Seasons within the Wildfire Season: Marking Weather-Related Fire Occurrence Regimes

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ABSTRACT

Weather and climate contribute to the multidecadal, seasonal, and daily cycles of the potential for fire ignitions and for the severity of fires. We used a long-term dataset of weather parameters to characterize comparatively homogeneous periods, or subseasons, within the fire season. First, we conducted an exploratory analysis of weather conditions using the univariate t-test to determine if natural breaks in the weather conditions could be identified. Then, we used multivariate analysis of variance (MANOVA) of each calendar day, based on before and after periods of twelve days to identify the most distinct, natural breaks as expressed by the combination of weather variables as they change throughout the fire season. From this analysis, we identified six subseasons between March 1 and September 30 and explored the average weather conditions during each subseason. These results were partially validated against databases containing 29 years of historical fires and 16 years of historical Energy Release Component (ERC) data. From these results, we concluded that fire-weather can assume a uniform state for anywhere from two to six weeks, and then change into a considerably different regime. The quantitative establishment of these fire subseasons defines homogeneous periods of weather regimes that will improve the outputs of some fire models by controlling for seasonality. Our method for identifying subseasons could be applied by scientists using data from other regions to obtain subseason boundaries appropriate for their climatic regimes. The definition of subseasons also enhances our understanding of plant growth and development throughout the seasons, and provides managers with an objective tool to anticipate and adapt to the changing weather conditions.

Keywords: climate, fire weather, fire seasonality, fire subseasons

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INTRODUCTION

The occurrence of fire ignitions and fire behavior are driven by natural factors, such as local and regional weather and climate conditions (Hubbard 1980, Bessie and Johnson 1995, Allen 2002, Westerling et al. 2003). Climate and weather exert a dominant control over fuel moistures (Fosberg 1972), ignitions from lightning (Fuquay et al. 1979, Johnson 1992) and the behavior of burning fires (Schroeder and Burk 1970, Turner and

Romme 1994). The affects of weather on fire can be manifested on a range of scales from hours to many decades. In this report, we examine the relationships between weather variables as they vary together within the fire season. We aim to identify regimes in average weather, lasting weeks or perhaps months, and relate these regimes to occurrences and extents of fires.

Long-term variations in climate conditions, including global climate change, are likely to have significant effects on many components of the biosphere, including wildland fire regimes (Swetnam 1993). Grissino-Mayer and Swetnam (2000) examined patterns in past centuries and have hypothesized that changes in rainfall patterns result in a climate forcing of fire regimes. Climate changes in the future may be associated with a long-term net increase in fire activity resulting from warmer climatic conditions that would increase the number of days of very high and extreme fire weather (Williams et al. 2001). This would be reflected in increases in total area burned and the number of large fires (Piñol et al. 1998, Lefort et al. 2003).

At the scale of individual fire seasons, variations in fire activity are controlled by seasonal climate fluctuations and their anomalies (Flannigan and Harrington 1988, Westerling et al. 2003). These effects of climate can be manifested throughout the United States (McCabe et al. 2004). For instance, El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), singly or in combination, are associated with fire activity levels in widely separated regions, such as Colorado (Donnegan et al. 2001), Florida (Brenner 1991, Beckage et al. 2003) and Washington State (Hessl at al. 2004). Patterns such as these can also be related to fuel moisture and duff moisture (Amiro et al. 2004). These and other factors have a net impact on the expected fire intensities as the fire season progresses (Gill et al. 2000, Williams et al. 1998).

The weather conditions that influence fires can also vary within seasons. The seasonality of the annual weather cycles produce a convergence of conditions that is conducive to varying levels of fire occurrence and fire behavior throughout the year. New Mexico and the Southwestern United States is a primary example of this relationship.

> *The climate of the Southwest shows strongly seasonal patterns both within and between years. Drought cycles are common, and most annual precipitation comes in the course of a summer rainy season. Rainfall is rare from March until the summer rains.* (Pyne 1997:516)

In northern New Mexico and through much of the Southwest, dry seasons typically occur in the spring and fall with greater amounts of precipitation occurring during the summer monsoon period, and it is the spring dry period (April through June) that is associated with the most extreme fire activity (Allen 2002). The period from April through June is characterized by persistent drought that is relieved at the onset of the monsoon season in July. Much of the annual precipitation is received during the summer monsoon (Bowen 1990). Although dry periods are also common from mid-September through November, shorter day lengths and cooler temperatures reduce the potential for fires to occur during these months (Allen 2002).

Dendrochronology studies support the conclusion that the seasonality of weather patterns is a strong influence on the frequency and size of fires. The position of the fire scar within the annual growth ring of a tree can be used to determine the approximate time period within the season that the fire occurred (Dieterich and Swetnam 1984, Swetnam and Baisan 1990). This technique has been used to estimate the approximate timing and relative sizes of fires within selected time periods of the fire season in widely separated geographic regions, such as the Black Hills of South Dakota (Brown and Sieg 1996), central Colorado (Brown et al. 1999), western Canada (Johnson et al. 1999), northwestern Mexico (Stephens et al. 2003), eastern European Russia (Drobyshev et al. 2004), southern Colorado (Grissino-Mayer et al. 2004), eastern Cascade Mountains of Washington (2004), along the central coast of California (Stephens and Fry 2005), and in the northern Sierra Nevada (Moody et al. 2006). In New Mexico and the Southwest, results from dendrochronology studies and other evidence suggest that pre-1900 fires occurred most often and attained the largest sizes from approximately April through June (Allen 2002) or during the summer months (Heinlein at al. 2005). This compares well with digitized data on fire activity where the greatest activity was observed to begin as early as May and June and end in August (Westerling et al. 2003).

Finally, diurnal variations in weather conditions and their influence on fuel moistures and fuel temperatures dictate fire activity through the course of a day. Fire behavior model outputs are extremely sensitive to these types of changes in fire weather, with corresponding impacts to the accuracy of the models and their results (Jones et al. 2004).

Some component processes, such as weather, that contribute to fire ignitions and to the extents of fires are substantially stochastic in nature (Grimm 1984). Since some of these processes can be considered to vary independently, the resulting probability of a fire is the product of probabilities of the individual components (Whelan 1995). It is this natural spatial and temporal variability of weather conditions that influences the occurrence of fire (Peng et al. 2005). For example, conditions that control or influence the varying areal extents of fires will play a role only if a fire ignition were to occur first. These concepts and their independent probabilities have found application to the modeling of fire occurrence (Anderson 2002, Balice et al. 2005).

In the research reported in this article, we utilized the stochastic and covarying nature of weather variables to characterize the patterns of weather within seasons that would influence the occurrence and extent of fires. The objective of this research was to utilize long-term weather data to examine the relationships between weather variables, evaluate their temporal patterns within the fire season, and relate these patterns to the occurrences of fire. We did this by analyzing shifts in weather, as evidenced by temporal trends of the weather variables, which emerged from univariate and multivariate analyses of several decades of weather data from the eastern Jemez Mountains region of northern New Mexico, USA (Figure 1). The goal was to use these seasonal variations to define time periods, or subseasons, during the fire season that are internally similar with regard to their fire weather conditions. Conversely, discontinuities between these subseasons would identify transitions between adjacent, internally homogeneous subseasons. The determination of subseasons within the more expansive fire season will increase the accuracy and relevancy of fire occurrence models (Balice et al. 2005). In addition to increasing the scientific basis of fire modeling and risk characterization, these results will also assist in the identification of time periods with relatively high or relatively low fire occurrence. The results will contribute to our knowledge of the ecological relationships of fire and to more optimal fire management.

METHODS

Weather data

This research was conducted in the eastern Jemez Mountains, which includes the Los Alamos National Laboratory (LANL),

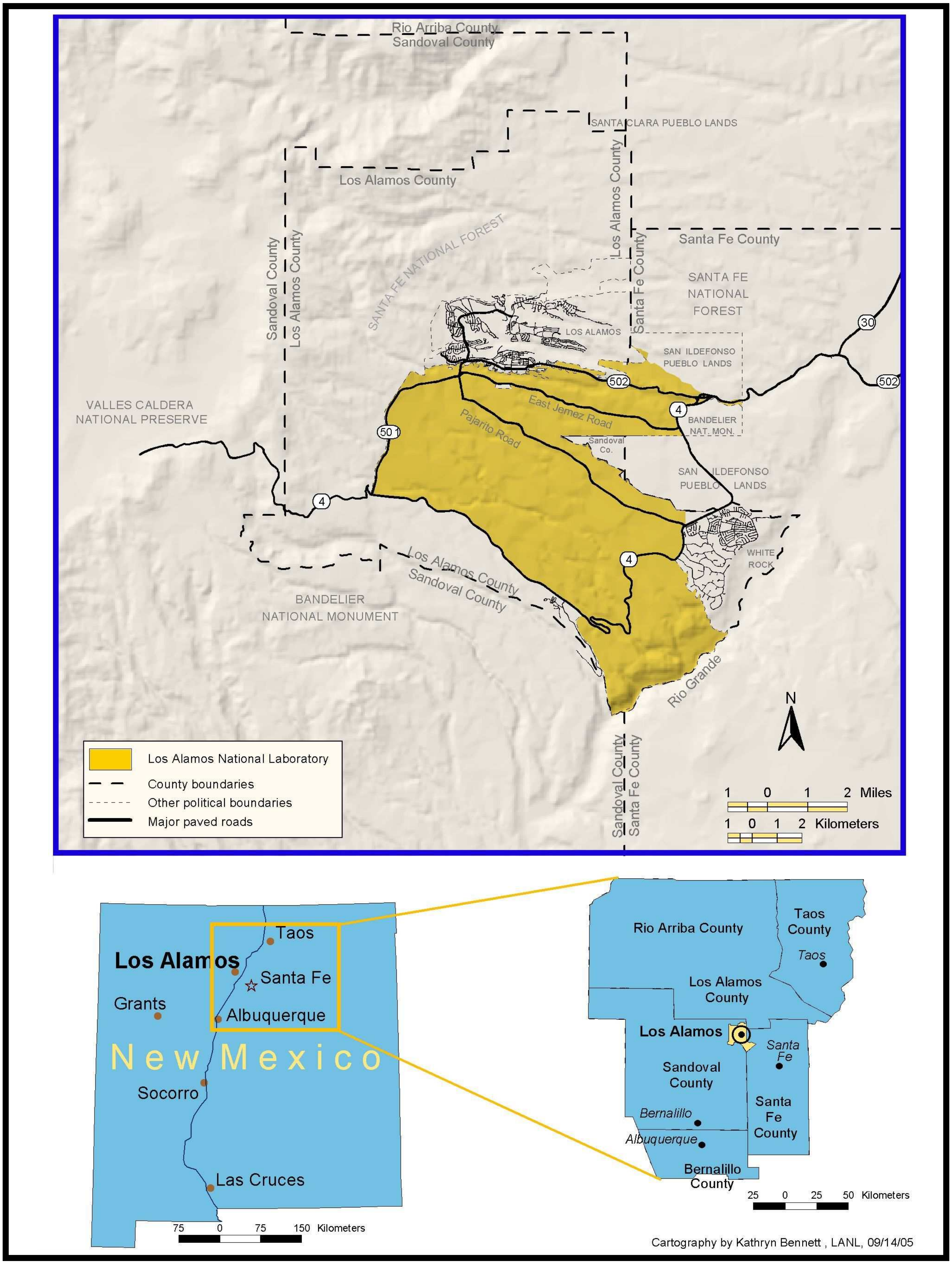

Figure 1. The eastern Jemez Mountains, New Mexico, including Los Alamos, Los Alamos National Laboratory, White Rock and Bandelier National Monument.

Bandelier National Monument, and the communities of Los Alamos and White Rock (Figure 1). LANL maintains a state-of-the-art meteorological measurement network (Baars 1998). We used data from four weather-monitoring towers that stand on upland, mesa positions roughly encompassing the 110 km^2 of the LANL facility. Figure 2 shows the entire weather-monitoring network including the four towers that supplied data for this study. The tower located at Technical Area (TA-) 6 is also presently the official weather measurement station for the town of Los Alamos, which is adjacent to LANL. The tower located at TA-54 is the official weather measurement station for the town of White Rock, located about 10 kilometers southeast of Los Alamos. Two other towers, located at TA-53 and TA-49, respectively mark the north and south borders of LANL. The system of weather towers spans an elevation range of nearly 270 m, from 1996 m to 2263 m above sea level. Towers at TA-41 and Pajarito contain very limited data and are not used in this study.

A wide variety of meteorological

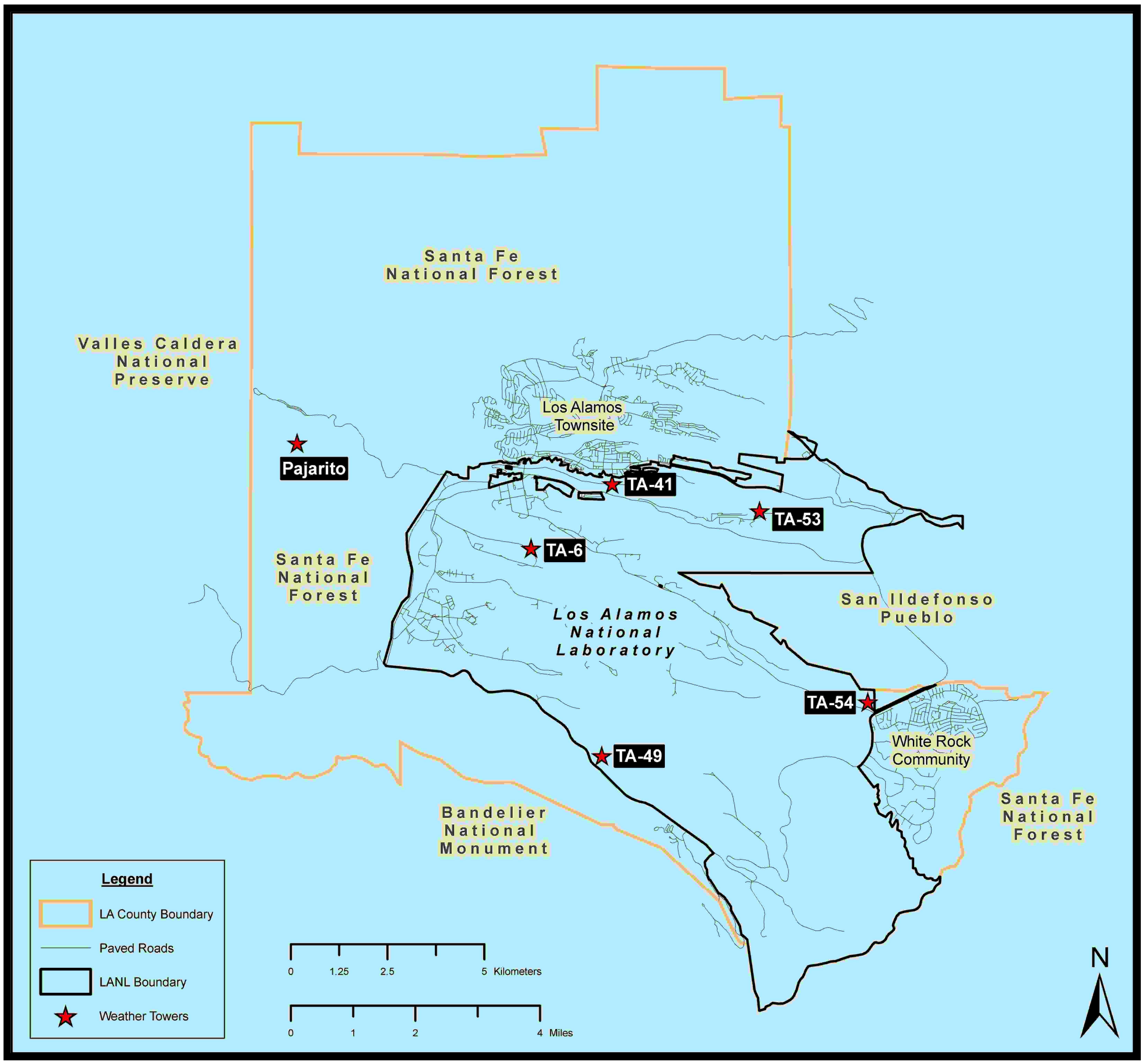

Figure 2. Locations of the weather towers at the Los Alamos National Laboratory.

Table 1. Periods of availability for each weather variable at each location.

Variable	Los Alamos	TA-6	TA-49	TA-53	TA-54
Temperature		1990-2005	1987-2005	1992-2005	1992-2005
Wind		1990-2005	1987-2005	1992-2005	1992-2005
Precipitation	1910-2005				
Lightning		1997-2005			
Relative humidity		1990-2005	1987-2005	1992-2005	1992-2005
Solar insolation		1990-2005	1987-2005	1992-2005	1992-2005

variables are measured including temperature, wind speed and direction, relative humidity, and downward shortwave (solar) radiation (Baars 1998). The TA-6 tower also measures combined cloud-to-cloud and cloud-to-ground lightning discharges, or "strokes". These lightning data are collected along with the time of the discharge, but are not location-specific. Measurements collected by the LANL network were collected starting in 1987 at TA-49, 1990 at TA-6, and 1992 at TA-53 and TA-54. Additionally, measurements of precipitation from the adjacent town of Los Alamos date back to 1910. Table 1 lists the weather variables used in this study and the periods covered by each variable at each weather tower.

The data for each weather variable from the four main towers within the LANL network were averaged to find the mean values, across tower and year, for each calendar day. Since each of these towers has approximately 15 years of data, a total of roughly 60 individual daily measurements was available to calculate calendar-day averages of temperature (degrees Celsius), wind speed (m/sec), relative humidity (percent), and downward shortwave solar radiation (MJ/m^2). It is worth noting that during the approximately 15 years of data from these towers, this region has experienced a steady warming and drying from wetter and cooler-than-normal conditions around 1990 to hotter and drier (drought) conditions at present.

Additionally, decimal fractions of the total number of days with measurable precipitation were calculated for each calendar day from the 95-year sequence of the historical data from the Los Alamos townsite archive, and eight years of lightning data spanning 1997 to 2005 were available from TA-6 to calculate the average number of lightning strokes for each calendar day.

Analytical methods

We began by estimating the fire seasons to begin on March 1 and end on September 30 and collected all of the weather data described above that pertained to this time period. Then we conducted an exploratory analysis of the univariate behavior of each weather variable. This was followed by classification of wildfire subseasons based on multivariate analysis and evaluation of the error rates for the resulting classification. The results were partially validated in two ways. First, we evaluated the dates of occurrence and the extents of 248 lightning-caused fires recorded in the Jemez Mountains. Second, we compared the results of this study with 15 years of Energy Release Component (ERC) data from Bandelier National Monument.

Individual weather parameters were analyzed to determine if significant shifts in their temporal patterns could be ascertained or if the seasonal changes in the weather descriptors were in fact gradual throughout the year. This was done by calculating the t-statistic, for each weather variable, for consecutive periods of calendar days throughout the fire season. The calculated t-statistics were based on twelve days before and after each test-day. The relative values of the moving t-statistic were used to determine the existence of major shifts in the temporal patterns of each weather descriptor.

This method was applied to each of the weather variables over the entire fire season to determine if shifts in weather behaviors are simultaneous for two or more variables, or if they occur haphazardly without organization. To determine shift dates more robustly, the t-statistic calculation was repeated three times with sample sizes of nine, twelve, and fifteen days before and after each test day. These three t-scores, for each day, were averaged. The resulting t-scores, one for each weather variable, were graphed against the calendar day.

Simultaneous analysis of all weather variables was conducted by employing the multivariate F statistic, as computed by the Statistical Analysis Systems (SAS) software package using the Multivariate Analysis of Variance (MANOVA) function (SAS Institute, Inc. 2001). This was done for each calendar day with twelve-day periods before and after each test day (degrees of freedom, numerator = 5, degrees of freedom, denominator = 18). Precipitation, wind, lightning ($\log_{10}$), solar radiation and relative humidity were used for this analysis. Since the graph of temperature was largely a monotonic function, this variable was not used in the multivariate analysis. Values for the multivariate F that achieved regional maxima, as defined by the difference between the maximum and the adjacent minima of at least ten multivariate F units, were selected as candidate subseason boundaries. Final subseason boundaries were selected from the candidates if at least three of the weather variables were significant on that day at the 0.05 level or less.

The performance of MANOVA in developing the classification of subseasons was evaluated with discriminant analysis (SAS Institute, Inc. 2001). The subseason categories, as defined by the final boundaries, were added numerically to the original database of six variables and used to calculate the error rates. The prior probabilities were set to be proportional to the sizes of the subseasons.

Although our objective methods involve techniques that are often applied to tests of significance, it does not necessarily follow that levels of significance must be incorporated here. For the sake of discussion, levels of significance could be applied if estimates of the number of degrees of freedom accounted for lack of independence between weather averages on adjacent calendar days. The effective number of degrees of freedom would be reduced, thereby reducing the significance levels. By calculating the effective number of degrees of freedom following Leith (1973), we found that reductions in the degrees of freedom would lead to reductions in significance of about 20% to 50% depending on the weather variable.

A larger reduction of significance of the peaks occurs due to the "a posteriori" manner in which the peaks are discovered. This follows from allowing any day during the wildfire season to mark a shift, rather than predicting the shift on a given day and confirming or rejecting the hypothesis that a shift occurs on that given day. As a rule of thumb, the probability of the null hypothesis would be multiplied by the number of days tested. Given that the entire fire season consists of approximately 200 days, for example, a probability of non-significance of 0.01% is increased to 2%.

Given these considerations, we estimate that the "a posteriori" significance levels of the univariate t-scores and the multivariate F statistic at subseason boundaries are approximately 95 to 98 percent. The reductions in significance are fairly uniform throughout the fire season and therefore do not shift subseason boundaries.

Partial Validation of the Results

We partially validated our results in two ways using data provided by the Bandelier National Monument Fire Unit. First, we analyzed a database containing 29 years of historical fire data recorded for the Jemez Mountains. This included a total of 373 fires from 1975 to 2003 that were recorded to be at least 0.04 hectares (0.1 acres) in size. We removed from further analysis all fires that were of unknown cause or were associated with non-lightning ignitions. This left 270 fires in the database, or approximately 72 percent of the total. Furthermore, all lightning fires that were ignited outside of the time period from March 1 to September 30 were removed, leaving 248 lightning-caused fires during the defined fire season. This was nearly 92 percent of the total lightning strikes. Next we categorized the remaining fires by subseason to determine if they supported the subseason definitions. Finally, we calculated the mean number of fires per day. We also calculated the mean number of acres per fire to estimate the average size of the fires and the quadratic mean to emphasize the average size of larger fires.

Second, we analyzed 16 years of Energy Release Component (ERC) data that had been gathered for the Los Alamos region. These ERC data were compiled from weather data collected at the Tower Station (290801), Bandelier National Monument, for the time period from 1900 to 2005, as calculated by FireFamily Plus (Bradshaw and McCormick 2005). For each calendar day, the number of years of data ranged from five to fifteen. The average and maximum ERC values for each calendar day over the time period from March 1 to September 30 were graphed and compared to the previously defined subseasons.

RESULTS

The analyses of individual weather variables supported the idea that major shifts in weather patterns would arise and be detectable in the climatology. Abrupt shifts in climatological patterns, in addition to the relatively smooth seasonal trends, were apparent. For instance, both the moving difference (Figure 3a) and the moving t-statistic (Figure 3b) exposed a major transition in the temperature data on May 30.

Furthermore, graphs of the original data and their corresponding t-statistics for the entire fire season demonstrated that major shifts in a number of weather variables can occur simultaneously (Figure 4). For example, during early July the t-statistics for every weather variable achieve large positive (or negative) values in the same approximate time period, signaling upward (or downward) shifts in each variable.

The subsequent application of MANOVA resulted in the identification of six subseasons within the wildfire season that begins on March 1 and ends on September 30 (Figure 5). These subseasons and their boundaries correspond to major shifts in the behaviors of at least three weather variables with intervening periods of relatively homogeneous conditions (Table 2).

The first subseason (March 8 to April 12) is initiated by a strong reduction in humidity and a corresponding increase in solar radiation. The potential for precipitation also decreases at this time. Temperatures increase correspondingly in early March (Figure 4). Thus, March 8 marks the beginning of the fire season. Wind speeds are typically low at the beginning of subseason 1, but increase after March 21.

Subseason 2 (April 13 to May 21) denotes a continuation of the trend from low to higher fire occurrence that was initiated in subseason 1, with a clear shift occurring on April 13. Solar heating is higher, and humidity and

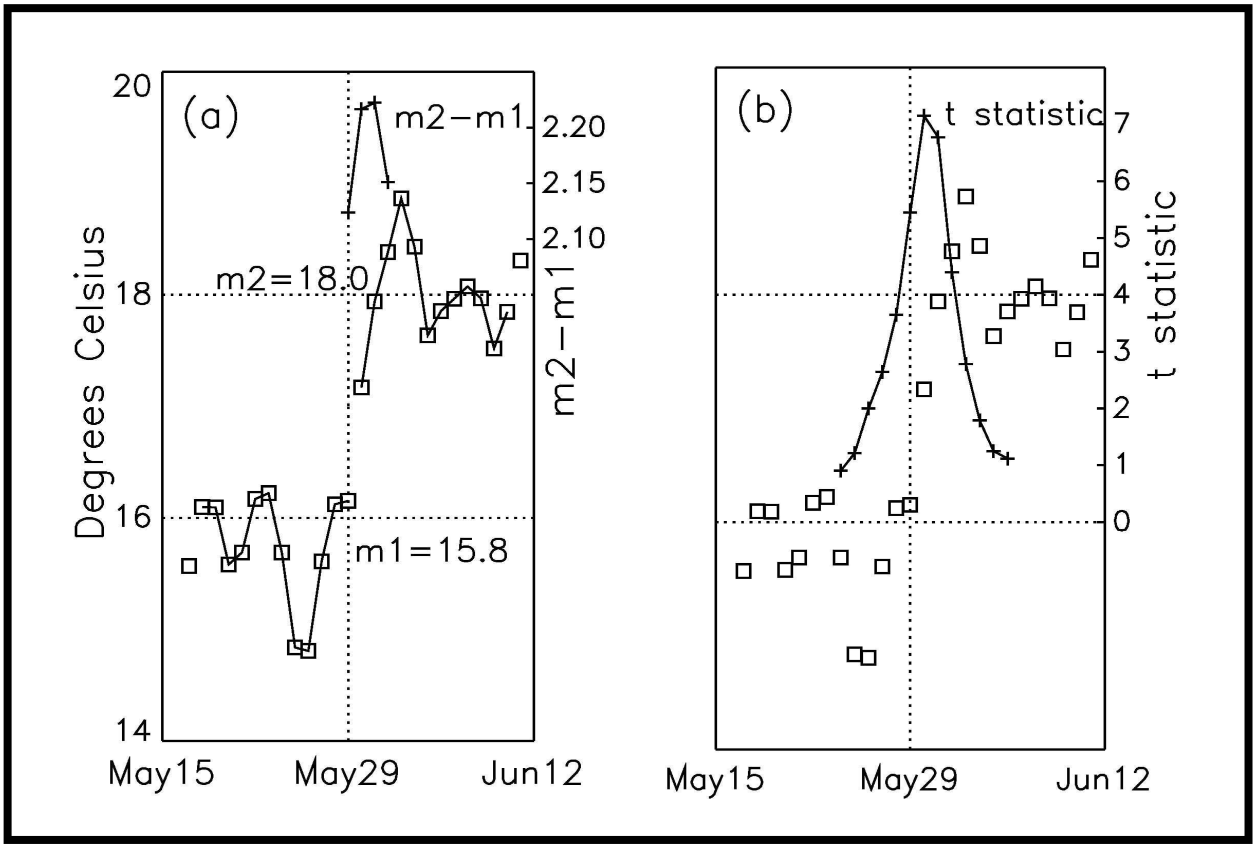

Figure 3. Temperature shift of May 30th. (a) Difference between twelve-days before-and-after temperature averages. Differences for four shift days are plotted, ranging from May 28/29 to May 31/June 1. (b) The t-statistic of thirteen twelve-day before-and-after groups is shown. The temperature shift with the largest t-statistic and smallest p-value occurs between May 29th and May 30th.

precipitation levels are lower. Lightning also becomes a factor during this time period. Moreover, wind speeds increase during this subseason and are greater than at any other time of the year. It is during subseason 2 that the Dome Fire (April 26, 1996) and the Cerro Grande Fire (May 5, 2000) occurred.

The beginning of subseason 3 (May 22 to June 23) is marked by a strong increase in lightning activity. Winds remain strong during this time period and precipitation levels are soon to decrease. As a result, this subseason marks the time period when all six of the weather variables are optimal for the occurrence of fire. The La Mesa Fire (June 16, 1977) occurred during subseason 3.

The fourth subseason (June 24 to July 8) is brief and is the most internally variable of all the subseasons identified in this study. The occurrence of wildfire can also vary during this time period, as the initiation of the monsoon varies from year to year. Precipitation increases to initiate subseason 4, whereas winds, lightning, and shortwave radiation decrease. The Oso Fire (June 27, 1998) burned during this subseason.

The fifth subseason (July 9 to September 1) marks the duration of the North American monsoon and considerable changes are seen in all six of the weather variables to begin this study. Lightning activity increases to a high level. However, this increased potential for lightning ignitions of fires is offset by a reduction in potential from each of the other variables. Temperatures decrease for the first time during the fire season. Precipitation and

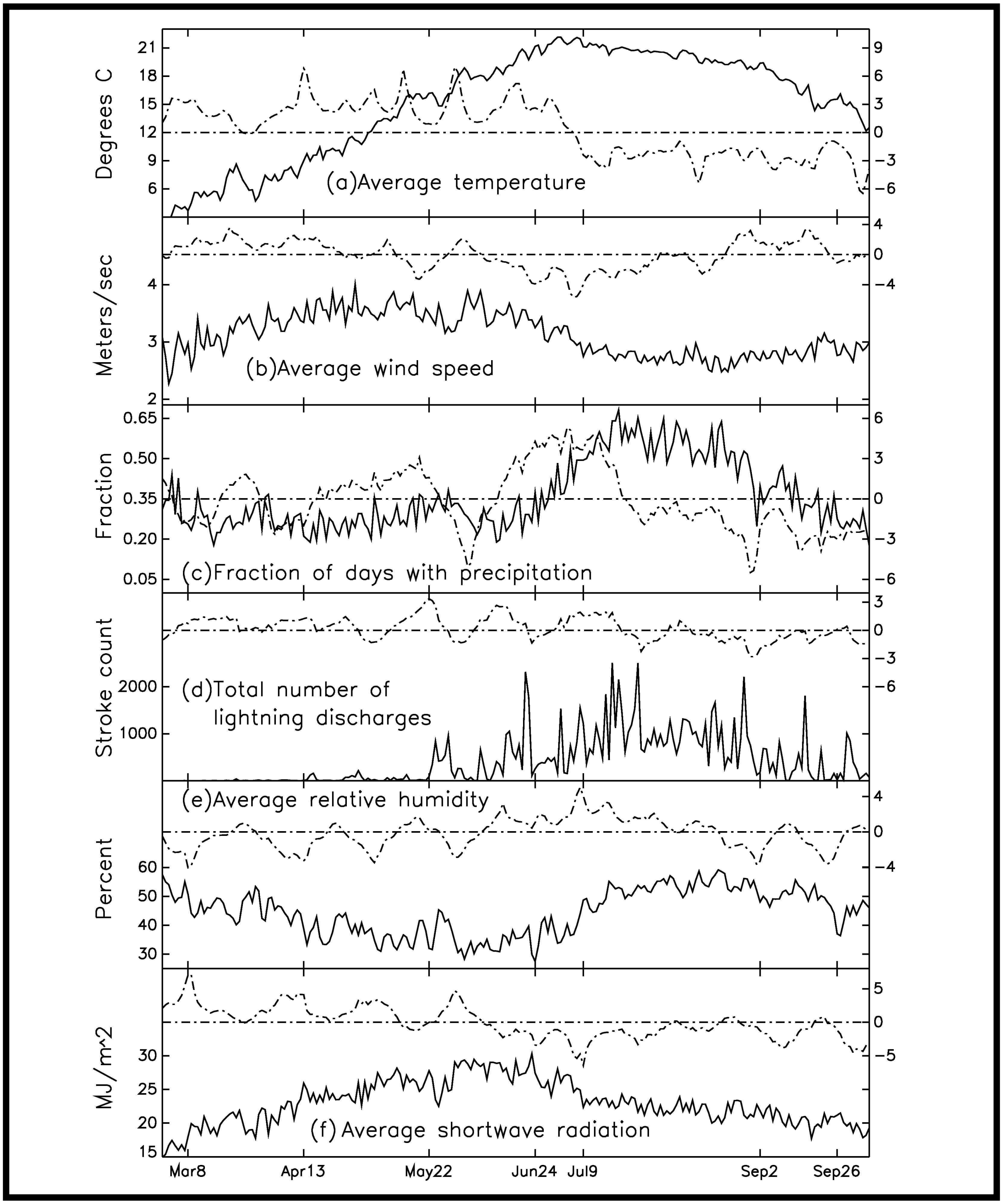

Figure 4. (a) Average temperature (solid lines, left y-axis) and t-statistic comparing neighboring nine, twelve, and fifteen-day periods before, and beginning with, each calendar day (dot-dashed lines, right y-axis). The t-statistic shown is the averaged t-statistic of the three period lengths. (b) identical presentation for wind, (c) fraction of each calendar day during which precipitation was measured, (d) total lightning discharges, (e) average relative humidity, and (f) incident shortwave (solar) radiation.

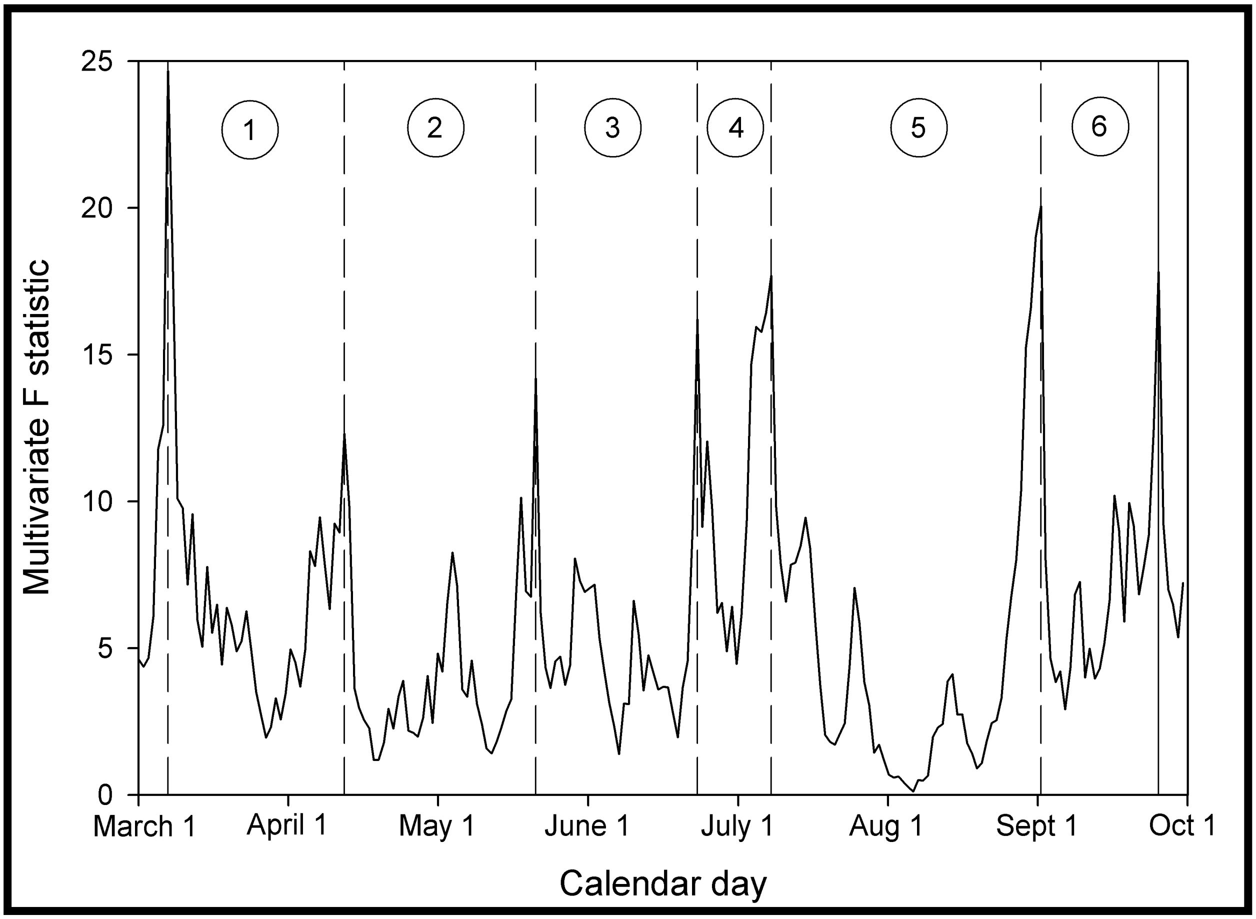

Figure 5. Results of multivariate analysis of weather variables. The a posteriori significance of all five marked peaks ranges between 95% and 98%.

Table 2. Definitions of boundaries between subseasons based on the results of MANOVA. P-values for individual weather variables in bold type are significant at the 0.05 level.

Boundary	Date	Julian day	F statistic	Pvalue	P(solar)	P(humid)	P(lightning)	P(wind)	P(precip)
1	8-Mar	67	24.66	<.0001	**<.0001**	**<.0001**	0.9037	0.2778	**0.0131**
1 to 2	13-Apr	103	12.31	<.0001	**0.0001**	**<.0001**	0.0536	**0.0142**	**0.0194**
2 to 3	22-May	142	14.18	<.0001	0.9407	0.7121	**<.0001**	**0.0010**	**0.0427**
3 to 4	24-Jun	175	16.20	<.0001	**0.0025**	0.2211	0.3171	**<.0001**	**<.0001**
4 to 5	9-Jul	190	17.69	<.0001	**<.0001**	**<.0001**	**0.0259**	**<.0001**	**<.0001**
5 to 6	2-Sep	245	20.06	<.0001	0.0734	**0.0003**	**0.0302**	**0.0250**	**0.0101**
6	26-Sep	269	17.82	<.0001	0.1098	**0.0062**	0.6861	0.582	**0.0017**

humidity increase. Downward solar radiation and winds decrease.

The sixth subseason (September 2 to October 1) is initiated by the termination of the monsoonal weather patterns. Precipitation, humidity, and lightning all decrease. Wind speeds increase somewhat as the monsoonal pattern becomes less dominant.

During subseason six, a large multivariate F value resulted on September 25, suggesting that another subseason boundary might be indicated. The large F-value for this date is associated with a decrease in precipitation and humidity. But fire occurrence is lower now, so we did not investigate this potential boundary any further.

In extreme years, the changes associated with subseason six have been characterized as constituting a "second fire season", particularly in association with human-caused ignitions. For instance, precipitation levels decrease to those that characterize subseason 2 and 3, which are considered to pose the greatest fire occurrence potential. However, none of the other weather variables achieve levels that are typical of the higher occurrence subseasons. In addition, shorter daylengths and increased overnight recovery ameliorate any fire potential.

The discriminant analysis classification of the days in the fire season using the original data resulted in approximately 97 percent accuracy as shown in Table 3. There was some confusion between subseasons 2 and 3, with additional error occurring between subseasons 5 and 6. Subseasons 2 and 3 are the time periods with the most severe hazard. The distinction between these subseasons is largely based on the increased lightning activity that occurs in subseason 3. Subseasons 5 and 6 exhibit lower fire hazards and are distinguished by the higher levels of precipitation and lightning that occur during subseason 5.

The results of validation against historical lightning-caused fires are shown in Table 4. The time periods outside of subseasons 1 through 6 did not experience any fires in the 29 years of data. After March 8, there are relatively few fires until May 22. After that, the numbers of fires increase to about 0.60 per day per 10 year period. After September 2, the number of fires returns to lower levels.

The highest daily fire frequency occurred during the monsoon subseason (number 5) from July 9 to September 1. However, these fires tended to be much smaller in size, reflecting the increased amounts of both lightning and precipitation during this subseason. Although the third subseason experienced slightly fewer fires per day than subseason number 5, these fires tended to be much larger. This would reflect the abundance of lightning and wind with less precipitation and drier fuel conditions during subseason three.

Table 3. Results of discriminant analysis using prior probabilities proportional to the sizes of the subseasons. The cell values are counts followed by percentages in parentheses.

From subseason	**To subseason**						**Total**
	1	**2**	**3**	**4**	**5**	**6**	
1	36 (100)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	36
2	0 (0)	35 (90)	4 (10)	0 (0)	0 (0)	0 (0)	39
3	0 (0)	1 (3)	32 (97)	0 (0)	0 (0)	0 (0)	33
4	0 (0)	0 (0)	0 (0)	15 (100)	0 (0)	0 (0)	15
5	0 (0)	0 (0)	0 (0)	0 (0)	54 (98)	1 (2)	55
6	0 (0)	0 (0)	0 (0)	0 (0)	2 (7)	27 (97)	29
Total	36	36	36	15	56	28	207

Table 4. Historical lightning-caused fires from 1975 to 2003 for the Jemez Mountains, by subseason.

Subseason	Start Date	End Date	Number of days	Number of fires	Number of fires/day	Mean acres	Quadratic mean acres
0	March 1	March 7	7	0	0	0	0
1	March 8	April 12	37	2	0.05	0.10	0.10
2	April 13	May 21	39	28	0.72	0.84	2.23
3	May 22	June 23	33	65	2.00	153.42	1034.96
4	June 24	July 8	15	22	1.47	144.75	353.52
5	July 9	Sept 1	55	118	2.15	52.06	561.55
6	Sept 2	Sept 26	25	13	0.52	0.58	1.31
00	Sept 27	Oct 1	5	0	0	0	0

The results of validation against the unsmoothed energy release component (ERC) are shown in Figure 6. Note that the shifts in the mean ERC tend to occur at the same time as the subseason boundaries, which are superimposed on Figure 6. The ERC levels outside of the defined subseasons are generally low. During subseason one, the ERC increased somewhat, but is still low. The trend of relatively high mean and maximum ERC values from subseason 2 through 4 suggests that fires during this period would tend to be more severe, if ignited. This complements the results in Table 4 where the numbers and sizes of fires increase as lightning ignition sources increase. The mean ERC during subseason four is a transition from the high levels experienced during subseason three and the low levels of subseason five. During subseason 6, the ERC levels increase somewhat, with the cessation of the monsoon.

The maximum ERC values indicate that during severe fire years, the tendency for higher ERC during subseasons two and three are extended and broadened into subseasons one and four. Moreover, the boundary of subseason one can be shifted towards March 1 and the boundary of subseason four can be shifted into the monsoon subseason (number five). Similarly, the maximum ERC levels during subseason six contrast with those from subseason five. However, the boundaries may shift to late August during more severe fire years (e.g., August 2003 and the Lakes Fire in the western Jemez Mountains).

DISCUSSION

Fire occurrence clearly depends strongly on climate (Westerling et al. 2003, Swetnam and Betancourt 1990, 1998). Therefore, determining shifts in climate determines shifts in fire occurrence and fire danger as well. This work shows that shifts in climate within the fire season, and thus shifts in fire occurrence within the fire season, can be identified using objective analysis of average weather.

The term "climatology" refers to average climate or average weather. The climatology of northern New Mexico, for example, includes windy springs, dry early summers, and moist late summers courtesy of the North American monsoon. Weather records spanning extensive time periods must exist for climatology to be defined. The World Meteorological Organization, for example, instructs that the period 1961-1990 be used to define standard weather normals (World Meteorological Organization, 1984). Climatology offers a weather forecast for as

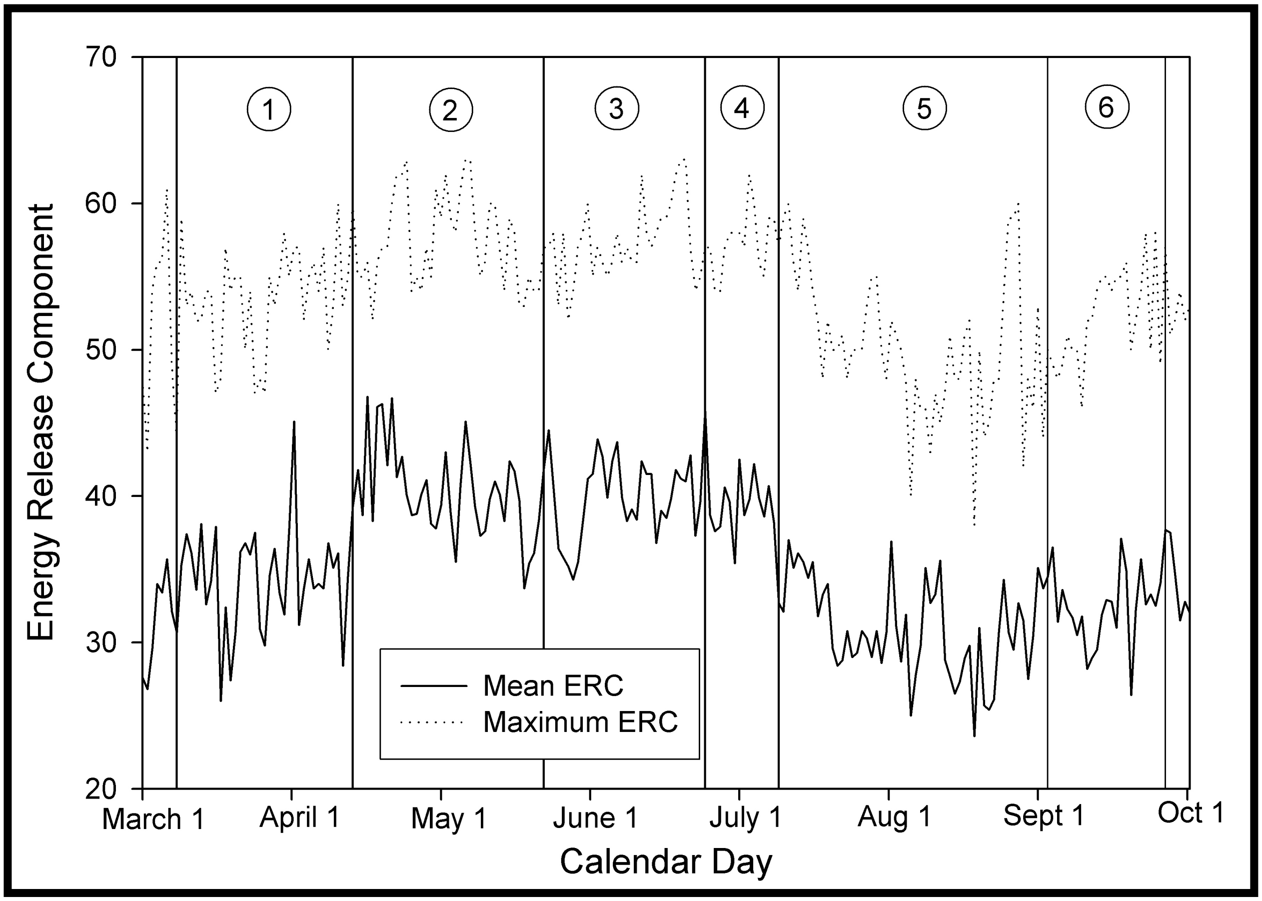

Figure 6. Average and maximum ERC from 1990 to 2005 for Bandelier National Monument by subseason.

many years in advance as the climate remains stationary. The climatology forecast is limited, in addition, by the sensitivity of the non-linear nature of weather and interannual climate mechanisms such as ENSO and the PDO.

Climatology provides a long-lead weather forecast, and therefore a long-lead forecast of fire occurrence as well. Our purpose has been to identify climatology to as fine a resolution as can be useful to the realm of fire management. We have found that fire-weather can assume a uniform state for anywhere from two to six weeks, and then change into a considerably different regime. This allows us to develop a distinct, climate-based definition of when and why the potential for fire varies. Despite the prominence of weather considerations in the wildland fire literature, a close look at the definition of the "fire season" and "fire seasonality" appears to be absent. A quantitative investigation of climatology adds valuable information by providing an objective and quantitative assessment of the "fire season" by dissecting it into homogeneous subunits.

The definition of subseasons and the establishment of boundaries between subseasons does not assert that one subseason ends exactly on a particular day nor does it attach precise measures of the uncertainty associated with such assertions. To do so would require the application of change-point detection methods, which present a very challenging statistical problem (Lai 1995, Mei 2006). Rather, our objective here is to present a relatively simple procedure that identifies subseason boundaries that are useful for characterization, development of risk models and management decision-making.

This high-resolution climatology should be expected to assume a different signature in different regions, just as fire occurrence is well known to vary among different regions (Westerling et al. 2003). Therefore, our method must be applied separately to different climate regions. However, our general method could be applied to data from other regions to obtain subseason boundaries appropriate for their corresponding climate regimes.

The analyses and results presented here support the development of climate-based, probabilistic fire occurrence models and seasonal fire danger forecasting tools (e.g. Anderson 2002, Carlson et al. 2002, Balice et al. 2005, Roads et al. 2005) by providing a method for temporally dividing the fire season into spans of homogeneous fire weather. Probability models can more easily be developed for each span, or "subseason", given that weather is effectively constant within each subseason.

The identification of fire subseasons is a contribution to the management of wildland fires and to fire planning and will complement models and tools already in use (e.g., Cohen and Deeming 1985, Carlson et al. 2002). Managers must make critical decisions regarding the allocation of fire-management resources. This may include fire-fighting teams and equipment as well as subject matter experts who may utilize their own resources in different ways during different subseasons. A quantitative method for determining seasonality of fire provides managers with another decision-making tool to respond to variations of fire occurrence during the broader fire season.

Seasonality of fire, in addition to fire intensity and other fire characteristics, may also be important in determining the effects of fire on biota (Whelan 1995). For plants, the survival of individual organisms from a fire will be determined by various life-history, anatomical, physiological, and behavioral characteristics, such as flowering, seed production, ability of seed to survive fire, productivity, and the ability of plants to exploit post-fire conditions. For New Mexico and the Southwest, where fires burn more frequently and more extensively in the late spring and early summer time period, the effect may be to split the growing season into two segments; one in the early spring and the second during late summer and fall. This would contribute to the tendency for plant life histories to take advantage of potentially fewer disturbances and greater amounts of moisture during each of these two disjoint growing periods

Identifying fire subseasons and their consequences to biota are important components of our historical ecological knowledge for the development ecosystem restoration processes and programs (see Swetnam, Allen, Betancourt 1999, Allen et al 2002). The seasonal timing of restoration activities can have a strong influence on their outcomes. Therefore, the understanding of the seasonal trends in fire occurrences and behaviors, and of the weather patterns that drive these trends, are important to the design of restoration prescriptions. However, knowing that climate changes in the future may not follow the same trajectories as the past weather and climate data that were used to determine subseason definitions and restoration prescriptions, the conditions, criteria and thresholds of these prescriptions must be expanded to allow for a potentially wider range of variability (Brown et al. 1999).

CONCLUSION

We have found that fire weather can assume a uniform state for anywhere from two to six weeks, and then change into a considerably different regime. These periodic shifts are more frequent than the change of seasons. Thus, fire weather, like many other ecological and evolutionary processes can be marked by punctuated equilibria (cf. Futuyma 1987, Sneppen et al. 1995, Bak and Paczuski 1995). These periods of stability separated by rapid changes have important implications to ecological responses, as well as management. Successful flowering and fruiting of plant species may be adapted to the length of the period that is characterized by conditions that are conducive to these phonological traits. Land managers can request support based on conditions that are likely to continue for several weeks, rather than days or months.

Within individual seasons, time periods that are conducive to fire are caused by convergence of relatively independent weather conditions (Parsons 1981). For New Mexico and the Southwest, a high level of lightning strikes occurs during the period of low and decreasing foliage moisture content, maximum temperatures, high wind speeds, and minimal precipitation. The time period for this convergence can be quite short, only a few weeks. However, during drought and other years of severe weather, this convergence of fire inducing weather can last for months. With or without lightning strikes, any ignition during this time period can cause a severe fire.

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