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Characteristics of Lightning and Wildland Fire Ignition in the Pacific Northwest

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ABSTRACT

Lightning is the primary cause of fire in the forested regions of the Pacific Northwest, especially when it occurs without significant precipitation at the surface. Using thunderstorm occurrence and precipitation observations for the period 1948–77, along with automated lightning strike data for the period 1986–96, it was possible to classify convective days as either “dry” or “wet” for several stations in the Pacific Northwest. Based on the classification, a discriminant analysis was performed on coincident upper-air sounding data from Spokane, Washington. It was found that a discriminant rule using the dewpoint depression at 85 kPa and the temperature difference between 85 and 50 kPa was able to classify correctly between 56% and 80% of the convective days as dry or wet. Also, composite maps of upper-air data showed distinctly different synoptic patterns among dry days, wet days, and all days. These findings potentially can be used by resource managers to gain a greater understanding of the atmospheric conditions that are conducive to lightning-induced fires in the Pacific Northwest.

1. Introduction

Fire is an important disturbance mechanism in forest ecosystems, and lightning is the primary cause of wildland fires in the western United States. While it is becoming more widely accepted that disturbances such as fire are integral components of forest dynamics, large outbreaks of severe fire not only are destructive to the forests, but can be costly in terms of loss of property, resources, and, in some cases, human life. In addition, the cost of fighting severe fires is high. A better understanding of the conditions under which lightning presents the greatest potential for fire ignition will improve the ability to anticipate and to plan for wildfire outbreaks, resulting in a significant reduction of these risks.

Because lightning long has been recognized as the principal ignition mechanism for forest fires in the Northwest, considerable work has been done to quantify its relation to fire. In an early study, Morris (1934) categorized a class of storm days on which the majority of cloud-to-ground (CG) flashes, and therefore lightning-caused fires, occurred. In a later attempt to quantify the relationship between lightning and fire, Fuquay et al. (1979) developed a lightning activity level (LAL) index to estimate the number of lightning-caused fire ignitions. The LAL, which is determined by the number of CG lightning flashes in a given area, the areal cov-

erage of precipitation radar echoes, the areal intensity of rainfall, and storm size and duration, is a standard component of the National Fire Danger Rating System (Deeming et al. 1977).

Some studies have investigated the relationship between flash polarity and lightning ignition (Fuquay 1980, 1982), while others have suggested that fire occurrence is correlated strongly to the total number of CG lightning strikes (Meisner et al. 1993). Climatologically, however, when fire starts were compared with strike locations, there was little or no correlation between positive, negative, or total strike locations (Fig. 1). This lack of correlation suggests that fire starts coincide more closely with available fuels than with the number or charge of lightning strikes, that some other characteristic of lightning influences ignition potential, or that the fire start data simply are not sufficiently accurate for comparison. Also, from the current analysis, it was found that fire start observations do not always coincide with ignition events because fires in remote locations may not become visible until they grow sufficiently large, which may be days to weeks after ignition, depending on fuel condition.

Because of the potential importance of dry fuels to fire ignition, this study distinguished days on which lightning occurred without precipitation that reached the ground from days when significant rainfall accumulated simultaneously with lightning. Reap (1986), in a comparison of lightning and radar data, found that almost half of all lightning strikes occur when no radar echoes are observed. He attributed this observation, however, to limitations in the radar network, with a paucity of

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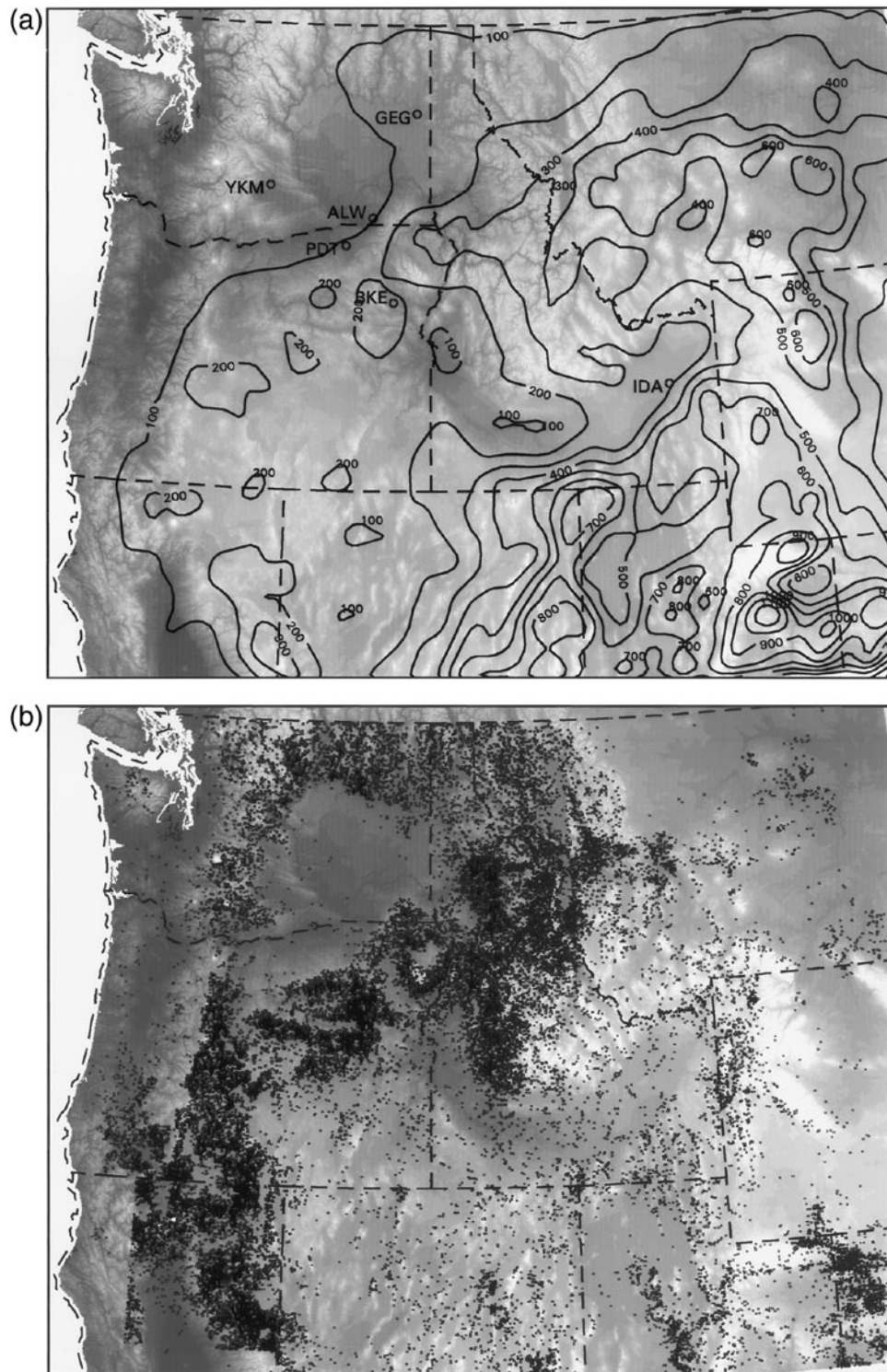


FIG. 1. (a) Contours of measured CG lightning strikes, 1986-93, overlaid on topography with higher elevations depicted by lighter shades. Locations of test sites are Spokane (GEG), Walla Walla (ALW), Yakima (YKM), Washington; Idaho Falls (IDA), Idaho; and Pendleton (PDT) and Baker (BKE), Oregon. (b) Lightning-caused fire locations, 1986-93.

radar sites in the remote and mountainous regions of the western United States. Nevertheless, experienced fire weather forecasters have noted that “dry” lightning (defined here as that occurring outside the area of precipitation or with precipitation that evaporates before reaching the ground) is a common and most dangerous contributor to wildfire ignition.

In addition to the significance of dry lightning in starting fires, it is believed that thunderstorms that produce little or no precipitation at the surface originate with a high base of moisture and are highly unstable. Therefore, the synoptic weather patterns should be distinctly different from those associated with “wet” lightning. For lightning to be accompanied by measurable precipitation, as in a wet lightning scenario, a thunderstorm should have deep layers of moisture and be conditionally unstable, causing significant convection to be limited except when the air mass experiences additional lifting, which could be triggered by either orographic or frontal mechanisms. The earlier studies cited did not demonstrate whether it is possible to distinguish between wet and dry lightning days based on the synoptic meteorological conditions. This study therefore was undertaken to explore further the relationship among lightning, precipitation, and synoptic weather conditions.

2. Analysis

To derive a quantitative method of distinguishing between wet and dry lightning days, long-period (1948–77) records of thunderstorms and precipitation were used that were available for Spokane, Yakima, and Walla Walla, Washington; Pendleton and Baker, Oregon; and Idaho Falls, Idaho (WeatherDisc Associates 1994; see Fig. 1a for station locations). Of these stations, upper-air radiosonde data are available only from Spokane. Therefore, data from Spokane were used to define a maximum likelihood discriminant algorithm to separate the two groups of convective days. The other stations provided an independent database to test the discriminant rule. The study was confined to the summer months (May–September) because this period is when the vast majority of all lightning strikes occur in the Pacific Northwest and wildland fire conditions are most critical.

Convective days at Spokane were categorized as either wet or dry according to the precipitation amount recorded at the station. A thunderstorm day was designated as wet if at least one convective storm was reported and the rainfall amount was equal to or greater than 2.54 mm. A dry thunderstorm day was designated as a day on which at least one storm (lightning or thunder observed) was reported and the recorded rainfall was less than 2.54 mm. Based on these criteria, there were 173 dry days and 133 wet days at Spokane for the summer months over the 30-yr period of record.

Most lightning occurs in the study area in the late afternoon and evening hours, centered around 0000 UTC, or 1700 local daylight time (LDT) the previous

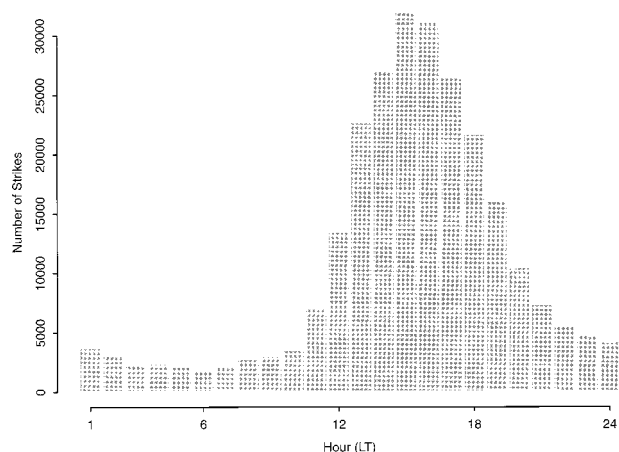


FIG. 2. Number of measured cloud-to-ground lightning strikes by hour (LDT) in the study area for a typical fire season (May–Sep 1989).

day (Fig. 2). Therefore, the 0000 UTC soundings were used to represent upper-air conditions over Spokane. Days with missing soundings were discarded from the analysis, leaving 135 dry days and 101 wet days in the sample. Stability indices (such as the K index) derived from upper-air soundings can be used as indicators of convection; however, these stability indices were designed to distinguish between convective and nonconvective days and therefore are not well suited to discriminate between dry and wet lightning days. Consequently, for the current study, individual upper-air variables were analyzed to help to determine atmospheric stability and the location and amount of moisture.

Table 1 lists variables in the lower atmosphere that indicate the potential for convection and rainfall, with mean values of each variable for all lightning days at 0000 UTC. The differences between the wet and dry groups were tested for significance using Student’s *t* test and were found to be significant for all variables, with the exception of 50-kPa dewpoint depression. In general, temperatures were warmer on dry days than on wet days. Also, decreases in temperature with height (85 kPa – 70 kPa, 70 kPa – 50 kPa, and 85 kPa – 50 kPa) were significantly higher (more unstable) on dry days than on wet days. Table 1 also shows mean values for all May–September 0000 UTC soundings from the same 30-yr period (wet and dry lightning days and nonlightning days). Wet days are distinguished from the long-term mean by significantly more (*t*-test results not shown) moisture at lower levels (very low dewpoint depressions at 85 and 70 kPa). Dry days have significantly larger temperature differences ($T_{85} - T_{50}$, for example) and greater instability compared to the long-term mean.

A discriminant analysis was performed to determine if these sounding variables could be used to classify correctly a lightning day as being dry or wet. Table 2 shows the values of the *F* statistic (Mardia et al. 1979)

TABLE 1. Mean values of 0000 UTC Spokane sounding variables for dry and wet days, 1948–77, and for all days in the 30-yr period of record. All units are °C.

	T850 ^a	T700 ^b	T500 ^c	DD850 ^d	DD700 ^e	DD500 ^f	T8 – T7 ^g	T7 – T5 ^h	T8 – T5 ⁱ
Dry	16.6	3.5	–15.0	13.2	7.9	9.7	13.1	18.5	31.6
Wet	11.9	0.3	–16.7	7.8	4.9	9.4	11.6	17.0	28.6
$P(\text{dry} = \text{wet})^j$	0	0	0.003	0	0	0.667	0	0	0
30 yr	14.2	1.7	–14.8	14.0	10.0	11.4	12.5	16.6	29.1

^a T850: 85-kPa temperature.

^b T700: 70-kPa temperature.

^c T500: 50-kPa temperature.

^d DD850: 85-kPa dewpoint depression.

^e DD700: 70-kPa dewpoint depression.

^f DD500: 50-kPa dewpoint depression.

^g T8 – T7: 85 kPa – 70 kPa temperature difference.

^h T7 – T5: 70 kPa – 50 kPa temperature difference.

ⁱ T8 – T5: 85 kPa – 50 kPa temperature difference.

^j $P(\text{dry} = \text{wet})$: probability that the mean values for dry and wet days are not significantly different.

for the four variables that had the most significantly different means between the groups. If the F statistic is significant for a given variable, then that variable is useful in the discrimination. The results suggest that the only useful variables in discriminating between wet and dry lightning days are the 85-kPa dewpoint depression and the temperature difference between 85 and 50 kPa. This finding is not surprising, considering a large 85 kPa – 50 kPa temperature difference suggests low-level warming and high-level cooling, resulting in rapid destabilization of the atmosphere. Also, lack of moisture at lower levels increases the likelihood of high-based thunderstorms, which tend to produce little if any precipitation at the surface. In fact, when these two significant variables are paired with each of the other variables individually (except 50-kPa dewpoint depression, which was not significantly different between the two groups), we see that these variables are indeed the only ones that are significantly useful in the discrimination (Table 3). Note that the F values in Table 2 generally are smaller than those in Table 3; this result is because, as more variables are used in the computation, the additional information carried by any one variable, which is not carried by the others, decreases (in other words, each additional variable is less likely to be helpful in discriminating between groups). Note that all the sounding variables are positively correlated and carry some redundant information. Therefore, finding only two variables that are critical for discrimination is not surprising.

TABLE 2. Values from the F -statistic significance test for selected Spokane sounding variables, all Spokane lightning days, 1948–77.

	F statistic
T850	0.015
DD850	6.771*
T8 – T7	0.909
T8 – T5	6.684*

* Significant at 99%.

Using the values of 85 kPa – 50 kPa temperature difference and 85-kPa dewpoint depression, a sample maximum likelihood discriminant rule, which simply assigns an observation to one group or the other, was used to classify the observations. Application of this rule to the data at Spokane from which it was formulated (in other words, the rule was tested on dependent data) resulted in the correct classification of 73% of all days in the sample, with 78% of the wet days and 71% of the dry days being assigned to the proper group.

Probability densities were computed and plotted for each group (Fig. 3). The probability of any given observation belonging to either group can be computed from these probability densities, and a prediction can be made to determine whether that observation belongs to the wet group or the dry group. To illustrate the potential application for this type of analysis, Fig. 4 shows the probability contours that were calculated using the discriminant rule based on the 1948–77 thunderstorm days. For example, a day on which convective activity is expected, with a 10°C dewpoint depression at 85 kPa and a 25°C 85 kPa – 50 kPa temperature difference, has about a 78% chance of belonging to the wet group and about a 22% chance of belonging to the dry group.

To assess the general utility of this algorithm, the discriminant rule developed from the Spokane thun-

TABLE 3. Values from the F -statistic significance test for DD850 and T8 – T5 paired with other variables, all Spokane lightning days, 1948–77.

	DD850	T8 – T5
T850	0.015	7.326*
T700	0.048	7.200*
T500	0.015	7.326*
DD700	0.014	7.646*
T8 – T7	1.216	13.699*
T7 – T5	1.215	13.699*

* Significant at 99%.

** Significant at 95%.

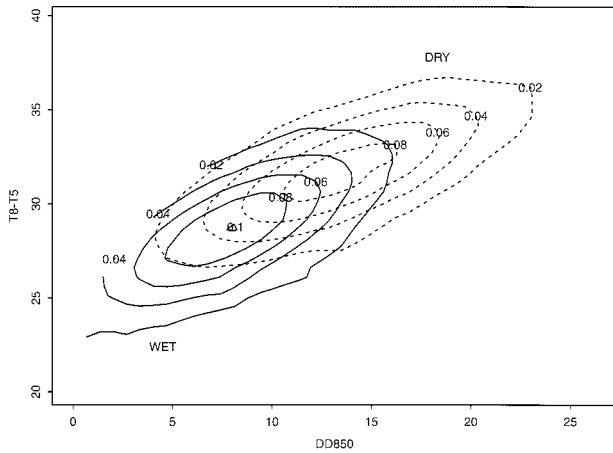


FIG. 3. Probability densities for wet and dry thunderstorm days at Spokane, 1948–77, based on 85-kPa dewpoint depression (DD850) and 85 kPa – 50 kPa temperature difference (T8 – T5).

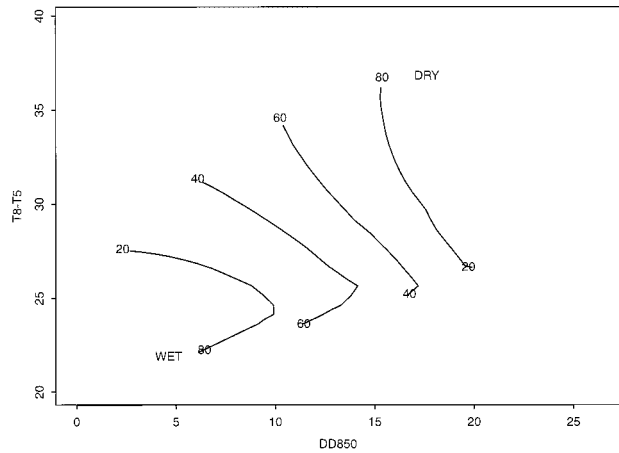


FIG. 4. Probability of a thunderstorm day belonging to the wet or dry group based on 85-kPa dewpoint depression (DD850) and 85 kPa – 50 kPa temperature difference (T8 – T5). Probabilities were generated from Spokane thunderstorm days, 1948–77.

derstorm and upper-air databases was tested at several different stations in Washington, Oregon, and Idaho. The same criteria were used to designate wet and dry thunderstorm days as were used at Spokane. Table 4 lists the stations and the number of wet and dry days at each station for the 1948–77 period of record. The results show that the percentage of days correctly classified by the Spokane discriminant rule ranges from 58% to 74% (Table 5). The best results were obtained at Pendleton and Walla Walla, while at Idaho Falls the rule correctly classified the smallest percentage of days.

These results indicate the discriminant rule is more effective in separating wet and dry days than the traditional stability indices used by forecasters to predict thunderstorm activity. For example, there is no significant difference in the K index between the two groups of Spokane thunderstorm days. The K index considers the temperature difference between 85 and 50 kPa and an indicator of low-level moisture, but these parameters are combined such that the resultant index is similar for both groups. Also, the total totals index, which is the sum of the cross totals (CT) and vertical totals (VT) indices, is not significantly different between the two groups. The VT is defined as the 85 kPa – 50 kPa temperature difference, and as such is included explicitly in the discriminant rule. The CT includes indicators of low-level moisture and temperature aloft. Again, when this index is added to the VT, the resulting values fall in the same range for both dry and wet days. The Haines index (Haines 1988), which also is a measure of stability and moisture in the lower atmosphere, commonly is used to estimate fire severity. This index also was found to be not useful in separating the groups because it is a categorical index, with values varying from 2 to 6, making it too coarse to differentiate between the two groups. The common characteristic of most of these indices is the use of some combination of stability and moisture to produce a probability of convection, but

these parameters often are combined in a manner that masks the differences between dry and wet convective days. Therefore this discriminant rule, which assigns a probability based on stability and low-level moisture individually, rather than cumulatively, proved to be both a simple and effective means of separating the two types of convective days.

3. Synoptic patterns

Because skill is shown in discriminating between groups at several stations, the potential exists for a regional analysis of lightning and precipitation, particularly if there is a synoptic cause for the convection. Fuquay et al. (1979) described high-level dry thunderstorms in the northern Rocky Mountains that usually are triggered by an upper-level cold front or other cold air advection aloft. Little or no precipitation from these storms reaches the ground from their bases, which can be as high as 3000 m above ground level. Although wet storms, like dry storms, also may be triggered by frontal mechanisms, because of their abundance of low-level moisture they usually are conditionally unstable and

TABLE 4. Number of wet and dry days for each location and each database (wet/dry).

	1948–77 thunderstorm database	1986–96 lightning database
Spokane, WA	101/135	36/74
Walla Walla, WA	66/104	15/44*
Yakima, WA	47/116	7/33
Idaho Falls, ID	172/374	35/207**
Pendleton, OR	74/142	26/80
Baker, OR	158/261	36/128

* Period of record for Walla Walla is 1986–94.

** Period of record for Idaho Falls is 1986–93.

TABLE 5. Percent correct classification using the Spokane 1948–77 discriminant rule.

	1948–77 thunderstorm database	1986–96 lightning database
Spokane, WA	73% (78% wet, 71% dry)	56% (92% wet, 43% dry)
Walla Walla, WA	71% (61% wet, 78% dry)	73% (73% wet, 73% dry)*
Yakima, WA	60% (47% wet, 65% dry)	73% (71% wet, 73% dry)
Idaho Falls, ID	58% (42% wet, 65% dry)	65% (49% wet, 68% dry)**
Pendleton, OR	74% (62% wet, 80% dry)	61% (65% wet, 59% dry)
Baker, OR	67% (52% wet, 76% dry)	60% (44% wet, 64% dry)

* Period of record for Walla Walla is 1986–94.

** Period of record for Idaho Falls is 1986–93.

may need additional lifting by orography. Therefore, the synoptic signature from wet storms is expected to be somewhat less distinctive than that of dry events, or at least different.

To view synoptic patterns, composite maps of mean 0000 UTC (1700 LDT) 50-kPa heights were generated for dry days and wet days in the 1948–77 Spokane database. These maps were based on a slightly smaller sample size (102 dry days and 78 wet days) because height grids were not available for some days in the early part of the record. Both maps (Figs. 5a,b) depict a trough over the Pacific coast with southwest flow over the region, which is similar to the 50-kPa flow pattern identified by Werth and Ochoa (1993), as being conducive to the spread of fire. These results are also somewhat similar to results from Hill et al. (1987), who stratified lightning frequencies over Idaho by 50-kPa map types. They found a trough over the western United States on days on which lightning was most frequent, while most other summer days were characterized by weak zonal flow over the region. There is a difference between the wet and dry patterns, however. The trough axis on dry days is farther west than on the wet days, and the heights are higher on dry days. The largest height differences between the dry and wet days are centered over eastern Oregon and Washington and over Idaho and extend into western Montana (Fig. 5c). Compared to the 30-yr mean 0000 UTC 50-kPa heights (not shown), the dry pattern depicts heights that are lower than the mean off the west coast of the United States; higher than the mean over Montana, Wyoming, and the eastern half of Utah; and not significantly different from the mean over the remainder of the western United States. The wet pattern, however, is significantly lower than the 30-yr mean heights over the entire study area.

To view surface patterns, composite maps of mean 0000 UTC sea level pressure also were generated for the Spokane thunderstorm days (82 dry grids and 68 wet grids were available). Both patterns are similar in that they depict a thermal trough over the western United States, which is consistent with the typical weather pattern leading to destabilization and convection (Werth and Ochoa 1993). Unlike the 50-kPa heights, there was no statistically significant difference between the wet and dry surface patterns (Fig. 6).

4. Spatial application

The station thunderstorm databases were very useful for the purpose of establishing a long period of record on which to base the discriminant rule. The presence of a thunderstorm reported by an observer, however, gives no indication of the occurrence of cloud-to-ground lightning strikes, which is important in the context of fire. Also, there are many places without observer records of thunderstorms or lightning. To help determine the spatial patterns of wet and dry lightning events, lightning strike data from the Bureau of Land Management (BLM) lightning detection network (Krider et al. 1980) were obtained for an 11-yr period from 1986 through 1996. These data include the ground location (latitude and longitude), polarity, peak current, number of strikes per flash, and the date and time of occurrence. The direction finders have an approximate range of 400 km, with an estimated detection efficiency of as much as 70%, which is a function of season, polarity, and distance from the detector. Flashes can be detected beyond 400 km but with a lower efficiency (Orville 1994). It is assumed that the detectors randomly “miss” lightning flashes, and there are no systematic errors in the data associated with detection efficiency.

A “lightning” day was designated if there was at least one lightning strike reported within 10 km of the station, and the 2.54-mm threshold was used to distinguish wet days from dry days. Because the period of record from the automated network encompassed only 11 yr (1986–96), the sample sizes ranged from only 7–36 wet days and 33–207 dry days (Table 4). Note that the period of record for Walla Walla is only 9 yr (1986–94) and that for Idaho Falls is only 8 yr (1986–93), because precipitation data from these stations were either missing or unreliable. Although the discriminant rule showed skill in separating the groups at all stations, correctly classifying between 57% and 73% of all days (Table 5), the smaller sample sizes preclude any confident conclusions. In addition, because convective precipitation often occurs over areas of less than 1 km in diameter, the single point precipitation value may not represent possible wetting conditions over the entire 10-km radius of lightning activity.

Because of temporal climate variability, it is possible

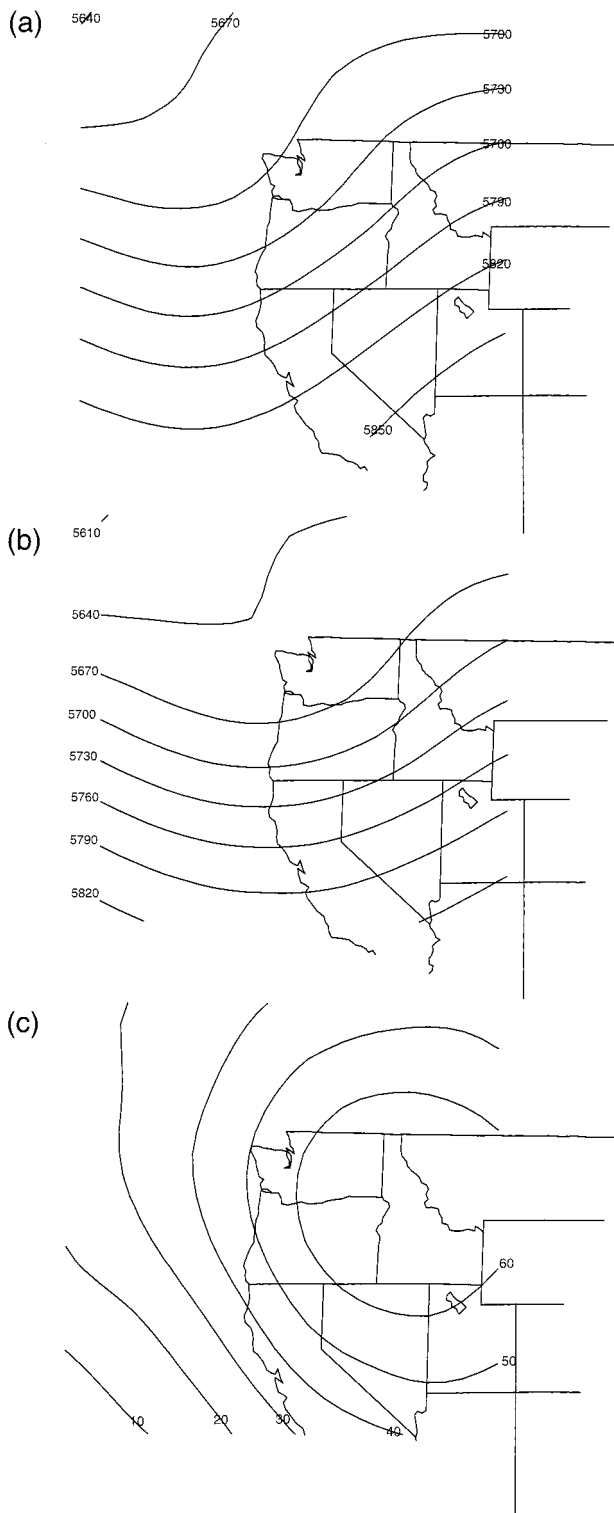


FIG. 5. Mean 50-kPa heights (m) for thunderstorm days at Spokane, 1948-77 for (a) dry days, (b) wet days, and (c) dry - wet days.

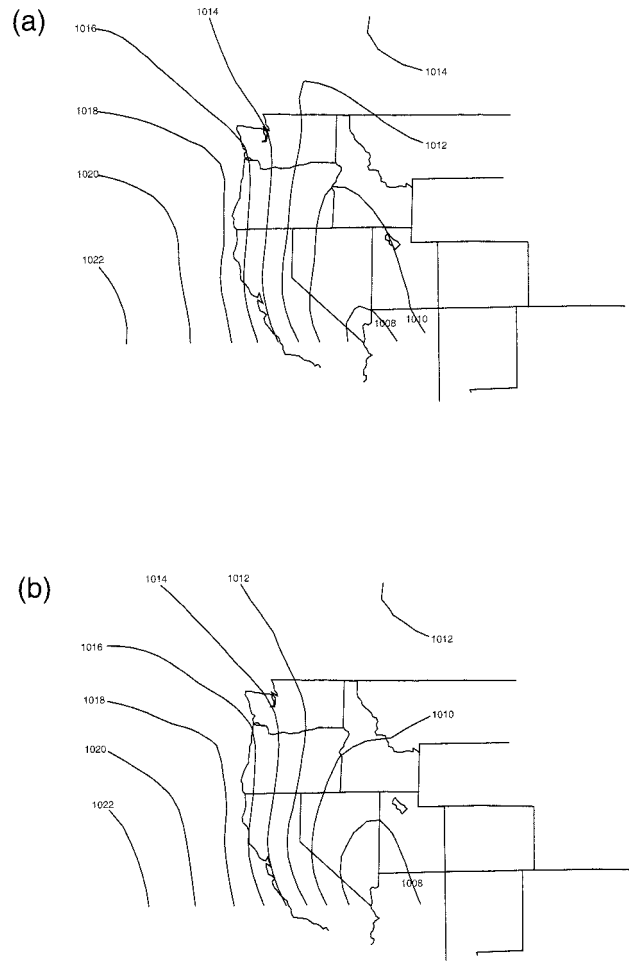


FIG. 6. Mean sea level pressure (hPa) for thunderstorm days at Spokane, 1948-77, for (a) dry days and (b) wet days.

that the discriminant rule developed from the 1948-77 Spokane database may not be the most effective tool to analyze the more recent data. The discriminant rule therefore was reformulated using the 1986-96 sounding data from Spokane, and this rule was then applied to the contemporary databases at each of the stations. These results are presented in Table 6. Application of this rule improved the results at all the stations, correctly

TABLE 6. Percent correct classification using the Spokane 1986-96 discriminant rule.

	1986-96 lightning database
Spokane, WA	67% (75% wet, 64% dry)
Walla Walla, WA	80% (60% wet, 86% dry)*
Yakima, WA	83% (57% wet, 88% dry)
Idaho Falls, ID	79% (40% wet, 86% dry)**
Pendleton, OR	64% (42% wet, 71% dry)
Baker, OR	74% (47% wet, 81% dry)

* Period of record for Walla Walla is 1986-94.

** Period of record for Idaho Falls is 1986-93.

classifying between 64% and 83% of the convective days. Again, assessing the significance of these results is difficult because of smaller sample sizes; however, it is encouraging that the discriminant rule continues to show skill in distinguishing between wet and dry days in the later database.

Matching distributed lightning data with distributed precipitation data was possible for 2 yr (1988 and 1989) with a database generated especially for the Columbia River Basin at a spatial resolution of 2 km² (Thornton et al. 1997). In this case, lightning days were designated somewhat arbitrarily as those days on which at least 1000 CG strikes occurred within the basin. The 0000 UTC soundings from Spokane were obtained for May–September for 1988 and 1989, and the Spokane discriminant rule was applied to categorize the lightning days. Two examples of this analysis are shown in Fig. 7, with the locations of lightning strikes superimposed on maps of rainfall amount. The date 16 July 1989 (Fig. 7a) was classified by the discriminant rule as having an 80% probability of belonging to the wet category. There is widespread rainfall throughout large portions of the basin, with most lightning strikes occurring in and near areas of precipitation. The date 26 July 1989 (Fig. 7b) was categorized as having a 98% probability of being dry, and on this day there were small, isolated areas of precipitation. Extensive lightning strike activity occurred where there was no rainfall. Figure 8 shows locations of fire starts that were reported on these two days. It is clear that on these two sample days there were many more fire starts reported on the dry day than on the wet day. A more quantitative comparison of lightning strike occurrence and fire starts is not possible with this database because the date assigned to each fire is the date when the fire was first detected, which may have been days after the initial ignition occurred. Comparison of the 50-kPa height fields for these two days (Fig. 9) reveals that the heights on the dry day are higher than on the wet day, and the trough axis is farther west on the dry day, which is in agreement with the composite height fields from the 1948–77 Spokane database (Fig. 5). These results are encouraging, and longer-period records of distributed precipitation would allow a more rigorous analysis.

5. Summary

A preliminary analysis to characterize lightning in the Pacific Northwest was performed using station thunderstorm records and data from the BLM lightning detection network. The results indicate there are two distinct atmospheric regimes associated with lightning days in the Pacific Northwest. Dry lightning days occur when

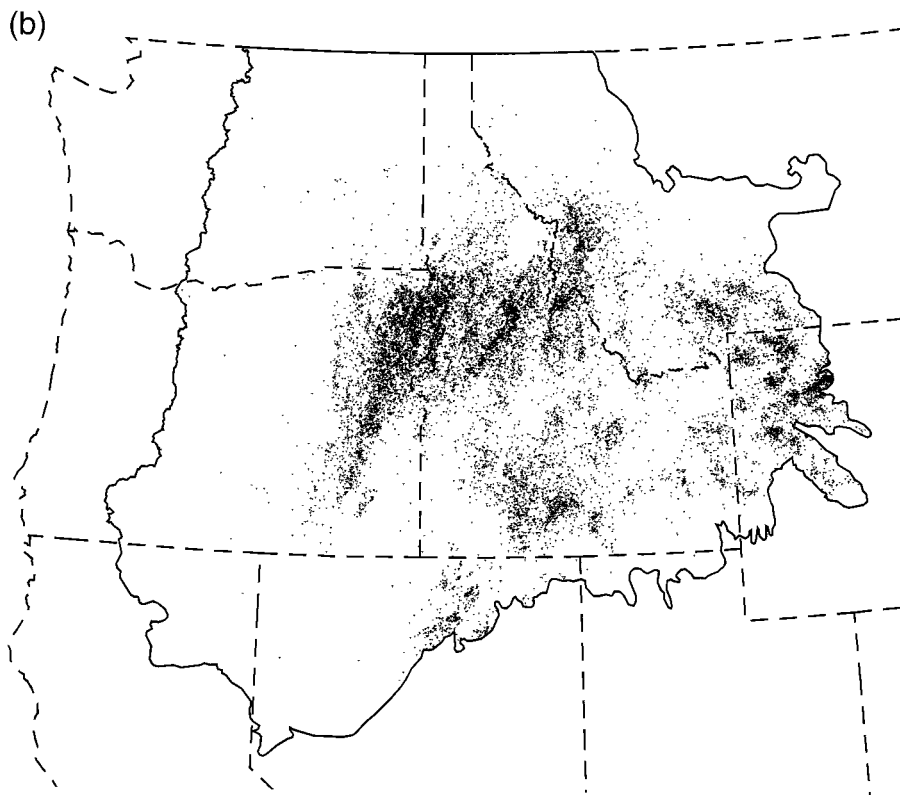
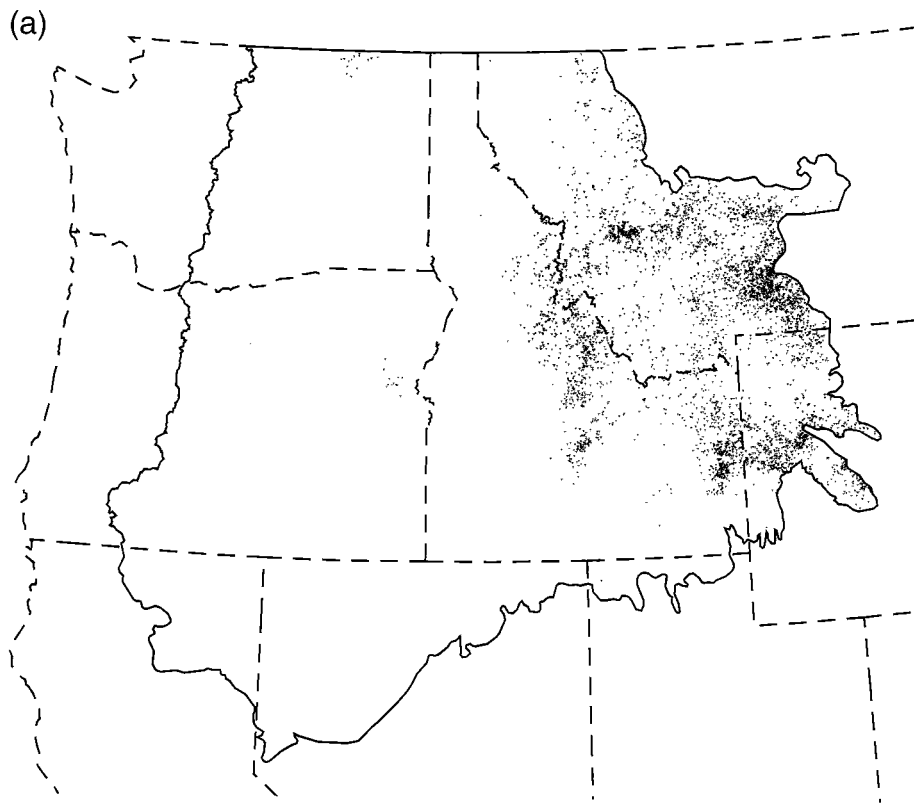
both stability and moisture levels in the lower atmosphere are quite low. The high instability, which is very conducive for convection, coupled with a dry air mass at lower levels, increases the likelihood that precipitation will evaporate before reaching the ground. Not coincidentally, this is the same synoptic regime that results in dry, gusty conditions that are likely to enhance the spread of severe fires. Wet lightning days occur when the atmosphere is more conditionally unstable and there exists a greater availability of moisture at low levels in the atmosphere. In this case, conditions still are ripe for convection and lightning; however, there is widespread precipitation at the ground because of sufficient moisture in the lower atmosphere.

Skill has been demonstrated in differentiating between wet and dry days for individual stations, using a sample maximum likelihood discriminant rule. This rule was developed from a 30-yr thunderstorm and precipitation database from Spokane, Washington, and was applied successfully to other locations in the region. It would be possible to formulate a similar rule for each station based on lightning and precipitation data from that specific station and sounding data from the closest (or most appropriate) upper-air station. Long periods of thunderstorm and precipitation data, however, are not available for many locations. This problem will be alleviated as the lightning detection network continues to provide an uninterrupted record of lightning strike activity, and when long periods of daily precipitation amounts can be generated at spatial scales on the order of 1 km.

This study has shown that dry convective storms (those without significant precipitation reaching the ground) occur when the lower atmosphere is dry and unstable, and wet convective storms more typically occur with ample moisture and conditionally unstable conditions. If lightning is expected, it is possible to compare the measured or forecast dewpoint depression at 85 kPa and the temperature difference between 85 and 50 kPa with the contours in Fig. 4 to determine the probability of the lightning being accompanied by rainfall. If no upper-air sounding data are available, the 50-kPa height analysis or prognosis may be compared with Fig. 5 to help to determine the potential for wet or dry convection. This comparison, in turn, should provide a better indication of lightning-caused wildfire potential in the sparsely populated regions of the Pacific Northwest.

Acknowledgments. The authors would like to thank Don Latham, Rocky Mountain Research Station, USDA Forest Service, for many helpful discussions and valuable advice in the early stages of the study, and for providing some of the lightning strike data. We also

FIG. 7. Lightning strike locations and precipitation amounts (mm) for (a) 16 July 1989 and (b) 26 July 1989. Shaded areas show rainfall ≥ 2.54 mm, solid line is boundary of Columbia River Basin, and dots indicate strikes.



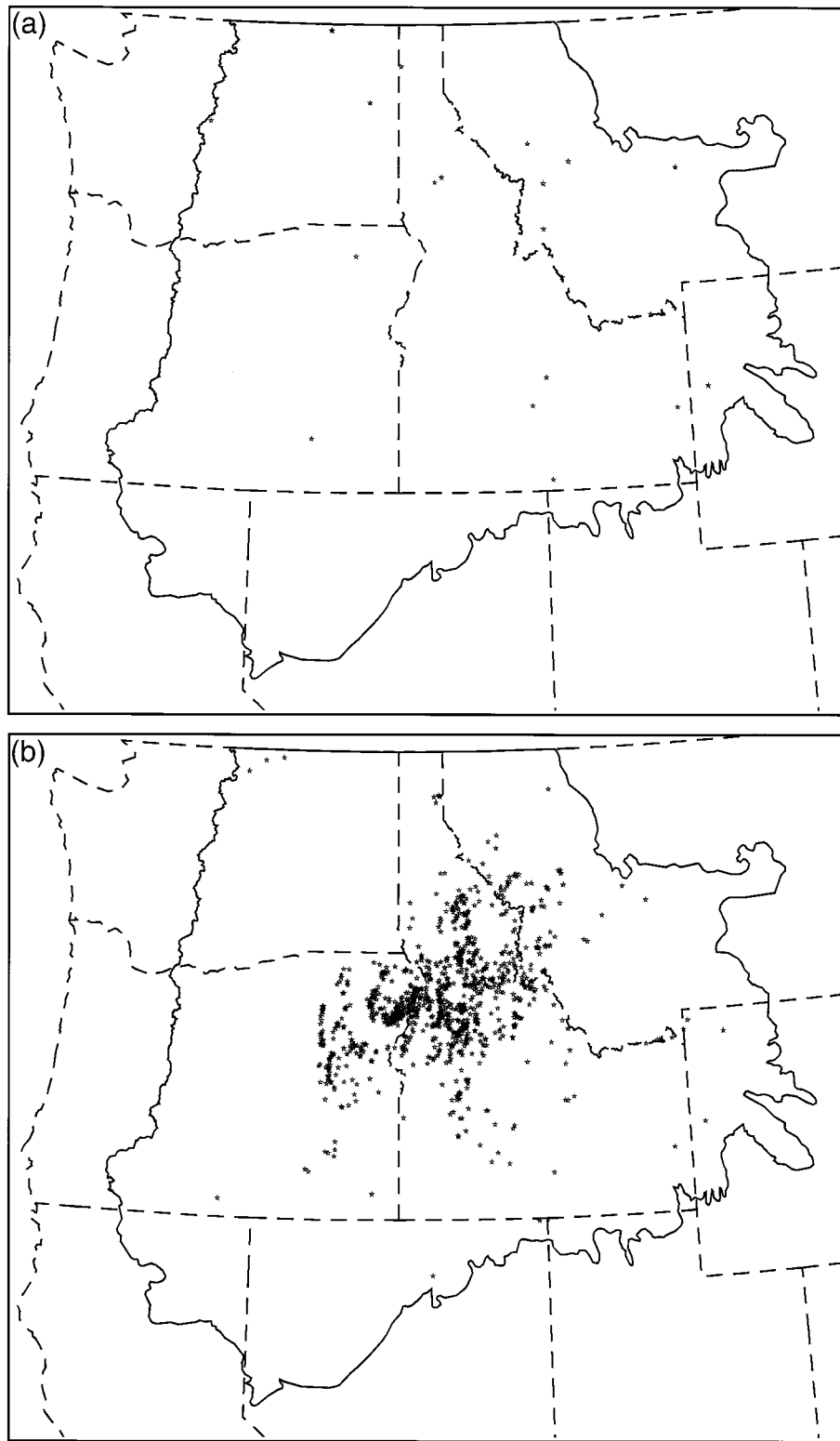


FIG. 8. Fire start locations and precipitation amounts (mm) for (a) 16 July 1989 and (b) 26 July 1989. Key as in Fig. 7, but stars indicate fire start locations.

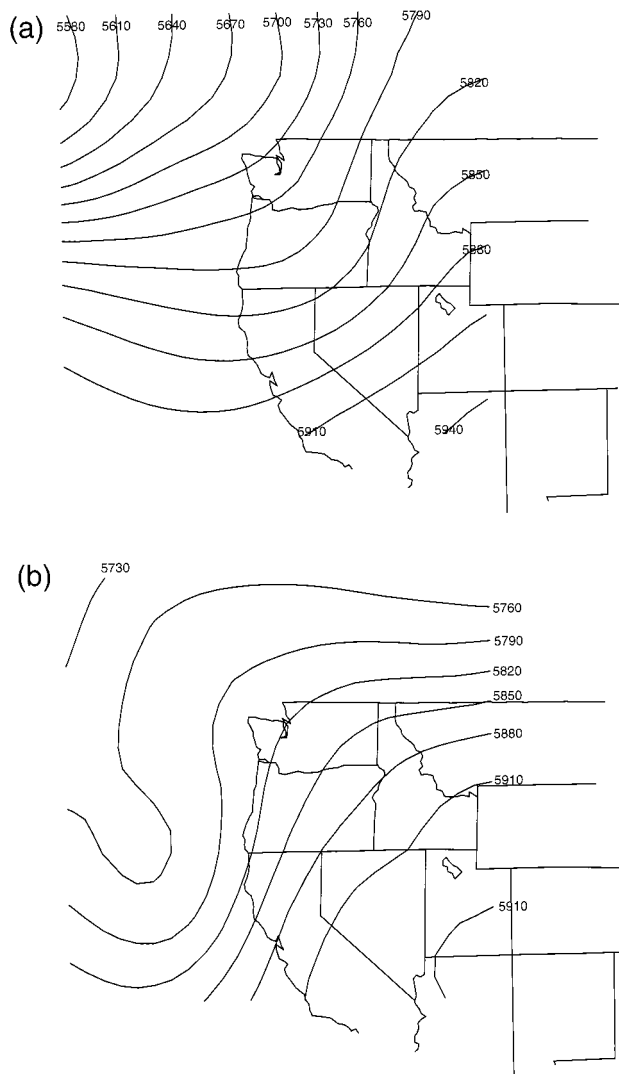


FIG. 9. The 50-kPa heights (m) for (a) 16 July 1989 and (b) 26 July 1989.

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