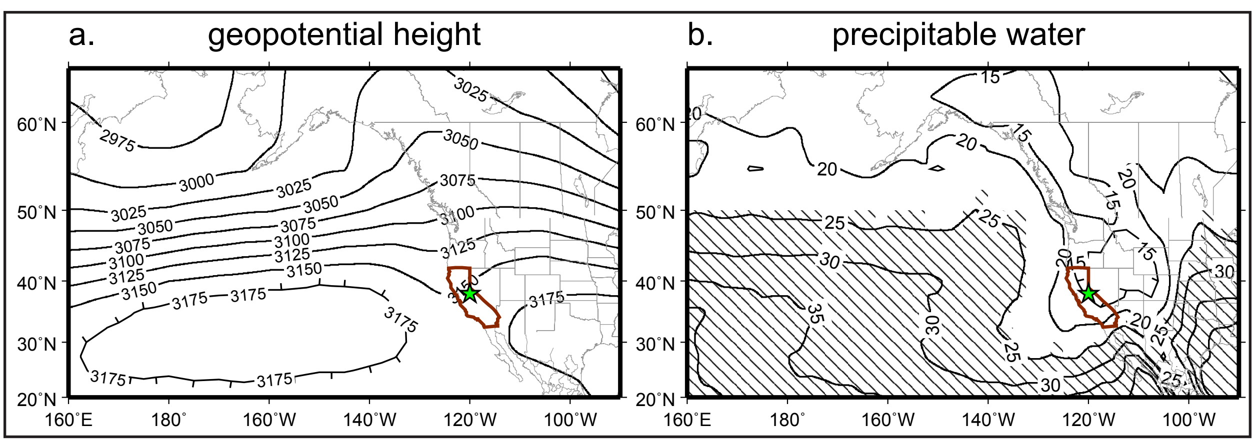

Figure 7. (a) The 700 mbar geopotential height (m) pattern corresponding to the 16 months with highest lightning occurrence from June, July, August, and September months, 1985-2000. The geostrophic flow represented by this pattern illustrates the strong influence of west-to-east flow into California from the North Pacific, and also more subtle northward flow around subtropical high centered over Gulf Coast US. (b) The associated mean precipitable water (Kg m^{-2}) pattern for these high lightning occurrence summer months. The stars indicate the location of the Sierra Nevada bioregion.

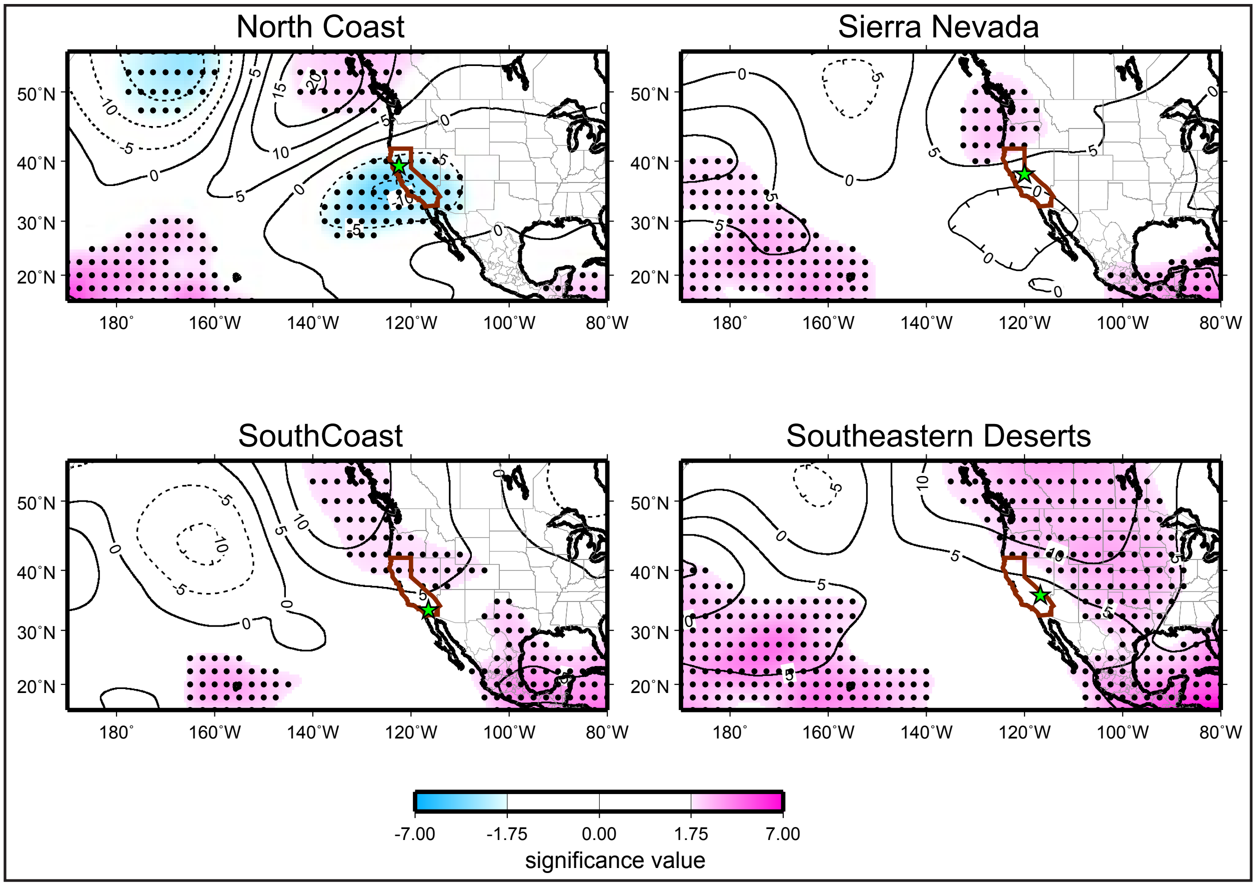

Figure 8. Composite 700 hPa geopotential height (m) anomalies for the 16 months with highest lightning occurrence during June, July, August, and September months, 1985-2000. Locations whose t values meet or exceed the 95 % significance level are designated by black stippling, and significance level is indicated by color scale. The stars indicate the locations of the selected bioregion subsections.

water anomalies, this circulation pattern produces higher than normal moisture over the north coast mountain region. Months with high numbers of lightning occurrences in Sierra Nevada are accentuated when anomalously high geopotential heights were positioned over the Pacific northwest; those with high numbers of lightning strikes in the Mojave region are associated with a broad center of anomalously high geopotential heights over the northwest and the intermountain west, and those with high numbers of lightning strikes in the southern California San Jacinto Mountain region are associated with positive 700 hPa height anomalies extending from the Pacific northwest down to the central California and Nevada. These anomalous high pressure (positive anomalies) patterns are symptomatic of warm temperatures and a circulation that carries moist air from the south or southeast into the Southeastern Deserts or Sierra Nevada bioregions. Each of these patterns minimizes the onshore movement of dry north Pacific air masses into California. Because these maps are a composite of monthly average conditions, it would be expected that the patterns described would be accentuated during the shorter periods (a few days) when lightning events are taking place.

Figure 9 is a set of composite maps of the anomalous atmospheric precipitable water during the 16 high lightning months that reveal heightened moisture content during the same high lightning periods. For the North Coast bioregion, a moderate, local center of above normal moisture is found over the region, but

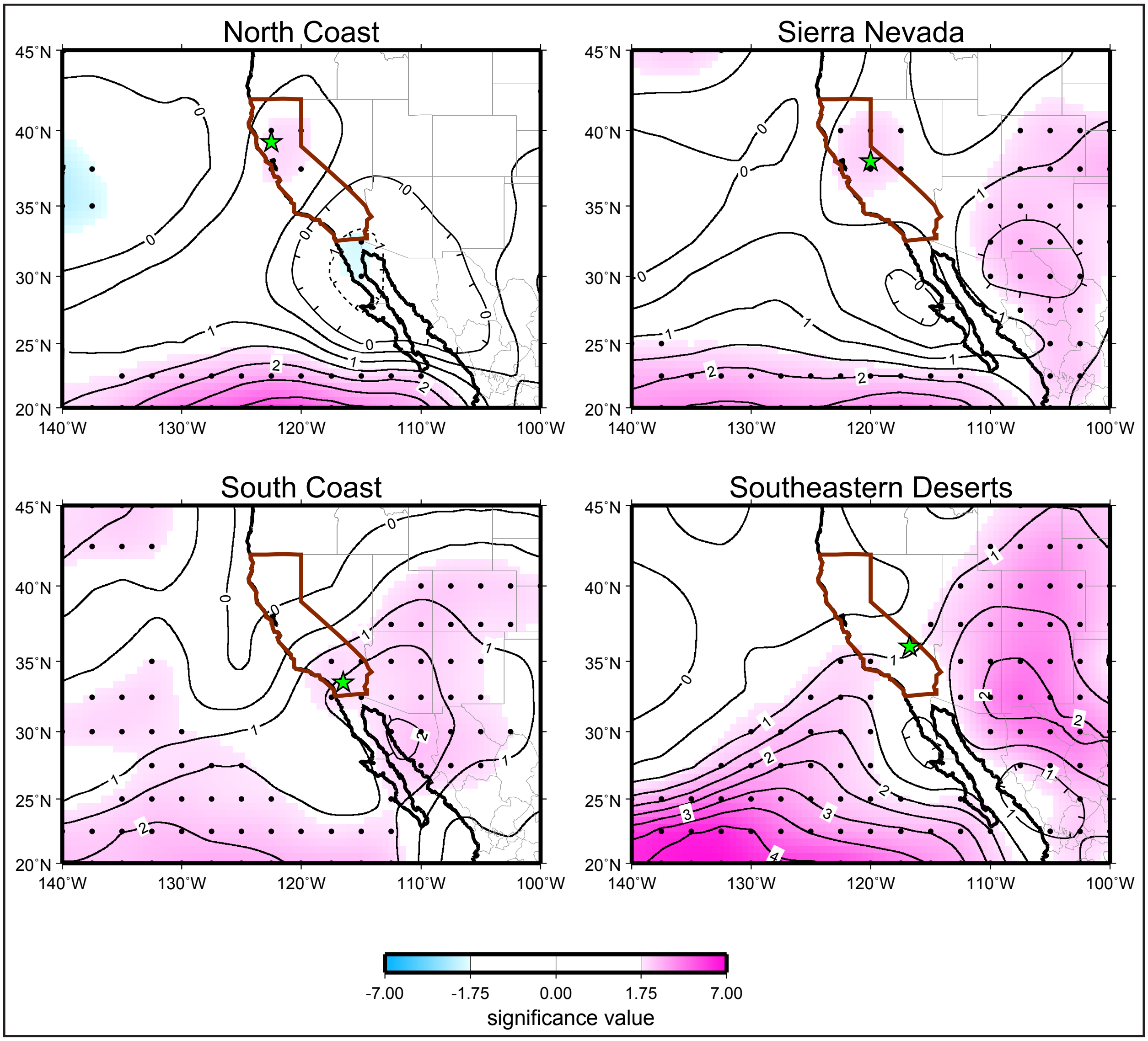

Figure 9. Composite precipitable water (Kg m^{-2}) anomalies for the 16 months with highest lightning occurrence during June, July, August, and September months, 1985-2000. Locations whose t values meet or exceed the 95 % significance level are designated by black stippling, and significance level is indicated by color scale. The stars indicate the locations of the selected bioregion subsections.

the configuration of the precipitable composite suggests that this enhanced moisture may be the northward portion of a plume that was carried up from the lower latitude North Pacific. A broad tongue of anomalously high humidity extends into the Sierra Nevada from sources to the east and south of the range. The Southeastern Deserts pattern is a similar but even stronger southwest monsoon pattern, and also contains an extensive region of positive moisture anomalies that extends into the region from the southwest. The composite pattern for the South Coast bioregion is very similar to that for the Southeastern Deserts but not as strong, suggesting that different circulation types may be mixed into the composite.

There is also a strong tendency for increased upward motion (negative omega) in each of the regions during months with high levels of lightning strikes, as indicated by the composite vertical velocity mapped in Figure 10. Each of the composites contains a broad

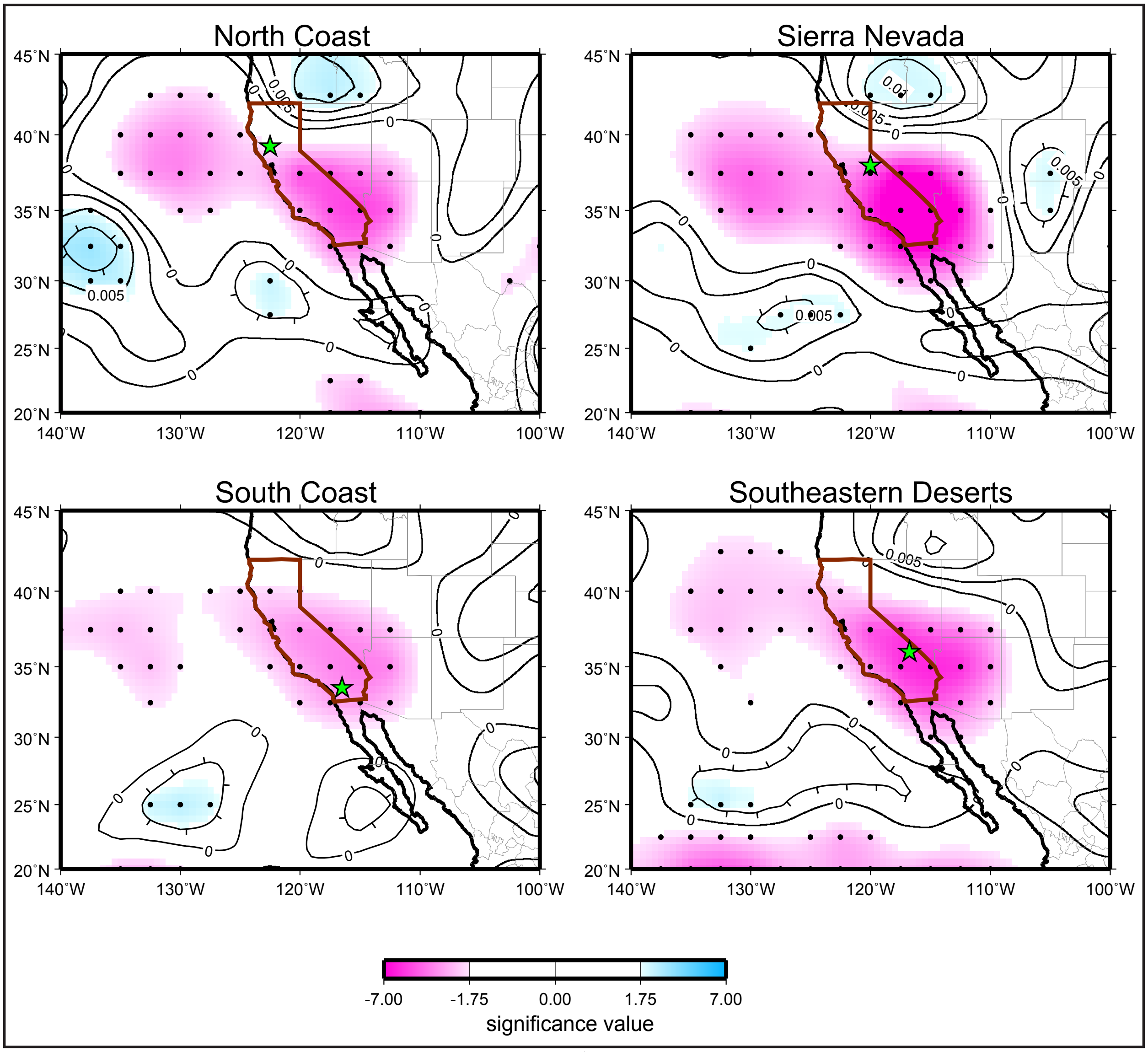

Figure 10. Composite 700 hPa vertical velocity (Pa s^{-1}) anomalies for the 16 months with highest lightning occurrence during June, July, August, and September months, 1985-2000. Locations whose t values meet or exceed the 95 % significance level are designated by black stippling, and significance level is indicated by color scale. The stars indicate the locations of the selected bioregion subsections.

pattern of negative omega anomalies (enhanced upward motion) that extends from an area offshore over the North Pacific at about 135° W, over the region of high lightning activity, and across into Nevada and Arizona. Areas of increased upward motion in an anomalously moist environment would be conducive for heightened lightning activity.

In contrast to the geopotential height patterns associated with high lightning occurrences, a very different pattern is present during months having very low numbers of lightning strikes (Figure 11). Although the magnitude and spatial extent of the composite anomalies in these low lightning occurrence maps are not as strong as those for the high lightning cases, these patterns are fundamentally different, featuring negative to neutral height anomalies over the west coast and positive height anomalies to the west over the middle latitude North Pacific Ocean. Wind flow appears to provide more

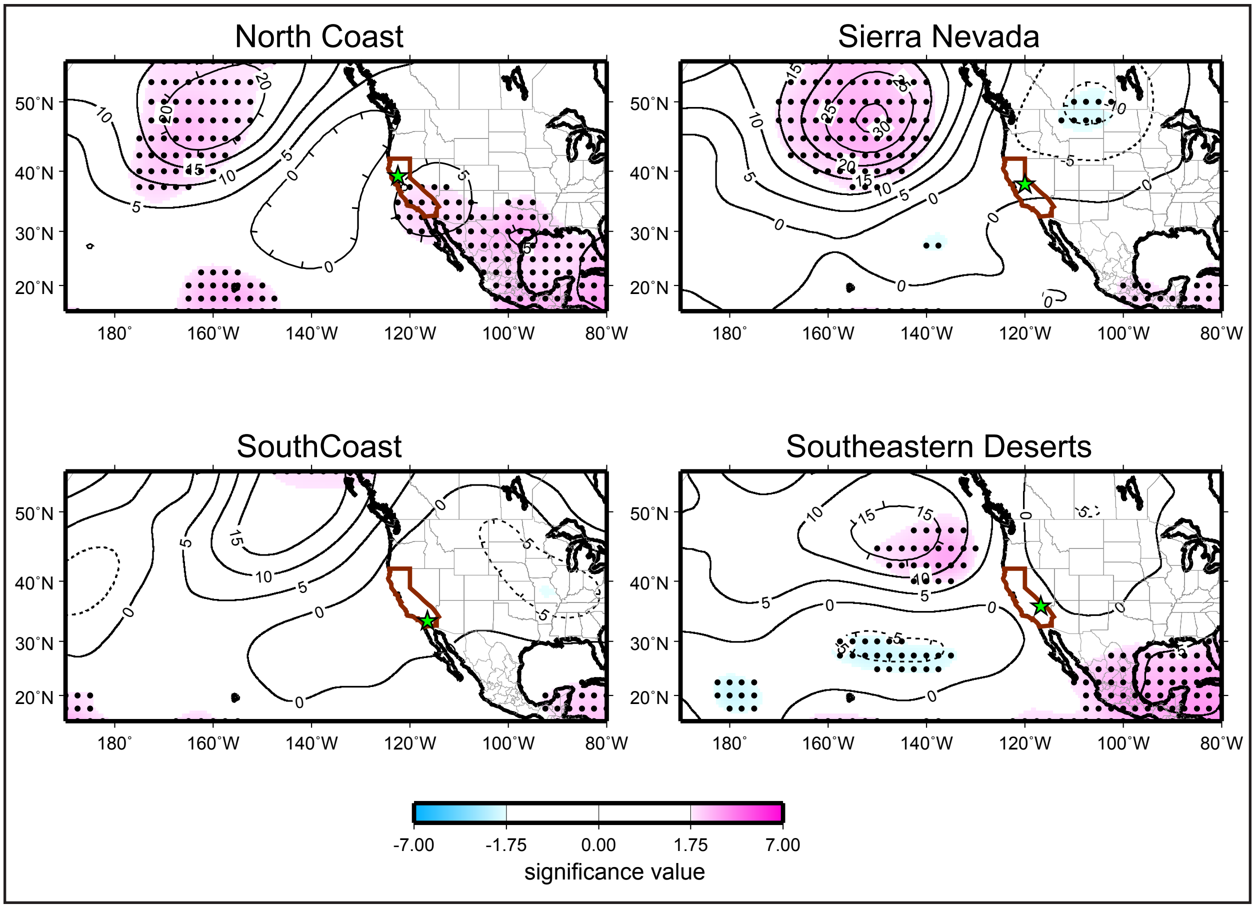

Figure 11. Composite 700 hPa geopotential height (m) anomalies for the 16 months with lowest lightning occurrences during June, July, August, and September months, 1985-2000. Locations whose t values meet or exceed the 95 % significance level are designated by black stippling and significance level is indicated by color scale. The stars indicate the locations of the selected bioregion subsections.

onshore ventilation from the North Pacific. An outstanding feature found in each of the low lightning composites is the reduction (negative anomalies) of precipitable water that appears (not shown) over each of the subregions during these months.

DISCUSSION

The number, density, and characteristics of lightning strikes in California varied in time and space. Annual variation in number of strikes from 1985 through 2000 was pronounced, with an over five-fold difference between the years with the highest and lowest number of strikes. Although there was considerable variation among bioregions in total numbers of lightning strikes, the annual trends were similar. In fact, bioregions were an excellent organizing scheme for distinguishing spatial patterns. Regional differences in location and elevation relative to storm patterns were manifested in the distribution of lightning.

There is a distinct warm season preponderance of lightning strikes, with summer months receiving the most lightning and winter months the least. Warmer surface air temperatures were cited by Williams (1994) as the cause of seasonal variation in lightning activity. In addition, monsoonal storms are more prevalent in summer. Monsoon flows from regions to the south and southeast reach their peak in August, and their effect on lightning is most pronounced during that month in the Southeastern Deserts and South Coast bioregions. These monsoon episodes are prevalent during periods with strengthened high pressure systems over southwestern United States, allowing tongues of moist air to flow into the California region. This period precedes the season of most extreme fire weather and Santa Ana winds (Wells and McKinsey 1995). Santa Ana winds are most common from October through March and occur during extremely dry episodes under very stable atmospheric conditions, conditions that are not conducive for lightning (Westerling *et al.* 2004). In the remainder of the bioregions, peak lightning activity coincides with summer weather conditions conducive for fire ignition and spread.

Hourly distributions of strikes for each bioregion were similar, with most strikes occurring in the mid to late afternoon and the least in the early morning. Late afternoon is also the time of the day when air temperature reaches its maximum and fires ignite and burn easily. This is particularly true in the Klamath Mountains, Southern Cascades, Northeastern Plateaus, and Sierra Nevada bioregions. Historically, sufficient fuel and burning conditions combined with lightning ignitions to produce frequent low to moderate intensity fires in those bioregions. The Southeastern Deserts, South Coast, and Central Valley bioregions were the exceptions with the lowest number of strikes coming between 0900 h and 1200 h. Those regions are most directly affected by summer monsoons, which reach their peak in the afternoon but do not taper off until mid-morning (King and Balling 1994). Afternoons are also when surface air temperatures and orographic lifting reach their maximum.

Lightning strike density was the highest in the mountain and desert bioregions. Coastal and valley bioregions had the lowest strike densities. In the mountains, this high density of lightning coincides with forests that produce heavy fuel loads. This combination, along with hot and dry weather conditions, sets the stage for an active fire role. In contrast, fuel loads in the desert are low and abundant lightning does not have as great an effect on fire frequency. Lightning density peaked in each bioregion before reaching the maximum elevation for that bioregion. Elevation has been shown to have a direct effect on lightning density in Colorado where strikes were concentrated just east of the Continental Divide (Lopez and Holle 1986). Reap (1986) used data from the BLM network for 11 western states and found a high correlation between elevation and the time of maximum lightning activity. For the 1983-1984 summer seasons, he found that strike density increased up to an elevation of 1700 m and then was fairly constant. In Alaska, Reap (1991) indicated that there was a sharp drop-off in lightning density above 1000 m. Orville (1994) found lower density values in the Appalachian Mountains than in areas to the east and west, perhaps due to their relatively low elevation and the high number of thunderstorm events in the east (Rakov and Uman 2003). Similarly, DeCaria and Babji (2003) reported a drop in strike density with an increase in elevation in southeastern Pennsylvania.

The proportion of negative to positive strikes was largest in the summer and smallest in the winter. This is consistent with other studies in the contiguous US (Orville and Huffines 1999). Brook *et al.* (1982) attributed the increase in positive strikes to wind shear during winter thunderstorms where positive leaders from the horizontally separated upper positive charge region are not intercepted by the lower negative charge. Because negative lightning strikes are 14 times as numerous as positive strikes and up to 40 % of them have long continuing currents, the distribution of negative strikes has a disproportional effect on fire ignitions. The proportion of positive strokes was less in the Southeastern Deserts bioregion, probably because most of the lightning there comes from summer thunderstorms. In the mountainous bioregions in northern California and in the Sierra Nevada, positive strikes during the summer have a high potential for starting fires. Although less frequent, positive strikes are more likely to have long continuing currents.

Mean peak current was greatest during the winter for positive strikes and varied slightly for negative strikes, a pattern found by Orville and Huffines (1999) for the contiguous US. Mean current of both positive and negative strikes was highest in the coastal bioregions. Orville and Huffines (1999) also noted geographic variation in amplitudes, with the highest peak positive values along the West Coast and in the upper Midwest, and the lowest peak negative values along the West Coast and in the area bordering Pennsylvania, Ohio, and West Virginia. They suggest that the transient luminous events observed by Lyons *et al.* (1998) might be related. In any case, the probability of igniting fuels was found to be independent of the current magnitude (Fuquay 1980).

The number of strokes per positive strike did not vary much over the months of the year. Negative strikes showed more variation with the highest number in July (1.94) and the lowest in January (1.31). Similar results were reported by Orville and Huffines (1999), although they recorded mean values exceeding three strokes per strike for areas of Georgia. In California, there was an increase in negative return strokes from the coast to the mountains. Orville and Huffines (1999) found continental increases from the Southeast to the Northwest and from Maine to Florida. They speculated that the variation in the number of negative return strokes was related to cumulus cloud size. From a fire ignition standpoint, a higher number of return strokes for negative strikes is important because it has been shown that negative strikes with more than one return stroke are more likely to have long continuing currents (Rakov and Uman 1990).

It is clear that the seasonal atmospheric environment, which is organized by extra-regional scale features of the atmospheric circulation, determines the distribution of moisture, vertical motions, and probably other important elements that dictate whether lightning activity is promoted or muted in California. Higher occurrences of summer lightning are favored by pressure cells over the North Pacific and the western US that tap atmospheric moisture reservoirs to the south, southwest or southeast, and that promote rising air masses. Low summer lightning periods occur when the West Coast is dominated by a trough of low pressure, allowing more onshore ventilation of the region with drier North Pacific air masses.

Lightning has been a pervasive element of the California environment for millennia. Its temporal and spatial distribution over the state plays a central part in the ecological role of fire in the state. This role is most pronounced in areas such as the Klamath Mountains, Cascade Range, and Sierra Nevada bioregions, where lightning is plentiful and fuels are abundant. As a result, fires often occur whenever a lightning storm crosses the low to mid elevations of these mountains. In other areas such as the Southeastern Deserts bioregion, which receives the largest amount of lightning, fuels are sparse and, consequently, fires are infrequent. In contrast, the North Coast bioregion has abundant fuel as a result of exceptional growing conditions, but lightning is infrequent, as are lightning fires. The time when lightning occurs is also important, as illustrated by the South Coast bioregion where lightning is infrequent under conditions conducive for high winds. In each bioregion, fire regimes are influenced by co-occurrence of lightning, fuel, and weather conditions.

Information about the distribution of lightning will provide insight into the role of fire in California's bioregions and will aid in predicting lightning fire occurrence. Knowing where and when lightning is most likely to occur will allow mangers to pre-position suppression forces, plan for fuel treatments, and prepare fire prevention and public safety materials.

Lightning will continue to be a major ignition source for wildland fires in California in the future. Global climate change will increase surface air temperatures. If this warming leads to more instability in the lower atmosphere, it could increase the amount of lightning (Price and Rind 1994*b*). Because climate change will likely produce longer, warmer, and somewhat drier summers, even the same density of lightning could cause more fires and change fire regimes. Fire management programs must be designed to anticipate and accommodate these changes.

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