WILDFIRE AND CLIMATE INTERACTIONS ACROSS THE SOUTHWEST UNITED STATES

by

Michael Alan Crimmins

A Dissertation Submitted to the Faculty of the

DEPARTMENT OF GEOGRAPHY AND REGIONAL DEVELOPMENT

In Partial Fulfillment of the Requirements
For the Degree of

DOCTOR OF PHILOSOPHY
WITH A MAJOR IN GEOGRAPHY

In the Graduate College

THE UNIVERSITY OF ARIZONA

2004

The University of Arizona ®
Graduate College

As members of the Final Examination Committee, we certify that we have read the dissertation prepared by Michael Alan Crimmins

entitled Wildfire and Climate Interactions Across the Southwest United States

and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy

Andrew C. Comrie	10/29/04 date
Katherine K. Hirschboeck	10/29/04 date
Timothy J. Brown	10/29/04 date
Thomas W. Swetnam	10/29/04 date
Gregg M. Garfin	10/29/04 date

Final approval and acceptance of this dissertation is contingent upon the candidate's submission of the final copies of the dissertation to the Graduate College.

I hereby certify that I have read this dissertation prepared under my direction and recommend that it be accepted as fulfilling the dissertation requirement.

Dissertation Director: Andrew C. Comrie — 12/6/04 date

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SIGNED: Michael A. Cimini

ACKNOWLEDGEMENTS

Many people made my time at the University of Arizona a fruitful and rewarding experience. Special thanks to my advisor Dr. Andrew Comrie for his exceptional mentoring as I made my way through the Ph.D. process. His practical and sound career advice will benefit me for years to come. Many thanks Dr. Katie Hirschboeck, Dr. Tom Swetnam, Dr. Gregg Garfin, and Dr. Tim Brown, my dissertation committee, for dedicating time to reading drafts and offering advice along the way. The WALTER project team also played a large role in forming the topic for my dissertation. I am especially grateful to Dr. Barbara Morehouse, Dr. Barron Orr, and Dr. Steve Yool who offered much useful advice and assistance through my time at the University of Arizona.

Friends and colleagues in the Department of Geography and Regional Development and from other departments across campus were an important part of graduate school for me. Many thanks to all of them for stimulating intellectual conversations and the willingness to go grab a beer at the drop of a hat. Special thanks to the Department's administrative staff, especially Linda Koski and Cathy Weppler, for the incredible amount of help they provided through my program.

This dissertation would have been impossible without the constant support and encouragement of my family. Much love to them and especially my wife, Theresa. Her editing skills, counsel on scientific matters, and emotional and spiritual guidance are evident throughout this work.

This research was funded in part by the University of Arizona Space Grant Fellowship Program and the U.S. EPA Science to Achieve Results (STAR) Program under grant #R-82873201-0.

DEDICATION

To my family, especially Theresa, for their support, guidance, patience, and unconditional love that made this possible.

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ABSTRACT

Variability in climate and wildfire activity are inextricably linked through complex and often poorly understood processes. The studies presented in this dissertation examine fire-climate relationships across the southwestern United States at different temporal and spatial scales. Collectively, they identify that low-frequency and high-frequency changes in climatic variables important to wildfire are connected through teleconnection patterns originating in the tropical and extratropical Pacific Ocean (El Nino-Southern Oscillation [ENSO] and Pacific Decadal Oscillation [PDO]). Variability in precipitation years prior to a wildfire season appears to affect the overall number of fires and total area burned by either promoting or limiting the growth of fine fuels and also controlling moisture levels in heavy fuels. The same mechanisms (ENSO & PDO) that play a role in precipitation variability across the Southwest also appear to modulate the frequency of extreme fire weather events during the spring fire season.

Identifying links between high and low frequency climatic variables important to wildfire variability provides additional insight into the complex mechanisms that link wildfire and climate. The results of this dissertation will aid in improving wildfire planning efforts that extend seasons to decades into the future.

CHAPTER 1. INTRODUCTION

Explanation of Problem

Fire plays a critical role in the maintenance of healthy grassland and forest ecosystems and is strongly regulated by climatic variability (Pyne 1984, Swetnam and Betancourt 1990). This is often forgotten as historic fire suppression has limited human's exposure to the natural fire cycle as regulated by local climate conditions. As public policy shifts towards more ecological land management techniques that include restoring natural fire ecologies, a better understanding of anthropogenic and environmental controls on fire regimes will be necessary. Fire regimes are strongly governed by human land use management policies as well as long-term and short-term climate conditions preceding fire incidents. Efforts to restore ecosystems with fire rely heavily on climate variables, like precipitation and temperature, that regulate the flammability of fuels and an ecosystem's response to fire (Brown and Betancourt 1999) The mesoscale response of ecosystems to long-term and short-term climatic controls is an important control of fire regimes, but poorly understood and in need of further research (Swetnam and Betancourt 1998).

The spatial and temporal scales of climate variability that impact mesoscale natural fire regimes range from global teleconnection patterns with decadal periods (e.g. ENSO) down to local scale variations in temperature, relative humidity and windspeed that vary through a diurnal cycle (Fosberg et al. 1993, Johnson and Wowchuk 1993, Bessie and Johnson 1995, Flannigan and Wotton, 2001). The local climate is nested in the larger synoptic atmospheric environment, which is inextricably linked to global scale circulation patterns. Inferences into the relationships between fire regimes and climate requires that climate variability be addressed at these varying spatial and temporal scales.

The southwest United States (Arizona and New Mexico) presents a unique study area to analyze fire-climate relationships. Strong teleconnection patterns exist between low-frequency changes in Pacific Ocean sea-surface temperatures (ENSO & PDO) and winter precipitation and temperature regimes across the Southwest (Redmond and Koch 1991, Gershunov 1998, Cayan et al. 1999). The variations in winter temperature and precipitation have also been linked to variability in wildfire activity through modulation of fuel moisture and fuel production mechanisms (Swetnam and Betancourt 1990, 1998). Fire seasons (April-May-June) are predictably hot and dry across this desert region making fuel availability an important determinant of wildfire variability. Extreme fire weather conditions beyond the climatological high temperatures and low relative humidities during this period are produced by wind events (Schroeder 1969). It is unclear what role these extreme fire weather conditions play in controlling overall seasonal wildfire activity due to their intermittent nature. Regardless, increases in the frequency of extreme events would increase the probability of a random fire event coinciding with these extreme fire weather conditions. Regional statistics of total area burned during a fire season are often dominated by one or two wildfire events that burn large areas. These fires are also often associated with extreme fire weather conditions.

This dissertation investigates fire-climate relationships across the southwest United States through various spatial and temporal scales. Through three separate studies

I investigate the role of antecedent climate conditions with respect to seasonal wildfire activity and examine how low-frequency climatic changes controlling these antecedent conditions may also be accompanied by changes in extreme fire weather events.

Approach

This dissertation research uses statistical methods and synoptic climatological techniques to examine fire-climate relationships. The first study uses multivariate statistical methods to analyze relationships between lagged climate data and variations in seasonal wildfire statistics (total area burned and total number of fires). The remaining two studies analyze climate data sensitive to predicting wildfire behavior, but do not draw on actual wildfire data due to data constraints. The resolution of available wildfire data is too coarse (spatially and temporally) to examine in association with the daily variability of fire weather conditions.

Traditional parametric statistics are used in the first study relying on correlation analysis, principal components analysis and linear regression modeling to identify fire-climate relationships. Studies two and three use non-linear and non-parametric statistical approaches in conjunction with synoptic climatological methods to examine extremes in southwestern U.S. fire weather. Changes in extremes often do not show up in the analysis of mean climatological variables (e.g. Gershunov 1998) and require specialized analyses to detect changes (Frei and Schar 2001). A neural network based clustering algorithm called the self-organizing map (Kohonen 2001) is used in the second study while the non-parametric logistic regression modeling technique is used in the third study. These techniques have not seen wide application in climatological studies, but are appropriate when examining extreme events and potentially non-linear relationships (Travis et al. 1997, Hewitson and Crane 1996, 2001).

Organization of the Dissertation

The research presented in this dissertation consists of three separate, but related, studies. Each study is presented as a separate paper in the appendix and is ready for submission to a journal for consideration of publication. Literature reviews for each study are found in their respective papers.

Appendix A, titled "Interactions between antecedent climate and wildfire variability across southeast Arizona" was co-authored with Dr. Andrew Comrie and has been accepted for publication in the International Journal of Wildland Fire. Dr. Comrie provided assistance in developing the methodology used in this study and provided extensive help in reviewing manuscripts. Relationships between antecedent climatic conditions and wildfire activity during the April-May-June fire season were quantified for southeast Arizona in this study.

Appendix B titled "A synoptic climatological analysis of extreme fire weather conditions across the southwest United States" was prepared for submission to the International Journal of Climatology. This study identifies synoptic circulation patterns critical to producing extreme fire weather conditions on the surface. A relatively new method of classification (Self-Organizing Maps) was employed in the analysis to develop a set of key circulation patterns that capture springtime variability across the southwest U.S.

Appendix C, titled "Inter-annual to decadal changes in extreme fire weather event frequencies across the southwestern United States", was prepared for submission to the Journal of Climate. The occurrence of daily extreme fire weather events is modeled using a logistic regression approach to estimate annual fire season (AMJ) frequencies for the period of 1958-2003. Inter-annual and decadal changes are related to known teleconnection patterns to identify potential mechanisms that may be modulating the changes in frequencies.

CHAPTER 2. PRESENT STUDY

The methods, results, and conclusions of this dissertation are distributed in the appended papers. Overall findings in the three separate studies underscore the complex role of climate variability in modulating wildfire variability across the southwest United States. Low-frequency changes in the primary modes of wintertime atmospheric circulation related to ENSO and PDO not only modulate precipitation important for fuel production and fuel moisture levels, but also appear to modulate the occurrence of springtime critical fire weather circulation patterns. These findings together portray that seasonal wildfire variability across the southwest U.S. is a synergy between longer-term fuel production and conditioning mechanisms and changes in the frequency of extreme fire weather conditions. Understanding the role of ENSO and PDO with respect to wildfire variability allows for better seasonal forecasting of wildfire activity and can help in suppression activities and fuel reduction prescription planning.

Appendix A - "Interactions between antecedent climate and wildfire variability across southeast Arizona"

Seminal work by Swetnam and Betancourt (1990,1998) identified the role of low frequency climate variability in modulating fire regimes across the southwest United States. Interannual to decadal changes in precipitation related to the Southern Oscillation were significantly correlated with wildfire activity years later. They hypothesized that this lagged response was related to the production of fine fuels that could enhance the spread of wildfire by increasing fuel connectivity at landscape scales.

The present study uses contemporary wildfire and climate data to examine if these relationships still exist under present forest management policies. Wildfire data collected by various local, state, and federal agencies were compiled into one coherent dataset for the state of Arizona and provided by the Laboratory of Tree Ring Research at the University of Arizona. These data were aggregated into seasonal totals for upper (>1500 m) and lower (<1500 m) elevations locations across a five county area of southeast Arizona.

Correlation analyses between lagged seasonal climate data (precipitation, temperature, and Palmer Drought Severity Index, Palmer Z-index) and seasonal wildfire statistics (total number of fires and total area burned) uncovered significant correlations similar to those found in Swetnam and Betancourt (1998). Larger low elevation fires were actually associated with wet antecedent conditions until just prior to the fire season. Larger high elevation fires were associated with wet conditions during seasons up to three years prior to the fire season. These positive correlations between lagged precipitation and total area burned highlight the importance of climate in regulating fine fuel production for both high and low elevation fires

Regression models built upon the strongest lagged climate-wildfire relationships could explain up to 75% of the variance in some wildfire statistics. Lagged precipitation and Palmer Drought Severity Index values could explain 35% of the variance in upper elevation total area burned while lagged precipitation and fire season temperature could explain 75% of the variance in the number of upper elevation wildfires during AMJ.

Appendix B – "A synoptic climatological analysis of extreme fire weather conditions across the southwest United States"

This study builds upon the work of Schroeder (1969) to identify synoptic circulation patterns related to extreme fire weather conditions across Arizona and New Mexico. A unique, non-linear clustering algorithm called the Self-Organizing Map (Kohonen 2001) is used to develop key circulation patterns that occur during the spring fire season (April, May and June). The classification of weather types developed for this study allows for the critical fire weather patterns to be examined with respect to the continuum of circulation patterns that characterize the springtime transition period.

Three circulation patterns are identified as critical fire weather patterns with respect to 90^{th} percentile exceedance days of the regional average Fosberg Fire Weather Index. The number of exceedance days associated with these critical fire weather types were significantly different from the expected number using χ^2 tests. Over 80% of the exceedance days identified for this study occur during days classified to one of these three patterns.

The frequency of the three patterns changes from April to June with the highest number in April. The most efficient relationship between exceedance days and critical pattern occurrence is during May when temperatures increase and relative humidity levels fall. May and June have especially efficient relationships between the co-occurrence of exceedance days and critical fire weather patterns. These patterns are also implicated in two high profile wildfire events that occur in New Mexico and Arizona during May and June respectively.

Appendix C – "Inter-annual to decadal changes in extreme fire weather event frequencies across the southwestern United States"

The third study builds upon findings from the second paper presented in this dissertation. Extreme fire weather conditions are examined again but with emphasis on temporal variability ranging from interannual to decadal scales. These temporal scales are commensurate with the low-frequency variations in ENSO and PDO and their teleconnective relationships to precipitation across the southwest U.S. (Gershunov and Barnett 1998, Gutzler et al. 2002, Brown and Comrie 2004). The main hypothesis tested in this study is that extreme fire weather conditions are modulated by these same teleconnections.

Fire weather observations in remote areas have been systematically collected since the late 1980's across Arizona and New Mexico through the Remote Automated Weather Station (RAWS) network. 700mb geopotential height anomaly composites of days when fire weather conditions were extreme (high winds, low relative humidity values) for Arizona and New Mexico show a strong height gradient across the region. This circulation pattern is used to identify extreme fire weather days back through 1958 using a consistent, upper level meteorological dataset (Reanalyis Data, Kalnay 1996). A logistic regression model predicts the probability of occurrence of an exceedance day based on the strength of the geopotential height gradient and relative humidity levels at the 700mb level across Arizona and New Mexico.

Predictions are most accurate during the calibration period (1988-2003) for May (r = 0.9) so the remaining analysis is constrained to this month. Predicted May exceedance day frequencies depict a great deal of interannual variability with values ranging from zero to eight through the study period. The early period of the record appears to possesses a great deal of variability with some of the highest and lowest frequency values being confined to the period of 1961-1976. The Pacific Decadal Oscillation was primarily in its negative phase during this period. A shift to the positive phase of the PDO after 1976 was accompanied by lower May exceedance day frequencies.

χ^2 tests show that a significantly different proportion of exceedance to non-exceedance days is evident when May values are grouped by PDO phase. Of the 101 May exceedance days predicted in this study, 69 are associated with the negative PDO phase. Further sub-compositing by ENSO state reveals that La Niña events during the negative PDO phase are associated with the highest number of exceedance days (36) of any ENSO state-PDO phase combination. Geopotential height anomalies (700mb) show that statistically significant anomaly patterns are associated with these sub-composites and help explain the higher and lower than expected exceedance day frequencies.

Summary

Important fire-climate relationships for the southwest United States have been identified in each of these studies. Overall, the main findings can be summarized through the following points:

- Antecedent climate conditions are an important determinant of wildfire variability in lower-elevation, grass dominated and higher-elevation Ponderosa Pine dominated communities. Fine fuel production and overall fuel moisture condition are modulated by antecedent climate.
- Extreme fire weather conditions (high wind speeds, low relative humidity/high temperatures) occur throughout the spring (AMJ) fire season, but are most frequent during the month of May. Prescribed burning and wildfire suppression activities are especially dangerous during May, because of the higher incidence of extreme fire weather conditions.
- The frequency of extreme fire weather conditions during May varies interannually and over decadal time-scales. These variations appear to be related to low-frequency variability in equatorial and north Pacific sea surface temperatures through teleconnection patterns.

The three studies presented in this study address the broad range of spatial and temporal scales where relationships between climatic variability and wildfire exist across the southwest United States. Collectively, they identify that low-frequency and high-frequency changes in climatic variables important to wildfire are connected through teleconnection patterns originating in the tropical and extratropical Pacific Ocean.

Linking changes in the frequency of extreme fire weather events with longer-term changes in precipitation and temperature patterns across the Southwest provides additional insight into the complex mechanisms that link climatic and wildfire variability. Improvements in the seasonal forecasting of ENSO and PDO may also allow for improvements in seasonal fire severity forecasting when used in conjunction with these results.

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APPENDIX A

INTERACTIONS BETWEEN ANTECEDENT CLIMATE AND WILDFIRE VARIABILITY ACROSS SOUTHEAST ARIZONA

MICHAEL A. CRIMMINS AND ANDREW C. COMRIE

(In press at the International Journal of Wildland Fire)

Abstract

Long-term antecedent climate conditions are often overlooked as important drivers of wildfire variability. Fuel moisture levels and fine-fuel productivity are controlled by variability in precipitation and temperature at long timescales (months to years) prior to wildfire events. This study examines relationships between wildfire statistics (total area burned and total number of fires) aggregated for southeastern Arizona and antecedent climate conditions relative to 29 fire seasons (April-May-June) between 1973-2001. High and low elevation fires were examined separately to determine the influence of climate variability on dominant fuel types (low elevation grasslands with fine fuels vs. high elevation forests with heavy fuels). Positive correlations between lagged precipitation and total area burned highlight the importance of climate in regulating fine fuel production for both high and low elevation fires. Surprisingly, no significant negative correlations between precipitation and seasonal wildfire statistics were found at any seasonal lag. Drought conditions were not associated with higher area burned or a greater number of fires. Larger low elevation fires were actually associated with wet antecedent conditions until just prior to the fire season. Larger high elevation fires were associated with wet conditions during seasons up to three years prior to the fire season.

Introduction

Fire plays a critical role in the maintenance of healthy grassland and forest ecosystems and is strongly regulated by climatic variability (Pyne 1984, Swetnam and Betancourt 1990). This fact is often overlooked as historic fire suppression has limited humans' exposure to the natural fire cycle that is inherently regulated by local climate conditions. As public policy shifts towards more ecological land management techniques that include restoring natural fire ecologies, a better understanding of anthropogenic and environmental controls on fire regimes is necessary. Currently fire regimes are strongly governed by human land use management policies as well as long-term and short-term climate conditions preceding fire incidents. Efforts to restore ecosystems with fire rely heavily on understanding climate variables such as precipitation and temperature that regulate the flammability of fuels and an ecosystem's response to fire (Brown and Betancourt 1999). The mesoscale response of ecosystems to long and short-term climatic controls is an important but poorly understood moderator of fire regimes (Swetnam and Betancourt 1998).

Much research has been done to characterize fire weather, that is, the weather conditions on the order of days to weeks preceding fire events (Flannigan and Wotton 2001, Schroeder 1969, Bessie and Johnson 1995). Little work has been done to reveal how weather conditions prior to fire events fit into a larger spatial and temporal setting. Several days or weeks of above normal temperatures and below normal precipitation are not always the only important climatic factors that dictate the elevation of fire risk (Flannigan and Wotton 2001). Seasonal, annual, and interannual variability in climate can regulate fire risk by controlling the production and conditioning of fuels in ecosystems (Swetnam and Betancourt 1990, Westerling et al. 2002). These longer-term climate variations are often much more important than short-term fire weather conditions in arid climates, such as the desert Southwest, where there is a seasonal climatology of favorable fire weather conditions that persist for several months every year. Large fire events in the desert Southwest appear to be related to complex climatic signatures in antecedent conditions up to several years prior to the event (Rogers and Vint 1987, Swetnam and Betancourt 1998, Barton et al. 2001, Grissino-Mayer and Swetnam 2000). The basin and range landscape of southeastern Arizona possesses a unique diversity of ecological community types with unique fire regimes that may be influenced differently by antecedent climatic conditions.

The aim of this study is to identify the importance of antecedent climatic conditions to wildfire variability (total area burned and total number of fires) across southeastern Arizona. A correlation analysis will help isolate relationships between wildfire and climate at specific lags while a regression analysis will be used to identify which combinations of lagged climate variables have the greatest power at predicting wildfire activity. Identification of lagged climate variables strongly related to wildfire variability helps to identify potential causal mechanisms and can be used in a predictive capacity to forecast wildfire activity.

Study Area

The study area (figure 1) is defined by the boundary of Arizona climate division number seven. This climate division includes the southeastern Arizona counties of Pima, Graham, Greenlee, Santa Cruz, and Cochise. A basin-and-range relief dominates most of the study area with elevations ranging from over 2800 meters at the highest range to 200 meters at western edge low desert locations. Climate in low desert locations is classified as arid with annual precipitation amounts rarely exceeding 200 mm. Annual precipitation amounts are bimodally distributed with most precipitation occurring in either the summer (JAS) monsoon season or winter (DJFM) season. Winter temperatures average around 10 ^{o}C while summer maximum temperatures can often exceed 40 ^{o}C at lower elevations. The highest elevations are subject to daily average temperatures ranging from 4 ^{o}C to 25^{o}C annually and precipitation amounts exceeding 1000 mm (WRCC 2003, SCAS 2003). The complex terrain produces high temperature and precipitation gradients over short distances. A rich diversity of community types is supported by the steep climatological gradients. Communities transition from desert scrub at lowest elevations up through desert grassland, open oak woodland, pine-oak woodland, pine-oak forest, pine forest, montane fir forest, to subalpine forest at highest elevations in the study area (Whittaker and Niering 1965).

Data and Methods

The Laboratory of Tree Ring Research at the University of Arizona compiled the wildfire data used in this study from county, state and federal sources for the state of Arizona. The multi-agency dataset included information for all reported fires in Arizona for the period of 1973-2001. Each record entry included the fire start date, end date, total area burned and specific location, if known, recorded by township, section, and range. All fires with locations were included in this study, regardless of ignition cause. This includes all lightning fires as well as human caused ignitions. Prescribed fires were not part of the original compilation of the wildfire dataset and hence were not used in the analysis.

Many challenges exist when using multi-agency wildfire data. Under-reporting and accuracy of fire location are common problems in wildfire datasets (Brown et al. 2002, Westerling et al. 2003). Less than five percent of the total number of fires in the present wildfire dataset had to be excluded due to lack of fire location information. This does not contain every fire that occurred during the period of record, but is adequate at defining general trends and patterns at the regional scale.

The study area (figure 1) was purposely confined to the boundary of Arizona climate division seven (AZCD7) to facilitate the use of divisional data. Monthly values for temperature, temperature anomaly, precipitation, precipitation anomaly, Palmer Z index, and Palmer Drought Severity Index (PDSI) were obtained for AZCD7 from the National Climatic Data Center. Climate division values are calculated by averaging many surface observations within a several county area so that a single time series can be generated. This method is often inadequate in areas with complex topography and few weather stations and can produce divisional time series that fail to capture higher elevation climate variability. Time series data generated for AZCD7 most likely suffer from these problems, however few upper elevation weather stations exist in this region for validation or to use in place of divisional data. Even with its limitations, the monthly divisional data is probably adequate at capturing the broader, regional variability in temperatures and precipitation amounts.

NCEP Reanalysis variables (700mb geopotential height, specific humidity, omega, zonal wind and meridional wind) were included in the original climatological dataset to investigate the importance of upper level circulation patterns and moisture levels on wildfire variability. Several time series of monthly average reanalysis variables were obtained from the Climate Diagnostics Center for the model grid point closest to the center of AZCD7. Time series data from surrounding grid points were highly correlated ($r>0.9$) with the target grid point, demonstrating the insensitivity of data point choice. Eight Reanalysis time series from the target grid point were screened in the initial correlation analysis. These correlations between the wildfire statistics and Reanalysis variables were very similar to the surface variables (PDSI, Z-index, precip. anomaly and temp anomaly). They did not provide additional explanatory power and were ultimately excluded to simplify the presentation of results.

An important aim of this study is to explore the complex fire-climate relationships that exist along steep ecological gradients where fine and heavy fuel production and conditioning are dominated by climate variability. High elevation fire events that occur in heavy, woody fuels are most likely influenced by different antecedent climate conditions than low elevation fires in fine, grassy fuels. Elevation was used as a proxy for fuel type by splitting the original fire events dataset into a high elevation set and low elevation set. Whittaker and Niering (1965) conducted an extensive vegetation sampling study on several southern Arizona mountain ranges to characterize the general change in vegetation types along topographic gradients. They determined that on most slopes desert grasslands transitioned into oak woodlands at around 1500 meters in elevation. This elevation was used as a breakpoint to separate low elevation grass fires from high elevation forest fires in the event dataset. Additional breakpoints at 1350 m and 1700 m were also used to evaluate the sensitivity of using elevation for data stratification. Slight differences in wildfire-climate correlations were observed depending on the breakpoint used, but results were generally similar. This study focuses on the results obtained using 1500 m elevation as the breakpoint between high and low elevations given the guidance provided by the Whittaker and Niering (1965) study. Misclassifications of high or low event fires are possible given the coarse township/range/section reporting of fire locations, but this is an unavoidable limitation of the data. Elevation in this dataset is a coarse approximation for fuel type and can only superficially represent the complex interaction between climate variability and different fuel types. Wildfire, climate and vegetation data at higher spatial resolution than currently available are needed to advance understanding of specific fire-climate relationships across a landscape of varying fuel types.

The high/low elevation wildfire events and monthly climate data were aggregated to a seasonal temporal resolution to aid in the interpretation of lagged relationships.

Seasons were defined as winter (DJFM), spring (AMJ), summer (JAS), and fall (ON). These seasonal definitions stray from the convention of regular, three-month seasons, but are more appropriate for the unique precipitation regime of southern Arizona. Precipitation is bimodal with more than 50% of the annual total occurring during the monsoon season (JAS) and 30% occurring during winter months (DJFM). Wildfire counts and total area burned were summed for each season between 1973 and 2001, while climate variables were converted into seasonal averages. AMJ was designated the fire season because it experienced the highest levels of fire activity (Table 1).

Both upper and lower elevation datasets of seasonal total area burned (TAB) and total number of fires (TNF) were positively skewed and required transformations before calculating statistics with normality assumptions. This type of skew in the data distributions suggested the need for a logarithmic transformation. The skew was effectively removed from each through the use of a $\log_{10}$ transformation. Several seasons with zero TAB or TNF were more than two standard deviations from the mean of the transformed dataset. Given that these values are unlikely in reality and most likely attributable to poor fire records, they were removed as outliers to further improve the shape of the distributions. Each distribution passed the Shapiro-Wilks normality test after transformation and removal of outliers. Climate variables were also examined for normality. None were excessively skewed or possessed outliers that would require transformations.

A matrix of bivariate Pearson's *r* correlations between the fire and climate datasets was developed. TAB and TNF values were correlated with coincident seasonal climate data as well as lagged seasonal climate data. As an example, this means that April-May-June TAB values were correlated with April-May-June temperature anomaly values as a correlation with no lag. Seasonally aggregated data were used rather than monthly data to clarify and aid in the interpretation of long lag relationships. Additional lagged correlations were calculated where AMJ TAB was correlated with the prior season (DJFM) temperature anomaly, two seasons prior (ON), and so forth, back sixteen seasonal lags (four years). Several studies have found significant relationships between fire activity and antecedent climate conditions with fire lagging climate by over three years (Barton et al. 2001, Swetnam and Betancourt 1998). A window of sixteen seasonal lags appears to be a long enough to capture the lagged relationships highlighted in these other studies. Auto-correlation functions (ACF) were calculated out to 20 lags for each of the climate variables to assess the potential impact of persistence or periodicity in the climate time series on the lagged correlations. The ACF fell to insignificant levels ($p<0.05$) after just one season for temperature anomalies, precipitation anomalies and the Z-index values. PDSI values have inherent persistence so it expectedly had significant autocorrelation for the first three lags. This is an important consideration when interpreting the lagged correlations between PDSI values and wildfire statistics. No significant autocorrelations were detected past nine months in the PDSI dataset.

Ultimately 272 correlations were calculated between four variables at seasonal lags ranging from zero to 16 for four different datasets (Upper TAB, Lower TAB, Upper TNF, and Lower TNF). This exercise was done to evaluate the discrete relationship between antecedent seasonal climatic conditions and wildfire variability and to also identify variables that would be the strongest predictors in regression equations built to forecast wildfire activity. To reduce the pool of potential predictors, only significant correlations ($p < 0.1$) were considered as candidates for the regression models.

To further screen the variables and to guard against modeling with many collinear predictors, surface variables with significant correlations ($p < 0.1$) were subjected to a rotated principal components analysis. Five components captured most of the variance for each of the four predictor subsets (Low Elevation TAB: 88.8 %, Low Elevation TNF: 67.4 %, High Elevation TAB: 85.6 %, High Elevation TNF: 78.7 %). The highest loading variables on each of the components were identified and used to form the final pool of predictors.

All combinations of variables in the final pool of predictors were used to develop the final regression model using SPSS v. 11.0. Regression models were developed with discrete variable combinations entered into each model (stepwise method not used). Each of the final regression models had the simplest structure with the greatest explanatory power. Overall model significance, coefficient significance, and explained variance (R^2) were used to assess model performance. Residuals in the final models were examined and indicated no violations of the assumptions of normality or equal variance and absence of autocorrelation.

Results

Upper Elevation Fire-Climate Relationships

Significant ($p < 0.1$) positive correlations between total area burned (TAB) and moisture-related climate variables (Z-index, precipitation anomaly, and PDSI) were concentrated in the period eight to four seasons (AMJ[-2] to AMJ[-1]) prior to the zero lag AMJ season (AMJ[0]) (Figure 2). This grouping of significant correlations was found during JAS[-1], ON[-1], and DJFM[-1] for precipitation anomaly and Z-index. Significant PDSI correlations occur during the same period plus an additional season (AMJ[-1]). An additional group of positive correlations between TAB and moisture-related climate variables was found at JAS[-3], the July-August-September monsoon season, three years prior to AMJ[0]. A significantly positive relationship between TAB and temperature anomaly occurs during AMJ[0] and the winter season two years prior (DJFM[-2]).

The total number of fires (TNF) at upper elevations had a different pattern of correlation with climate variables than the TAB values (Figure 3). Temperature anomaly had highly significant positive correlations with TNF at short seasonal lags (AMJ[0], DJFM[0], and ON[0]). PDSI and TNF were significantly related during seasons JAS[-1] and DJFM[-1] and at longer lags (DJFM[-3] through AMJ[-4]). Correlations between TNF and all moisture-related climate variables were highly significant ($p < 0.05$) during JAS[-3] just as TAB correlations were at the same seasonal lag.

The regression model developed to predict upper elevation TAB used two predictor variables that explained 43% of the variance in AMJ total area burned. The precipitation anomaly for JAS[-3] and the average Palmer Drought Severity Index (PDSI) value for the winter season the year prior (DJFM[-1]) both entered into the final model. The lagged precipitation anomaly variable was the stronger predictor in the model with a standardized (β) coefficient of 0.46 over the PDSI β coefficient of 0.349. The model performed reasonably when cross-validated using the 'leave one observation out' method producing a predicted residual sum of squares (PRESS) statistic of 0.354.

The upper elevation TNF regression model performed exceptionally well with two predictors entering into the final model and accounting for 75% of the variance in AMJ total number of fires. JAS[-3] precipitation anomalies were again the most important predictor (β = 0.615) with the AMJ[0] temperature anomaly as the second predictor (β = 0.478). Model cross-validation produced a PRESS statistic value of 0.705. This value was comparable to the overall model R^2 of 0.75, demonstrating the stability of the regression equation with respect to individual observations.

Lower Elevation Fire-Climate Relationships

Most significant correlations between low elevation TAB and moisture-related variables were found during seasons of the concurrent year or year prior to AMJ[0] (Figure 4). Precipitation anomaly and Z-index were significantly correlated with TAB during the seasons of DJFM[0], AMJ[-1], DJFM[-1], and also during the longer lag season of JAS[-2]. Z-index had an additional significant correlation during the AMJ[0] while precipitation anomaly did not. PDSI was significantly correlated at all seasons from JAS[-3] to the AMJ[0] season. Seasonal temperature anomaly was only significantly correlated with TAB during the AMJ[0] season.

No correlations between lower elevation TNF and either precipitation anomaly or Z-index were significant at any seasonal lag (Figure 5). Only two seasons (JAS[-3] and AMJ[-4]) were significantly correlated for PDSI and TNF correlations. Significant correlations between temperature anomaly and TNF were found for nine of the seventeen seasonal lags tested. Seasons with highly significant correlations ($p<0.05$) include several spring seasons (AMJ[0], AMJ[-1], and AMJ[-4]) and one winter season (DJFM[-1]).

Three predictor variables were entered into the final lower elevation TAB regression model. The beta values for DJFM[0] Z-index (0.676) and AMJ[0] temperature anomaly (0.637) were very similar indicating that both variables weight equally important as predictors. The third variable was DJFM[-1] precipitation anomaly. With $\beta=0.243$, this variable added a small amount of additional explanatory power to the overall model R^2 of 0.354. Model cross-validation by the 'leave one out' method produced a PRESS statistic of 0.285.

Correlations were generally weak and insignificant between climate variables and lower elevation TNF. This limited the initial number of potential predictors considered in the regression model. The regression equation for lower elevation TAB included DJFM (0) Z-index suggesting that winter moisture was important factor in lower elevation fire size. Correlation patterns in the lower elevation TNF moisture-related variables were not significant for DJFM(0) but still indicated that a weak correlation may exist. This guided the inclusion of DJFM(0) Z-index, precipitation anomaly and PDSI into the final pool of predictors with AMJ(0) temperature anomaly. The combination of DJFM(0) precipitation anomaly and AMJ(0) temperature anomaly, produced a model R^2 of 0.505, which was better than any other combination of predictors from the final pool. When comparing β values, the temperature anomaly variable (0.645) was slightly higher than the precipitation anomaly variable (0.538). Cross-validating the final regression model produced a PRESS statistic of 0.397.

Discussion

Short-term weather conditions have traditionally been viewed as the most important interaction between the atmosphere and wildfire variability (Schroeder 1969, Bessie and Johnson 1995, Skinner et al. 1999) Several studies have established that important relationships between wildfire variability and antecedent climate conditions exist across the western United States (Rogers and Vint 1987, Swetnam and Betancourt 1998, Barton et al. 2001, Grissino-Mayer and Swetnam 2000, Westerling et al. 2002). Variability in precipitation and temperature over a period of years can regulate the accumulation of fine fuels and dictate moisture levels in heavier fuels over large regions. Our study reveals that even more complex fire-climate relationships exist when upper and lower elevation fires are considered separately because of different dominant fuel types.

Correlations indicate that upper elevation TAB is significantly related to wet conditions during the year prior to larger fire events in the dataset. Perennial native grasses in southeast Arizona respond primarily to warm season precipitation (Neilson 2003) and may account for the positive correlation between TAB and moisture-related surface climate variables. Wetter monsoon conditions may spur on more perennial grass productivity, creating a greater continuity of fine fuels across the landscape that would support wildfire spread. This phenomenon is probably more important for fires occurring at the lower elevations (close to the 1500m threshold) of the entire upper elevation dataset, where grasses are still strongly present as they are in the open oak community (Whittaker and Niering 1965).

Higher elevation forest communities are likely influenced by some combination of other climate-regulated fine fuel production mechanisms and the one described above. The wet conditions during all seasons of the year prior may be an indication that fine fuels are produced by different species in different ways. The accumulation of leaf litter from deciduous trees may be more dependent on an autumn wet signal while conifers may drop more needles with higher snowfall amounts. Both would result in an accumulation of fine fuels available to carry fire in the following year.

'Wet' fire-climate correlations, linked to fuel production, occur during the year prior to the fire season (AMJ[0]), but not necessarily during the year of the current fire season. Neither wet (positive) nor dry (negative) correlations were observed between TAB and the three moisture-related surface variables (PDSI, Z-index, and precipitation anomaly). This suggests that dry conditions were not consistently a precursor to large upper elevation fire events. These results are counterintuitive and contradict several fire history studies conducted in the desert Southwest that found more large forest fires occurring during unusually dry years (Swetnam and Betancourt 1998, Barton et al. 2001, Grissino-Mayer and Swetnam 2000). This is most likely a product of the relatively short time span of the fire event data used in this analysis. The period of record of the dataset is almost coincident with a period (1976-2001) known to be exceptionally wet with several

El Niño events producing record amounts of winter precipitation across southeast Arizona. PDSI values indicate that no long periods of moderate drought (PDSI <-2) occurred between 1973-2001 (Figure 6). This lack of exceptionally dry conditions may have suppressed the signal of other fire-climate interactions important to seasonal wildfire activity across the study area (e.g. extended drought conditions and wildfire activity in upper elevation forests).

Variables entering into the final upper elevation TAB regression equation include PDSI for DJFM(-1) and precipitation anomaly for JAS(-3). Both of these variables most likely represent long-lag, fuel production mechanisms and together provide a modest degree of explanatory power when predicting upper elevation TAB values. It is unclear whether the three-year lag on the precipitation anomaly variable is related to a fuel production and accumulation process that actually takes three years, or if it is an artifact of some areas not burning immediately after fine fuels are produced. The entire study area does not burn every year, so the lagged relationship may extend several years even though fuel production is occurring on a much shorter timescale. Wet seasons may actually induce conifer needles to drop prematurely and accumulate as fine fuels. Reich et al. (1994) found that needle life-span was inversely proportional to water availability in most major conifer species. Wet conditions may cause faster needle turnovers and higher fine fuel accumulation rates during this three-year period between wet signal and TAB response. Needle accumulations would experience minimal decomposition over the three-year period, especially in the ubiquitous *Pinus ponderosa* (ponderosa pine) stands found at upper elevations in the study area. Murphy et al. (1998) found that *P. ponderosa* needles decompose very slowly in semi-arid environments due to high lignin content. In their study, most sites retained over 70% of their original mass after 700 days.

Upper elevation TNF was dominated by a short-lag, positive temperature correlation reflected in surface temperature anomalies and also a long-lag, positive moisture variable correlation at JAS[-3]. This short-term temperature and long-term moisture pattern enters the upper elevation TNF regression model as temperature anomaly from AMJ[0] and precipitation anomaly from JAS[-3]. Above normal temperatures at short lags, from two seasons prior through the fire season may be related to the drying of fuels. Most moisture-related climate variables were negatively correlated with TNF during these seasons, but not significantly. The long-lag precipitation anomaly, which is also present in the TAB correlations and regression, is most likely related to a fuel production process. Together, short-term drying and longer-term fuel production may boost the number of possible fires that become large enough to be reported. Analyses with TNF are particularly sensitive to reporting errors in the original data. It is likely that many small fires from lightning ignitions were never observed and reported during the period of record. The fires captured in this analysis probably were large enough to be easily observed and, in turn, needed the fuel production mechanisms to achieve that minimum size.

Lower elevation TAB has 'wet' correlations through seasons of the year prior that extend right up to the AMJ[0] fire season. This is different from the upper elevation fires in that fine fuel production may be occurring in the seasons just prior to AMJ[0] or during AMJ[0] itself. This is primarily reflected in the significantly positive (wet) correlations between PDSI and TAB at DJFM[-1] and DJFM[0]. These wintertime, wet correlations suggest that fine fuel production may be in the form of annuals rather than native perennial grasses which typically respond to warm season precipitation. Sonoran desert annuals are known to respond to winter precipitation and can provide a continuous source of fuel across the landscape in time for the fire season (Rogers and Vint 1987). Positive correlations at both DJFM[0] and DJFM[-1] also suggest that annuals may both accumulate as litter from previous years and quickly senesce to be available as fuel for AMJ[0] fire activity.

The nonnative and invasive perennial grass *Eragrostis lehmanniana* (Lehmann lovegrass) has quickly spread across southeastern Arizona after being introduced by the Soil Conservation Service in the early 1950's as a soil stabilization tool (Cox et al. 1984). *E. lehmanniana* has a distinct advantage over most native perennial grasses in that it is more productive with winter season precipitation, when other native grasses are dormant (Cable 1971). The abnormally wet winters attributed to increased El Niño activity over the past 30 years may have provided an opportunity for the species to spread at an unprecedented rate, quickly invading areas once dominated by native species. *E. lehmanniana* is known to produce more continuous fine fuels than native grass species and can do so even during dry years (Cable 1971). The litter is also highly lignified, meaning that it decomposes slowly, allowing for fine fuels to accumulate over longer periods, which increases fuel loads (McPherson 1995). The 'wet' correlations in AMJ[0], DJFM[0], and DJFM[-1] may all be related to the increasing presence of *E. lehmanniana*, because of its ability to utilize precipitation during these seasons where other grasses are dormant.

Precipitation anomaly for DJFM[-1] and Z-index value for DJFM[0] both entered the lower elevation TAB regression equation and express the importance of fuel production, potentially by mechanisms discussed above. The third regression predictor, temperature anomaly at AMJ[0], likely represents the importance of fuel conditioning on lower elevation grass fires. Very little precipitation typically falls during a normal April-May-June season in southeastern Arizona, so a negative precipitation anomaly is not necessary to characterize dry conditions. The absence of a negative correlation between AMJ[0] TAB and precipitation is likely due to conditions being climatologically dry during this period. Yet, above normal temperatures could aid in the senescing and drying of grassy fuels needed to carry low elevation fires. This was also an important factor in predicting total number of fires, with temperature anomaly during AMJ[0] entering as the most important value for the lower elevation TNF regression model.

No significant positive correlations emerged between moisture-related climate variables and lower elevation TNF as would be expected if antecedent wet conditions and grassy fuels production were important to the number of fires. There does appear to be a relationship between the number of AMJ low elevation fires and soil moisture, but not a clear, linear one. Fire counts (shown in Figure 6) did not fluctuate from year to year but steadily rose between 1982 and 1994 and then steadily decreased until the end of the record in 2001. The steady rise in fire counts after 1982 is strikingly coincident with the very wet period between 1983 and 1989 where two El Niño events (1982-83 and 1985-

86) brought record amounts of precipitation to southeastern Arizona. In addition, the 1994 peak in fire counts may be a lagged product of the above normal precipitation associated with the 1991-1992 El Niño event. These unusually wet periods may have promoted high productivity in perennial and annual grasses, which in turn helped to overcome fuel continuity limitations usually present across the desert landscape. Areas with typically sparse vegetation would then have fine fuels to carry fires. The total area burned associated with these fires does not increase steadily over the same time period. This may be attributed to the wet conditions of the period, limiting the ability of fires to quickly spread. Also, many of the low elevation fires were reported to have occurred close to major roads and highways. Road access may have aided firefighting, keeping fire sizes small.

Southern Arizona is especially sensitive to teleconnection patterns induced by strong El Niño events in the tropical Pacific (Redmond and Koch 1991). Strong El Niño events tend to alter winter storm tracks across the western United States, bringing above normal precipitation amounts to southern Arizona (Sheppard et al. 2002). Five of the ten strongest El Niño events of the last century occurred between 1973 and 2001 (Livezey et al. 1997, NCDC 1998) with Arizona experiencing some of its wettest winters on record during this period (NCDC 2003). There is some evidence that multi-decadal variability in ENSO may modulate the winter precipitation teleconnection pattern over southern Arizona (Gershunov and Barnett 1998, Gutzler et al. 2002, Brown and Comrie 2004). The Pacific Decadal Oscillation (PDO) appears to capture this low frequency variability in ENSO and can be useful in tracking large-scale regime shifts in Pacific Ocean sea surface temperature patterns (Mantua et al. 1997). A regime shift, as indicated by a change to positive PDO index values, occurred during the late 1970s which is coincident with the beginning of a period marked by strong El Niño activity and above normal winter precipitation in southern Arizona. This wet period may be ending with some indications of another regime shift in the Pacific Ocean during the late 1990s, which may change El Niño -winter precipitation relationships in the southwest U.S. If conditions indeed tend toward below normal or even average precipitation in the coming years, the statistical relationships developed between wildfire and climate, using data from the 1980s and 1990s, may experience diminished predictive ability. Drought conditions may then be more important in drying heavy fuels that drive large wildfires. The longer-term build-up of fine and medium size fuels spurred on by the wet conditions of the last several decades will only exacerbate conditions by ensuring fuel continuity across the landscape.

Conclusions

Wet antecedent conditions during seasons from one to three years prior to fire activity appear to be important in controlling fine fuel production. This relationship was observed in both the high elevation and low elevation datasets. Wet conditions most likely promote grass growth as fine fuels for lower elevation fires, but the mechanism related to upper elevation fine fuel production is less clear. A complex interaction between different species producing different litter types (leaves, grasses, needles) further regulated by antecedent climate conditions may be occurring at upper elevation sites.

Fuel conditioning did not appear to be as important as fuel production with respect to wildfire variability across our study area. No strong relationships between below normal antecedent moisture levels and wildfire TAB or TNF were observed in either the high or low elevation datasets. Short-term drying of fine fuels is most likely facilitated by the hot and dry conditions normally experienced during the April-May-June fire season and may not show up as a strong negative correlation between wildfire and moisture variables. The exceptionally wet conditions of the study period may have also precluded strong dry signals (with respect to wildfire variability) from emerging in the analyses.

The quality of wildfire data strongly limits the inferences that can be drawn from analyses like the ones performed in this study. Lack of complete and detailed fire location information clouds potentially strong and insightful relationships between wildfire and climate. Knowing specifically where fires start and stop would help to characterize dominant fuel types that could then be related to antecedent climatic conditions. The ecosystem response through fuel production and conditioning to climate can only be weakly inferred using the current, poor quality of wildfire data.

Given these other factors, the importance of climate relative to wildfire variability will be different from location to location and through time depending on the local land management history of the site. Fire-climate interactions are driven by processes through the continuum of climatic scales, but can only be fundamentally understood at the local scale after accounting for these non-climatic factors.

Acknowledgements

This research was funded in part by the University of Arizona Space Grant Fellowship Program and the U.S. EPA Science to Achieve Results (STAR) Program under grant #R-82873201-0. The authors wish to thank Steve Yool, Theresa Mau-Crimmins, Jay Miller, Calvin Farris, Susan Taunton, Tom Swetnam, Dave Brown, Barbara Morehouse, the WALTER team, and several anonymous reviewers for their comments on sections of this paper and technical assistance on various study related issues.

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Table 1. Mean, minimum, and maximum seasonal total area burned (TAB) in acres and total number of fires (TNF) for southeast Arizona for the period of 1973-2001. Minimum and maximum values are shown in parantheses.

Elevation Group	Data Type	DJFM	AMJ	JAS	ON
Upper Elev. (>1500 m)	TAB	99 (0, 2,156)	2,953 (0, 41,376)	800 (0, 10,791)	20 (0, 157)
	TNF	0.9 (0, 7)	7 (0, 30)	3.5 (0, 18)	0.7 (0, 5)
Lower Elev. (<1500 m)	TAB	655 (0, 4,394)	7,184 (0, 58,864)	2,520 (0, 28,023)	48 (0, 283)
	TNF	16 (0, 89)	55 (0, 170)	28 (0, 99)	6 (0, 26)

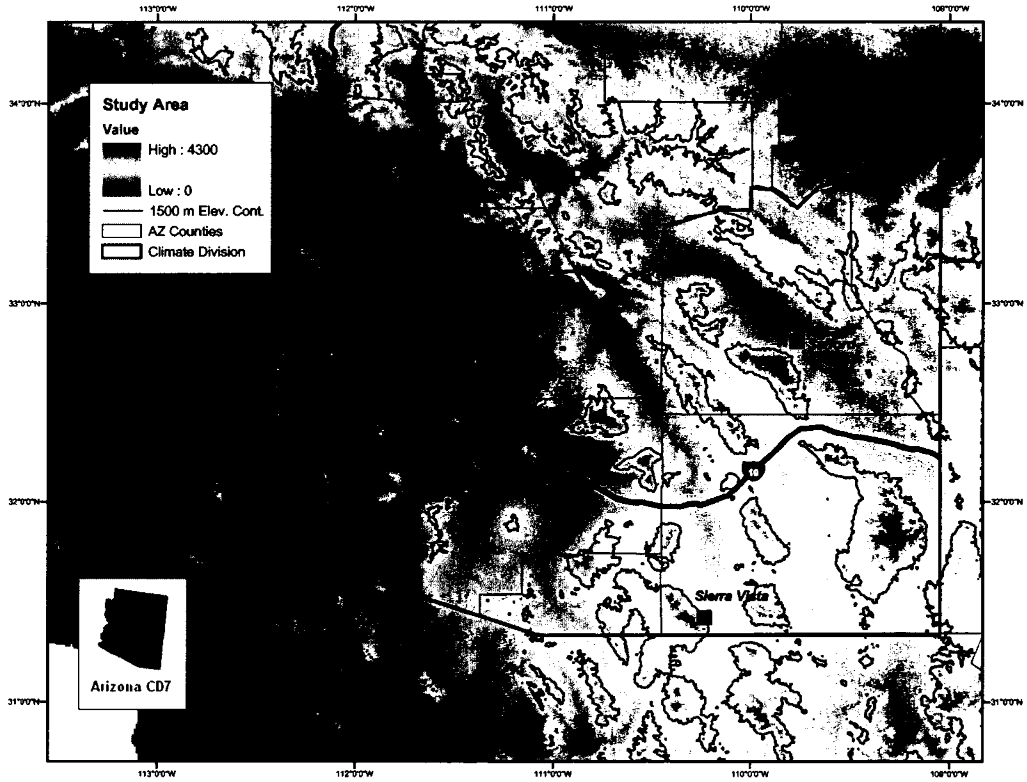

Figure 1. Study area in southeastern Arizona.

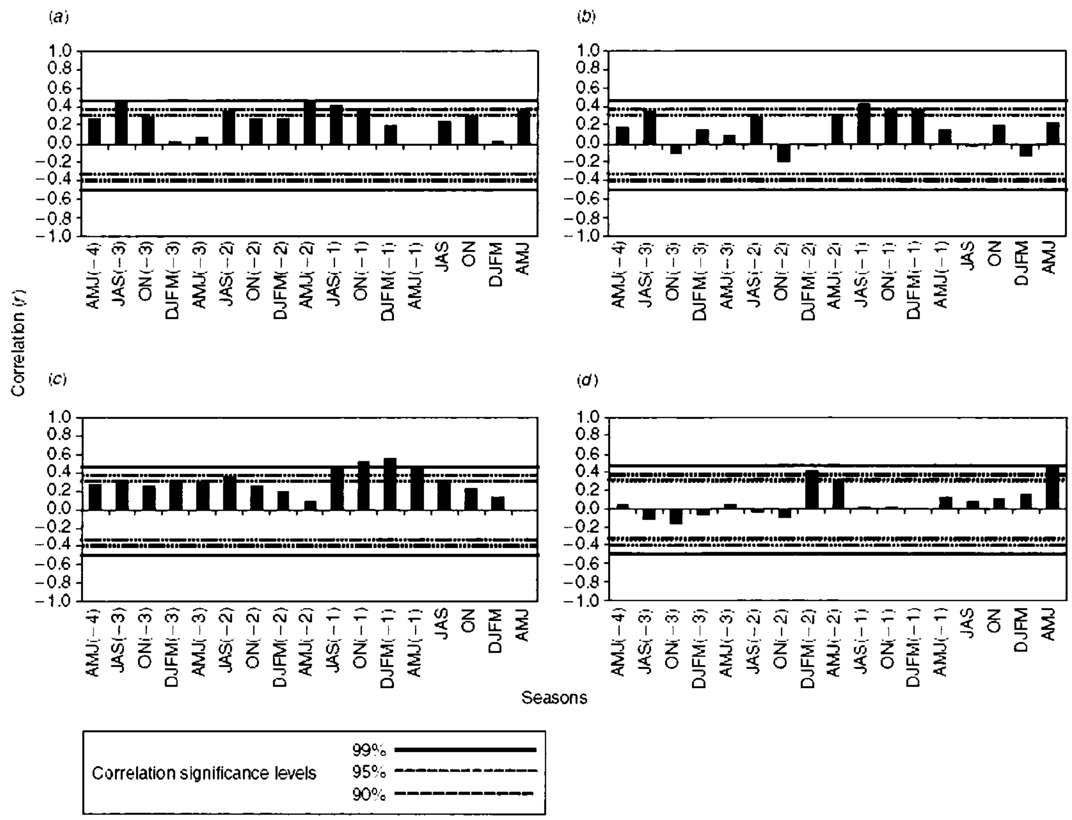

Figure 2. Correlations between upper elevation total area burned (TAB) and climate variables (n=27 seasons). Time moves from the left over 4 years up to the fire season in the right-most column. (a) Z-index, (b) climate division 7 precipitation anomaly, (c) Palmer drought severity index, and (d) climate division 7 temperature anomaly.

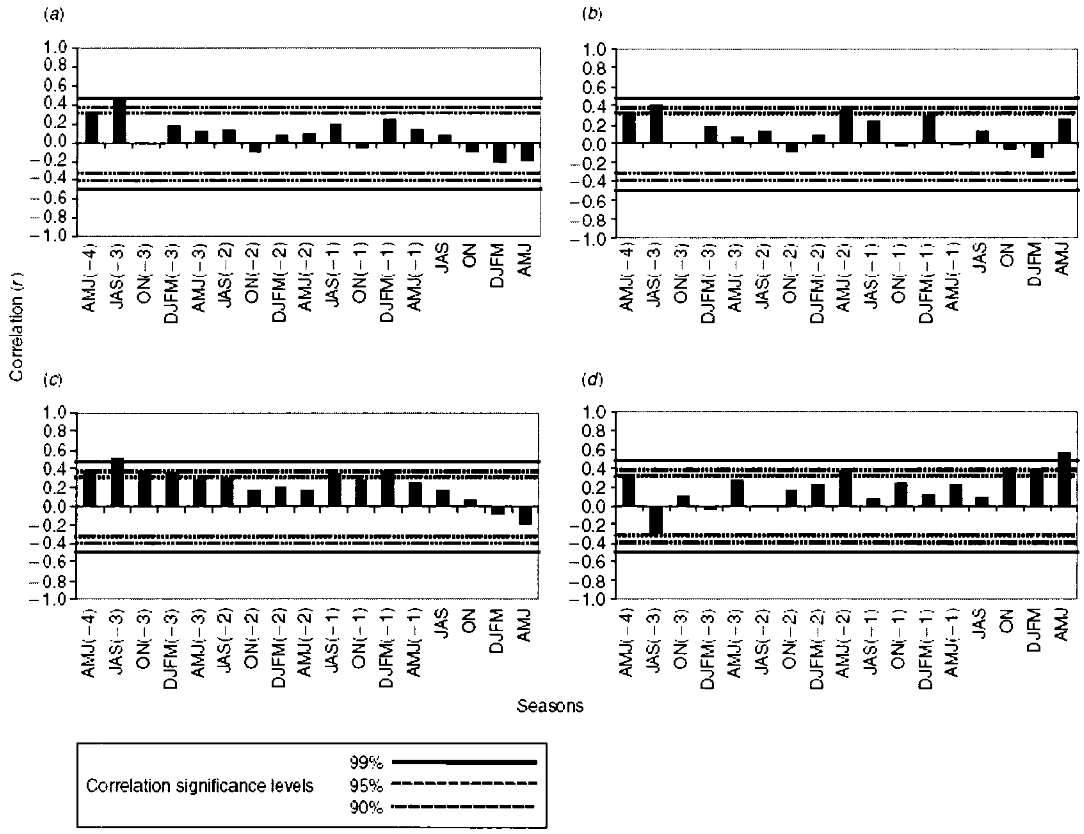

Figure 3. Correlations between upper-elevation total number of fires (TNF) and climate variables (n=27 seasons). Time moves from the left over 4 years up to the fire season in the right-most column. (*a*) Z-index, (*b*) climate division 7 precipitation anomaly, (*c*) Palmer drought severity index, and (*d*) climate division 7 temperature anomaly.

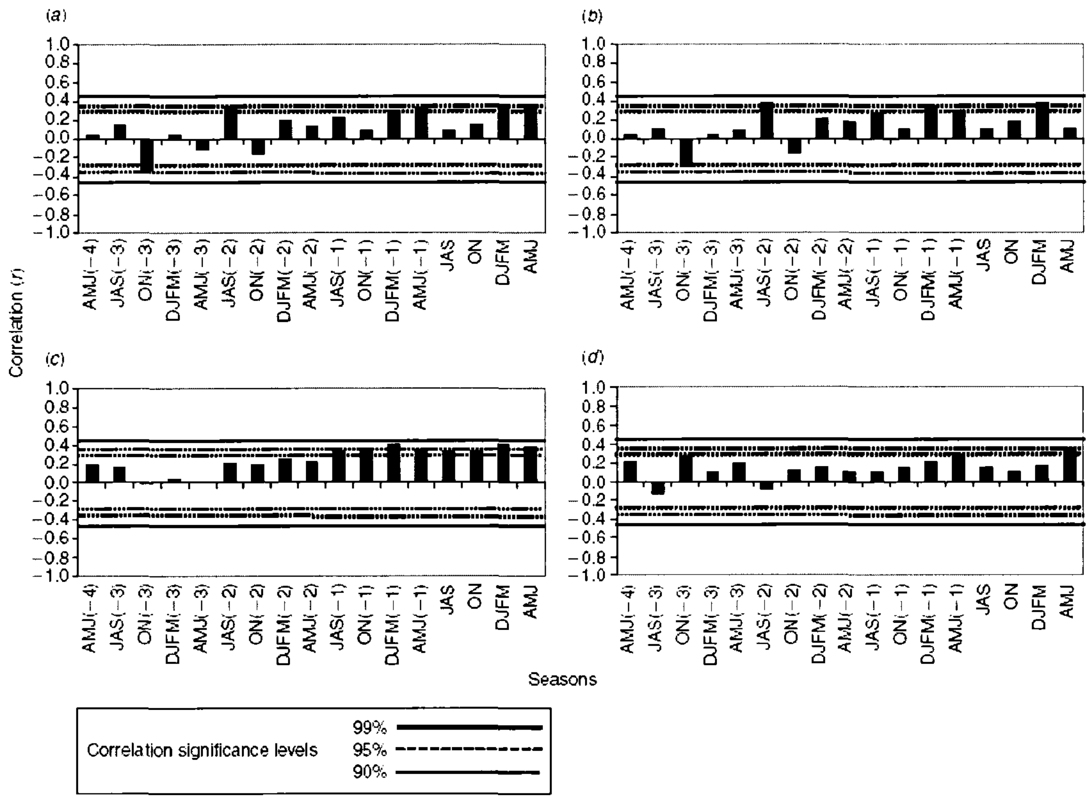

Figure 4. Correlations between lower-elevation total area burned (TAB) and climate variables (n=28 seasons).Time moves from the left over 4 years up to the fire season in the right-most column. (*a*) Z-index, (*b*) climate division 7 precipitation anomaly, (*c*) Palmer drought severity index, and (*d*) climate division 7 temperature anomaly.

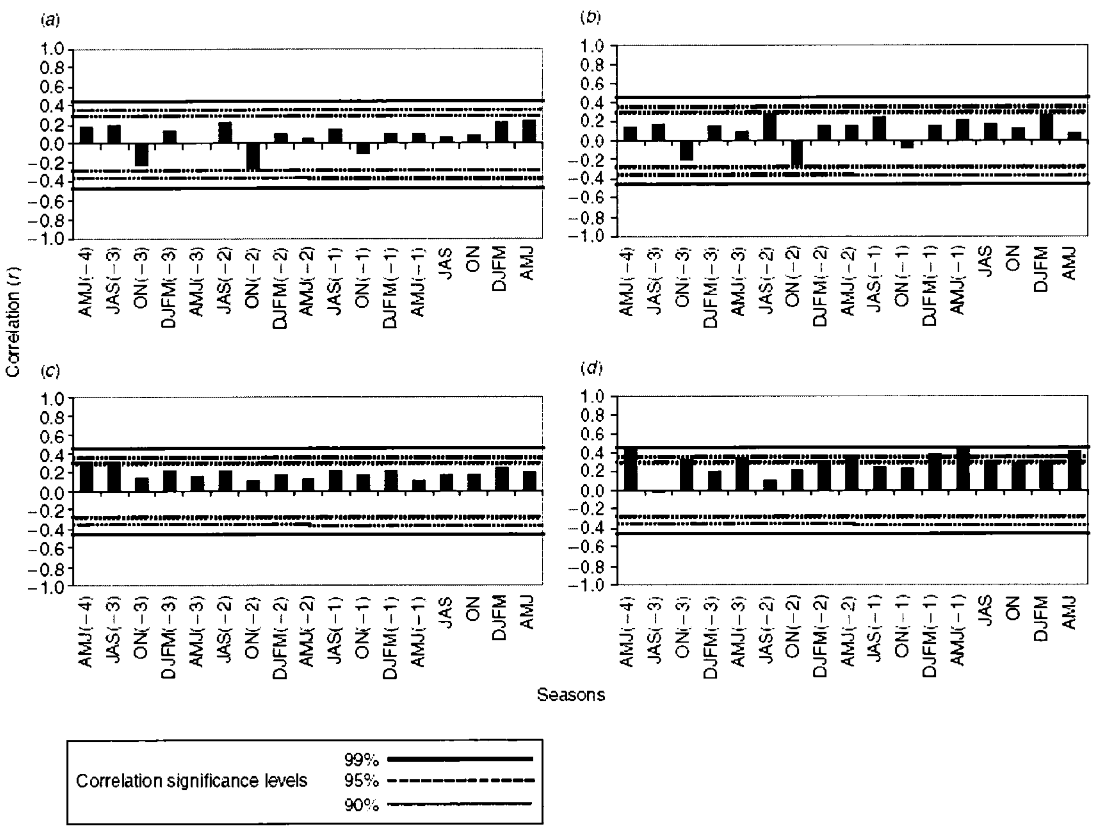

Figure 5. Correlations between lower-elevation total number of fires (TNF) and climate variables (n=28 seasons). Time moves from the left over 4 years up to the fire season in the right-most column. (*a*) Z-index, (*b*) climate division 7 precipitation anomaly, (*c*) Palmer drought severity index, and (*d*) climate division 7 temperature anomaly.

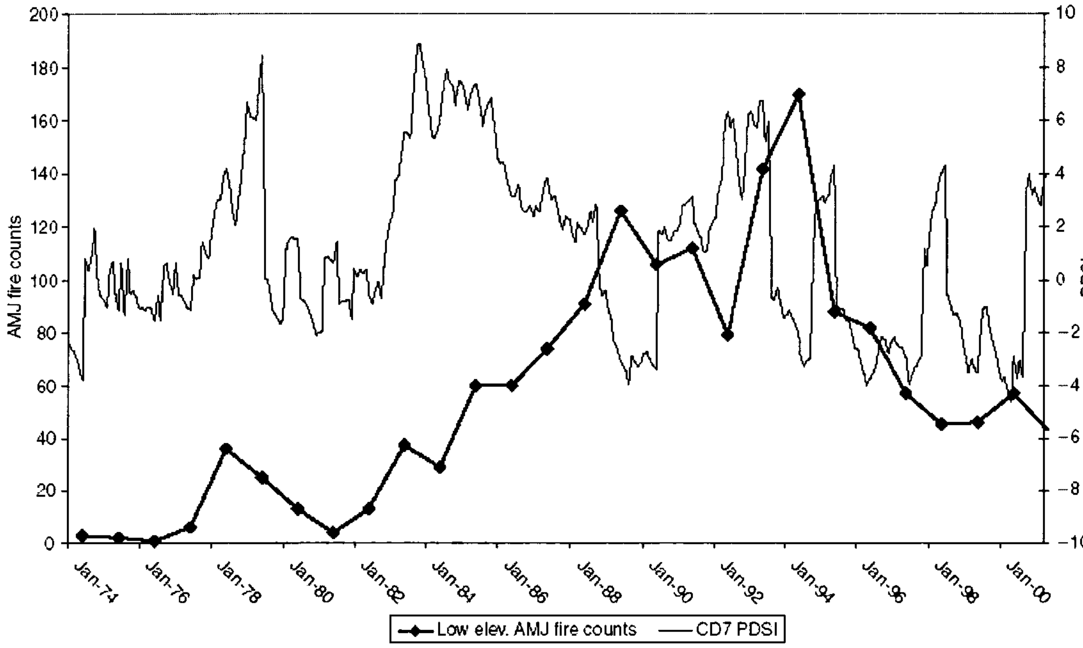

Figure 6. Time series of lower-elevation total number of fires during the April–May–June (AMJ) season and monthly Palmer drought severity index (PDSI) for Arizona climate division 7 (CD7).

APPENDIX B

A SYNOPTIC CLIMATOLOGICAL ANALYSIS OF EXTREME FIRE WEATHER CONDITIONS ACROSS THE SOUTHWEST UNITED STATES

MICHAEL A. CRIMMINS

(To be submitted to the International Journal of Climatology)

Abstract

Extreme fire weather conditions are usually thought of as discrete events rather than part of a continuum of meteorological and climatological variability. This study uses a synoptic climatological approach (weather typing) to examine the seasonal climatology of extreme fire weather conditions across the southwest United States (Arizona and New Mexico) during the period of 1988-2003. Three key circulation patterns representing broad southwesterly flow and large geopotential height gradients are associated with over 80% of the extreme fire weather days identified in this study. Seasonal changes in relative humidity levels, strength of height gradient, and geopotential heights all modulate the relationship between these key circulation patterns and extreme fire weather days. Examination of the daily incident summaries for two recent wildfires (May 2000 and June 2003), show that wildfire activity can be strongly regulated by these critical fire weather circulation patterns.

Introduction

The importance of weather conditions to the behavior and rate of spread of a wildfire is well documented (Flannigan and Harrington 1988, Bessie and Johnson 1995, Burgan et al. 1997, Flannigan and Wotton 2001). Studies of the interaction between fire weather conditions and wildfire activity have focused on modeling short timescale meteorologic and wildfire behavior variability (Fujioka 1997, Andrews and Queen 2001). Modeling efforts have helped to quantify the role of weather variability relative to fuel conditions and amounts and local topography (Deeming et al. 1977, Burgan 1988, Pyne et al. 1996). The development of fire danger rating systems has allowed for the integration of longer-term (seasonal) climatic variability and short-term meteorological variability into decision support tools for fire management. Seasonal changes (drying or wetting) of fuels can be tracked with metrics like the energy release component (ERC) and integrated with daily weather indices such as the spread component (SC, both components of the U.S. National Fire Danger Rating System) to evaluate daily fire danger.

The integration of cumulative indices (e.g. ERC) that represent seasonal climatological changes with daily fire weather variability represent only part of the temporal range important in controlling interannual wildfire activity. The role of low frequency climatic variability in controlling seasonal wildfire activity, especially in the southwest U.S., represents a newly discovered dimension of wildfire climatology. Recent studies in the southwest U.S. have found that antecedent conditions (i.e. years prior to wildfire seasons) can influence overall wildfire activity through precipitation either limiting or promoting the growth of fine fuels and through direct control of fuel moisture levels (Swetnam and Betancourt 1990, 1998, Westerling et al. 2002, 2003, Crimmins and Comrie 2004). Southwestern wildfire regimes respond to both short-term and long-term atmospheric variability through precipitation-fuel production mechanisms, seasonal and interannual drought conditions, and daily fluctuations in relative humidity, wind speeds, and temperature. All of these components are inextricably linked to synoptic scale circulation patterns, which can provide diagnostics of both high and low frequency variability within the context of a global system. Examining the connection between synoptic circulation patterns and surface fire weather conditions is a crucial component in attempting to construct a more complete understanding of the interactions between wildfire and climate variability across the southwestern U.S.

Schroeder (1969) recognized that linking large-scale synoptic patterns with regional to local scale fire danger was an effective way to construct a fire-weather climatology for the conterminous United States. He developed daily fire danger ratings for several regions across the United States and then evaluated the dominant synoptic circulation patterns that occurred on days with extreme ratings. His study, published over 40 years ago, is arguably the most utilized example of a fire-weather climatology. It is an integral part of training fire managers and fire suppression personnel in basic fire weather concepts. Several studies have analyzed the synoptic circulation patterns associated with wildfire events (Brotak and Reifsnyder 1977, Johnson and Wowchuk 1993, Takle et al. 1994), but few have employed a synoptic climatological approach to examine daily fire weather variability. The Schroeder (1969) study used daily weather data for the period of 1951-1960 and has not been re-evaluated with more contemporary data to examine the stability of the findings.

The objective of this study was to relate daily surface fire weather index values to their respective synoptic circulation patterns. It focuses on determining the synoptic weather patterns associated with elevated fire danger across the southwest United States and examines the circulation patterns associated with three case study wildfire events. The seasonal continuum of synoptic types is considered to evaluate if seasonal changes in extreme fire weather conditions are associated with changes in circulation patterns. This detailed examination of critical fire weather circulation patterns will be useful in further diagnostic studies linking low-frequency climate variability and variability in regional fire weather.

Data and Methods

Synoptic Circulation Classification

Daily synoptic-scale circulation patterns were classified into different key weather types using an unsupervised classification technique known as the self-organizing map (SOM) algorithm (Kohonen 2001). It is essentially a non-linear, iterative clustering algorithm. This technique has been utilized in many different disciplines for several years, but has only recently seen wider utilization within the field of climatology (Cavazos 2000, Cavazos 2002, Hewitson and Crane 2002). Most automatic synoptic classifications or weather typing procedures use conventional statistical methods based on correlation fields or clustering algorithms (Yarnal 1993, Yarnal et al. 2001). These methods require that input data fit particular distributional assumptions and produce results that are often insensitive to inherent non-linearities within the datasets. The SOM algorithm is able to discern non-linear relationships within input datasets and does not require that the data fit any particular frequency distribution. It is an iterative algorithm that 'learns' the patterns of the input data vectors and organizes them onto nodes within the SOM space (Hewitson and Crane 2002). In developing a self-organized map, the user determines the dimensionality of the SOM space (i.e. number of 'clusters') prior to the classification. For example, a 4 node by 3 node map would produce a map with 12 different weather types. These 12 'reference nodes' are initially seeded with random data vectors. The SOM algorithm examines input data vectors iteratively with respect to the reference nodes and assigns the input vector to the closest matching reference node. This 'winning' reference node is updated to resemble the input vector. Surrounding nodes are also updated to resemble the input vector, but with a much lower weighting. Iteratively updating the reference nodes and surrounding nodes through a neighborhood function eventually produces a spatially organized representation of the key weather types that span the continuum of types in the input data set. This organization ensures that like patterns are in neighboring nodes and the most unlike patterns are in nodes farthest from each other along one of the diagonals of the SOM. This develops a continuum of types rather than discrete classes, which is particularly useful in examining daily transitions between weather types (Hewitson and Crane 2002).

The SOM-based classification developed for this study used a 4x3 SOM to develop a 12 weather-type classification using daily 18Z 700mb geopotential heights. The SOM algorithm used in the classification procedure was found in the SOM_PAK software package (Kohonen et al. 1995). The gridded daily data were from the Reanalysis dataset produced by the National Centers for Environmental Prediction (NCEP) and

National Center for Atmospheric Research (NCAR) (Kalnay et al. 1996). The Reanalysis data represent model reconstructions of various atmospheric fields from daily observations at a grid resolution of 2.5 degrees. These data provide a spatially and temporally consistent global dataset are widely used in all types of climatological studies. The global dataset was clipped to a 7° x 7° grid-point window centered over the southwest U.S. (Figure 1). The 700mb level was used because of its proximity to the higher elevation areas of the Southwest. The use of geopotential heights allows for both the examination of changes in surface temperatures and gradients that may control surface wind regimes.

A 4x3 SOM was chosen as the optimal classification size because of its ability to identify a diversity of patterns without overgeneralizing. This was determined by producing a 2x3 classification and 7x5 classification. The 7x5 SOM produced a very similar classification in pattern to the 4x3 classification with a slightly higher level of detail. On the other hand, the 2x3 classification eliminated several patterns and appeared to be too general when compared to the patterns in the 4x3 and 7x5 SOM's. Parsimony guided toward the selection of the 4x3 SOM. It appears to capture the key daily patterns for April, May and June (1988-2003) within a relatively small and easily interpretable number of classes.

Daily Fire Weather Index

The study period length was dictated by the availability of the surface data used to calculate the daily fire danger ratings. Surface data used in this study included daily weather observations from 15 remote automated surface weather stations (RAWS) for April, May and June for the period of 1988-2003 (Figure 1). RAWS are designed to measure fire weather conditions in remote locations and are sited on south facing slopes in exposed areas to increase their sensitivity to extreme meteorological conditions (NWCG 2000). Initially 33 stations from across Arizona and New Mexico were considered for inclusion in the study. Short periods of record and missing data forced the exclusion of 18 stations. The final 15 stations included in the study represent the best spatial coverage of stations for the longest period of time.

Daily fire danger levels were determined by calculating the daily Fosberg Fire Weather Index (FFWI) values for each of the 15 stations. This index is essentially a non-linear filter that is extremely sensitive to changes in wind speed and relative humidity levels (Fosberg 1978, Goodrick 2002). High winds and low relative humidity values result in high FFWI values (Fosberg 1978). The FFWI is very similar in structure to the National Fire Danger Rating System (NFDRS) spread component with a fixed fuel model. The FFWI integrates the Rothermel (1972) rate of spread calculation and the Simard (1968) equilibrium moisture content calculation to gauge fire weather conditions in a similar manner as the NFDRS spread component index. Time series of daily FFWI and spread component (fuel model G) values were highly correlated ($r>0.95$) for all 15 stations. The FFWI was used because of its higher sensitivity to fine fuel moisture changes and its simple calculation with basic meteorological data. A statistical study by Haines, et al. (1983) found the FFWI to be a strong and significant predictor of wildfire activity when compared to historical records in the northeastern United States.

The daily FFWI values from the 15 RAWS sites were combined into one time series, by first converting the individual station time series into z-scores and then averaging them all together. It is understood that averaging the individual time series created a loss of information, but the regional signal was the desired component of the variability in daily fire danger. Sub-regional variability in daily fire danger does exist, but is not addressed in this study.

The single, regional time series of FFWI z-scores was converted to rank-percentiles with the highest values being the highest percentiles. The 90th percentile was chosen as the breakpoint to determine extreme fire weather conditions. This is a common threshold used by the fire management community to identify extreme fire weather conditions (Fosberg et al. 1993, Schlobohm and Brain 2002). Chi-square tests were used to evaluate whether significant relationships existed between days with certain weather types produced by the SOM and days with 90th percentile FFWI values. Three, particularly large and destructive Arizona and New Mexico wildfires were then examined with respect to the springtime weather types.

Results and Discussion

Identifying Critical Fire Weather Patterns

Classification of the daily height patterns into discrete classes allows for a more detailed examination of the high frequency variability that characterizes the transition from winter circulation patterns to summer circulation patterns. Especially important to this study is the examination of the occurrence of steep horizontal height gradient patterns that produce high wind events at the surface. The synoptic pattern classification produced by the SOM algorithm is shown in figure 2. This is a classification of all 700mb geopotential height maps for each April, May and June day for the period of 1988 through 2003 (1456 total days). Maximum class dissimilarity is oriented along the axis from node 02 (ridge pattern; weak height gradient) to node 30 (trough pattern; strong height gradient). The seasonal signal is evident in this synoptic classification, but is an important part of this analysis (Figure 3). The combined AMJ classification allows for consideration of all seasonal circulation patterns at once and to evaluate how these patterns evolve temporally. The lower height patterns in the lower right quadrant of the SOM are naturally more frequent in April while the higher height patterns in the upper left quadrant are more often associated with June days. The sequence of daily weather types through a season in any given year of the study period is actually highly variable with a mixture of typical early season patterns occasionally occurring in June and late season patterns occurring in April. The occurrence of early season patterns (steep north-south height gradients) in May and June are of particular interest to this study because of their efficiency in producing high surface wind events that strongly influence wildfire behavior and spread.

The number of 90^{th} percentile exceedance days associated with each weather type is shown in Table 1. Expected frequencies representing no association between the number of exceedance days and each weather type were calculated based on 10% of days within each type producing an exceedance. Chi-square tests between observed and expected exceedance counts within each type show that nodes 10, 20, and 30 have significantly ($p<0.001$) more exceedance days than would be expected by chance alone. Nodes 00, 21, and 31 have observed and expected frequencies that are not significantly different, while the remaining nodes all have significantly ($p<0.05$) less exceedance days than should be expected. Node 02 has the largest membership of any node with 247 days (17% of total days) and not one exceedance day is associated with this weather type. Over 80% of the total number of exceedance days are associated with either node 10, 20, or 30. This finding indicates that these are important circulation patterns that elevate fire weather conditions to extreme levels over the entire southwest U.S. simultaneously. These patterns are consistent with the findings of Schroeder (1969). His study identified a longwave trough-ridge pattern over the western United States that produced southwest flow at upper levels (500 mb) as a critical fire weather pattern for the southwest U.S. region.

Nodes 10, 20, and 30 all reflect this general pattern but with subtle differences in mean geopotential heights across the region, trough and ridge positions and gradient intensity. Lowest geopotential heights are found in node 30 with increasing heights towards node 10 along the bottom row of the SOM classification. The pattern shift from node 30 to node 10 shows a retreating of the mean trough over the western United States towards the northwest and a ridge building from the southeast. These results identify a higher level of detail in critical fire weather patterns for the southwest U.S. than previously identified by Schroeder (1969).

Seasonality of Critical Fire Weather Patterns

Examination of the seasonal occurrence of nodes 10, 20, and 30 in figure 3 shows that node 30 is primarily an April pattern while nodes 10, and 20 occur throughout April, May and June. The relationship between these circulation patterns and the occurrence of extreme fire weather conditions changes throughout the AMJ season. Node 30 is both the most frequent critical fire weather pattern and is associated with the most April exceedance days (Table 2). Twenty-seven percent of node 20 days were associated with exceedance days compared to 25% for node 30. The occurrence of node 10 days was infrequent and associated with an expected small number of exceedance days (2).

Typical Southwest springtime circulation patterns reflect increasing sun angles and increasing heights to the south. A strong baroclinic zone across Arizona and New Mexico is gradually displaced from the southeast by a subtropical ridge with weaker height gradients. The strong baroclinic zone is typically an early season (April) phenomena that dissipates through May and is virtually absent during June. This is evident in the gradual decrease through May and June in frequency of nodes 10, 20, and 30. Extreme FFWI values do not follow this same seasonal trend. The number of 90th percentile exceedance days linked to the critical weather types actually increases from April (43) to May (47) and then decreases into June (Table 2). The actual efficiency (exceedance days associated with weather type divided by the total number of weather type days) of the relationship between exceedance days and the critical weather types increases to a maximum in June (0.47) indicating that 47% of all days classified to either nodes 10 or 20 are also 90th percentile exceedance days. Even though the occurrence of circulation patterns represented by nodes 10 and 20 are rather infrequent during June, they are critically important because of their efficiency in producing region-wide extreme fire weather conditions. May stands out as having a relatively high efficiency ratio with all three critical weather types and the highest overall frequency of exceedance day events. May is a critical fire weather month with respect to wind events because of this higher frequency of exceedance days.

Meteorological Characteristics of Critical Fire Weather Pattern Days

The changing efficiency ratios between different nodes into different months appears to be related to seasonal changes in the co-occurrence of low surface relative humidity values and high wind speeds. Average monthly 700mb relative humidity values drop across the region from 34.9% in April to 31.7% in June (Table 3). The transition to circulation patterns that limit moisture advection into the region combined with increasing geopotential heights causes mean relative humidity values to drop through the spring season (Burnett 1994, Sheppard et al. 2002). The overall mean horizontal geopotential height gradient responsible for regional scale surface wind regimes is relatively high in April (42.1 m/1000km) and May (42.8 m/1000km) but decreases sharply into June (32.3 m/1000 km) with the subtropical ridge beginning to dominate the region. The relative humidity and geopotential height gradient values associated with the critical fire weather types deviate quite strongly from the average monthly values, helping to explain their association with extreme fire weather conditions. Monthly average height gradient values for each of the critical fire weather types are above their respective monthly averages, indicating that the pattern represents above average surface wind conditions. Relative humidity values are also generally above the monthly means for non-exceedance days indicating that these patterns are generally more humid than other circulation patterns occurring during the month. This is especially true for node 30 in April and May. Average relative humidity values are significantly lower on exceedance days relative to non-exceedance days. Node 30 has the highest relative humidity values for non-exceedance days and is most frequent during the beginning of the circulation pattern transition from winter into spring. The lower heights and connection to late season winter moisture sources make this the 'wettest' of the critical fire weather types. This is especially evident during April when non-exceedance days have an average relative humidity of over 45% while exceedance days have an average relative humidity of 34.5%.

Critical weather types are very frequent during April, but relative humidity values associated with these types are often too high to produce extreme surface fire weather conditions. Average relative humidities drop and mean height gradients increase as the season progresses into May. The overall frequency of critical weather types decreases, but the ratio of exceedance days to total days increases with the convergence of these optimal fire weather conditions. Node 30 non-exceedance days bring the highest relative humidities to the region, but occur much less frequently compared to April. More May node 30 days have relative humidity values and height gradients sufficient to produce FFWI 90th percentile exceedances than not. Daily circulation patterns markedly shift towards node 10 and 20 days. Exceedance days associated with these patterns have much lower relative humidities and much higher height gradients than the May average of all days for these values.

The critical fire weather patterns occur much less frequently during June as compared to May and April, but have the highest association with exceedance days when they do occur. Only nodes 10 and 20 occur during June occurring 22 times out of 480 June days classified in this study. The high ratio of exceedance days to non-exceedance days associated with nodes 10 and 20 in June (0.47) could be attributed to June having the lowest average relative humidity (31.7 %) when compared to April (34.9%) and May (31.7 %). Relative humidity values actually increase in June for nodes 10 and 20 for both exceedance and non-exceedance days. This is most likely associated with early season monsoon moisture seeping into the region from the southeast. Regardless, the humidity levels are low enough to efficiently produce extreme fire weather conditions when coupled with high wind events. The ratio of exceedance days to non-exceedance days (0.53) found in node 20 appears to be related to the extremely high height gradients consistently associated with exceedance days. The ten node 20 exceedance days in June produced a mean height gradient of 107.4 m/1000 km compared to the June average of 32.3 m/1000km. Node 10 also has a relatively high ratio of exceedance to non-exceedance days that appears to be more a function of both low relative humidity values and a relatively high height gradient for that pattern and not just extreme height gradients as found in node 20.

Synoptic Climate and Wildfire Events

It is difficult to determine the importance of extreme fire weather conditions in producing large fire events when examining raw seasonal fire statistics or even daily fire records. Most long-term fire records do not contain information on the daily progression of individual wildfire events. Wildfires can burn for weeks, but may accumulate most of their total area burned during only a few days associated with extreme fire weather conditions. Three case studies are used to examine the relationship between daily fire progression, critical fire weather types, and weather type transitions.

Two of the case study wildfires include the Aspen wildfire of June 2003 in southern Arizona and the Cerro Grande wildfire of May 2000 in northern New Mexico. An examination of the weather types and daily fire activity for each of the wildfires reveals that active fire days (large changes in fire size) were associated with the critical fire weather types identified in this study. The Aspen fire in southern Arizona interacted with the critical fire weather circulation patterns during its first week of burning in June of 2003. The synoptic circulation over the southwest U.S. transitioned from the more typical June, ridge dominated pattern of node 02 to the high height gradient patterns of nodes 10 and 20 (Figure 4). Extreme fire weather conditions persisted for more than a week with these patterns dominating the entire Southwest. The fire was especially active on June 23, burning more than 8,500 acres in one day (Arizona Daily Star 2003). Calmer winds returned when conditions transitioned back to the ridge dominated pattern of node 02 on June 26th. The fire continued to burn for several more weeks and charred a total of 82,000 acres.

The Cerro Grande wildfire of 2000, a major Southwestern wildfire event, similarly transitioned from low fire activity to extreme rates of growth when encountering the critical fire weather types. It was a prescribed fire that escaped on May 5th eventually consuming more than 43,000 acres and destroying more than 400 homes in Los Alamos, New Mexico. A weaker gradient circulation pattern (node 11) was present on May 4th, the initial day of the prescribed burn. The transition to a steeper gradient pattern (node 10) on May 5th, brought higher winds to northern New Mexico causing the fire to escape prescription. Height gradients continued to increase over the next several days with a deepening west coast trough (Figure 5). This was reflected in the synoptic classification with days transitioning from node 10 to node 20 on May 10th. The occurrence of a node 20 circulation pattern on May 10th brought extremely high winds, causing the fire to grow in size dramatically and burn over 8,000 acres in one day (Table 4).

Synoptic Circulation Patterns and the Cerro Grande Fire

Examination of the sequence of synoptic types prior to and during the Cerro Grande wildfire can help explain if these weather conditions were extraordinary for May in the southwest U.S. A shortwave trough had just exited the region the previous week leading to a transition pattern classification (node 22) on May 2nd, two days prior to the prescribed fire at Cerro Grande (Table 4 and Figure 6). Transition probabilities between all synoptic weather types were calculated to determine the preferential sequences of weather types that occur during May (Table 5). These probabilities were calculated by dividing the transition frequency (between two weather types) by the overall frequency of the base weather type. The node 22 weather type on May 2nd had the highest probability of persisting another day based on 1988-2003 record, but also had a relatively high probability of transitioning into a ridge pattern found in either node 11 or node 12. Ridging behind a departing shortwave is common, but the transition to node 11 instead of 12 indicates that the ridging was not very strong and that subsequent days would experience circulation patterns with increasing geopotential height gradients across the region (weak ridging).

The node 11 circulation pattern persisted another day, but had almost equal chances of transitioning into a weaker gradient, ridge pattern (node 01) or having the height gradient strengthen with the pattern in node 10. The establishment of the node 10 patterns shifts the subsequent probabilities away from quickly returning to strong ridging and weaker height gradients found in the upper left hand corner of the SOM classification. Once in node 10 (May 6th), the highest probability transition is to a deepening trough pattern to the west (node 20) or to have the ridge flatten (node 21).

The ridge flattened on May 7th (node 21) and persisted for three days bringing cooler temperatures and lighter winds. The total acres burned per day reflect the calmer conditions experienced on these days. An important transition occurred from May 9th to May 10th when the circulation moved towards the critical fire weather pattern of node 20. The highest probability transitions from node 21 were along the diagonal axis of the SOM, with a 15.9% chance of transition to node 32 and a 18.2% chance of transition to node 10. The highest probability transition on a node 21 day, besides persistence, is the transition towards the critical fire weather pattern of node 10. The lower probability (13.6 %) actual transition to node 20 had the same effect of dramatically increasing the geopotential height gradient across the region and increasing surface winds.

Over 8,000 acres burned on May 10th with the increase in wind speeds, including over 400 homes in the town of Los Alamos (NPS 2001). The transition to node 30 on the 11th brought even higher winds to the area, pushing the fire onto the grounds of the Los

Alamos National Laboratory and consuming almost 20,000 acres in one day. A relatively unusual and fortunate change in circulation occurred from May 11th to the 12th. The deep western trough on May 11th (node 30) moved to the east on May 12th bringer a weaker gradient and calmer winds (node 32) to northern New Mexico. Of the 33 days in this study classified as a node 30 pattern, a one-day transition to a node 32 circulation pattern has only occurred twice. The more frequent node 30 transitions include persistence or a rebuilding of the ridge to the south (node 20); both produce continued high surface winds. Total area burned per day was substantially less over the next several days as gradients weakened slightly with circulation patterns transitioning back towards the pre-fire conditions of node 11 and node 00 (Figure 6).

The transition probabilities were calculated for May alone, which reduced the overall sample size and robustness of the probability values. This was necessary because transition probabilities will be very different between June patterns and April patterns. Days would be biased towards lower height days in April and higher height days in June, because of the normal increase in geopotential heights over the region through the spring season. The May transition probabilities need to be interpreted with care because of the very low number of transitions in some node combinations. Regardless, the probabilities allow for a diagnosis of preferential transitions and level of persistence in comparison to actual events and may be useful in operational fire weather forecasting.

Large Wildfires and Non-critical Fire Weather Types

The three critical fire weather circulation patterns in this study (nodes 10, 20, and 30) are related to elevated fire danger because they produce both high surface wind speeds and low relative humidity values. These meteorological conditions can produce high rates of spread during wildfire events, hampering suppression efforts and quickly pushing fires to large sizes. These conditions are not always directly related to the larger-scale synoptic circulation. The third case study wildfire is used to illustrate this point. The central Arizona Rodeo-Chediski wildfire in June 2002 burned over 460,000 acres in less than four weeks (Schoennagel et al. 2004). 10 of the first 13 days of the wildfire event were classified to the node 02 circulation pattern, which represents strong ridging (Figure 2). Wilmes, et al. (2002) determined that the combination of exceptionally dry fuels from the Southwestern drought, topography, and the development of plume driven fire dynamics drove the extreme fire behavior experienced during the duration of the Rodeo-Chediski fire. A plume-dominated wildfire will periodically develop a large convective cloud of ash and hot gases that cools and collapses back into the center of fire activity. This collapse produces extreme surface winds and can drive high rates of spread and create new spot fires well away from the flaming front (Pyne et al. 1996). The meteorological conditions important to this Rodeo-Chediski wildfire were more local-scale and related to atmospheric stability than to larger-scale synoptic flow patterns. More work will be done to assess the average atmospheric stability associated with each weather type in this study.

Conclusions

Over 80% of extreme (>90th percentile), regional FFWI values are associated with the weather types represented in nodes 10, 20, and 30. These patterns represent circulation patterns of high gradient, southwest flow across the southwest U.S. and are very similar to the critical fire weather pattern identified by Schroeder (1969). The three critical fire weather types identified in this study are different seasonal representations of the broadly defined Schroeder 'southwest flow' pattern. The intensity of the height gradient, average relative humidity values, and average geopotential height change from month to month in response to seasonal changes for each of the critical fire weather types. The characteristics between exceedance days and non-exceedance days also change through the season with the greatest differences occurring with nodes 20 and 30 in April and May. Early season variability in relative humidity levels appears to be a factor that controls the level of FFWI values associated with node 30 days.

The occurrence of critical fire weather types decreases through the season from April into June. May has the most efficient relationship between the occurrence of exceedance days and critical weather fire weather types. High geopotential height gradients and low relative humidity values characterize exceedance days that occur with nodes 10, 20, or 30. Ridging from the expansion of the subtropical high dominates most days by the end of May into June. Critical fire weather types are very infrequent in June, but do occasionally occur. About 50% of node 10 and 20 days that occur in June are also exceedance days.

The critical fire weather patterns identified in this study have proven to be important to recent catastrophic wildfire events. Strong winds with the node 10, 20, and 30 weather types caused the Cerro Grande fire to burn more than 400 homes in Los Alamos, New Mexico. It is difficult to determine how often wildfire events interact with these critical circulation patterns. Long-term records of wildfire statistics typically do not provide daily progression summaries for the duration of wildfire events. Only recently have wildfires been documented in this way, limiting the present analysis to case studies. Characterizing the interannual variability in the frequency of these weather types may help explain some of the variance in seasonal wildfire activity. These critical weather types are nested within the global atmospheric circulation and may be subject to preferential modes of variability and part of low-frequency teleconnection patterns. Identification of these critical patterns allows for further analysis into global climate variability and regional wildfire variability. The connections between high and low frequency climatic variability are an important, but poorly understood component of overall wildfire-climate interactions.

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	Node 02	*Node 12*	*Node 22*	*Node 32*
Total days	247	136	130	89
Observed	0	0	1	0
Expected	24.7	13.6	13	8.9
χ^2 p-value	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	Node 01	*Node 11*	*Node 21*	*Node 31*
Total days	88	119	93	98
Observed	1	4	10	5
Expected	8.8	11.9	9.3	9.8
χ^2 p-value	**0.009**	**0.024**	1	0.147
	Node 00	*Node 10*	*Node 20*	*Node 30*
Total days	89	105	115	147
Observed	8	23	44	45
Expected	8.9	10.5	11.5	14.7
χ^2 p-value	0.888	**<0.001**	**<0.001**	**<0.001**

Table 1. Results of Chi-square tests between observed and expected FFWI 90th percentile exceedance counts associated with each weather type. Expected exceedance counts based on 10% of days within each weather type being associated with a 90th percentile exceedance by chance alone.

		Node 10	Node 20	Node 30	Combined
April	Total Days	25	49	114	188
	Exc. Days	2	13	28	43
	Efficiency	0.08	0.27	0.25	0.23
May	Total Days	52	47	33	132
	Exc. Days	9	21	17	47
	Efficiency	0.17	0.45	0.52	0.36
June	Total Days	28	19	0	47
	Exc. Days	12	10	0	22
	Efficiency	0.43	0.53	NA	0.47
Total	Total Days	105	115	147	367
	Exc. Days	23	44	45	112
	Efficiency	0.23	0.38	0.31	0.31

Table 2. Efficiency of Critical Fire Weather Types at producing FFWI 90th Percentile Exceedances by Month (Exc. Days = Exceedance Days).

		Node 10	Node 20	Node 30	All Days
April	GH (m)	3134 (3140)	3096 (3140)	3033 (3048) *	3098
	RH (%)	29.1 (19.6)	37.1 (28.1)	45.1 (34.5) **	34.9
	Grad (m/1000km)	67.7 (91.6)	80.6 (97.5) *	73.1(93.2) *	42.1
	Days	23 (2)	36 (19)	86 (28)	480
May	GH (m)	3133 (3133)	3091 (3098)	3047 (3050)	3131
	RH (%)	27.1 (25.5)	33.6 (24.8) **	39.4 (29.7) *	33
	Grad (m/1000km)	70.8 (109.1) **	78.7 (99.5) **	77.9 (90.7)	42.8
	Days	43 (9)	26 (21)	16 (17)	496
June	GH (m)	3130 (3134)	3092 (3099)	NA	3169
	RH (%)	32.6 (26.7)	33.7 (29.9)		31.7
	Grad (m/1000km)	71.3 (84.5)	74.9 (107.4) *		32.3
	Days	16 (12)	9 (10)		480

Table 3. Average atmospheric properties for exceedance days and non-exceedance days associated with critical weather types. Non-exceedance day values are shown with exceedance day values in parentheses. All values were calculated from daily 18Z Reanalysis grid point values (locations shown on Figure 1). *Exceedance vs. non-exceedance day values are significantly different (* $p<0.05$ and ** $p<0.01$).
[Note] GH: Geopotential Height, RH: Relative Humidity, Grad: Geopotential Height Gradient

Date	Synoptic Weather Type	Acres burned/day	Adjusted Transition Probability	Frequency of Transition Occurrence: 1988-2003
5/2/00	22	*Pre-fire*		
5/3/00	11	*Pre-fire*	15.7	8
5/4/00	11	*Prescription*	19.6	10
5/5/00	10	*Declared Wildfire*	18	9
5/6/00	10	805	20	10
5/7/00	21	1553	18.2	8
5/8/00	21	857	18.2	8
5/9/00	21	660	18.2	8
5/10/00	**20**	**8127**	13	6
5/11/00	**30**	**19542**	31.3	10
5/12/00	32	2852	16	4
5/13/00	11	6300	3.92	2
5/14/00	00	1563	9.68	9
5/15/00	00	414	32.3	10

Table 4. Progression of Cerro Grande wildfire and synoptic weather types. Adjusted transition probabilities were calculated by removing the transitions that occurred during the period of May 2nd, 2000 through May 15th, 2000.

Day 1 \ Day 2	00	01	02	10	11	12	20	21	22	30	31	32	Total Days
00	34.4 11	9.4 3	3.1 1	28.1 9	12.5 4	3.1 1	3.1 1	6.3 2	0 0	0 0	0 0	0 0	32
01	18.2 4	22.7 5	18.2 4	9.1 2	18.2 4	13.6 3	0 0	0 0	0 0	0 0	0 0	0 0	22
02	6.4 3	10.6 5	51.1 24	0 0	2.1 1	27.7 13	0 0	0 0	2.1 1	0 0	0 0	0 0	47
10	9.6 5	1.9 1	0 0	21.2 11	9.6 5	0 0	25.0 13	17.3 9	5.8 3	7.7 4	0 0	1.9 1	52
11	8.0 4	8.0 4	6.0 3	20.0 10	22.0 11	10.0 5	4.0 2	6.0 3	16.0 8	0 0	0 0	0 0	50
12	5.6 3	7.4 4	24.1 13	1.9 1	13.0 7	27.8 15	0 0	0 0	20.4 11	0 0	0 0	0 0	54
20	0 0	0 0	0 0	6.3 3	0 0	2.1 1	29.2 14	12.5 6	4.2 2	22.9 11	16.7 8	6.3 3	48
21	2.1 1	2.1 1	0 0	19.1 9	19.1 9	0 0	14.9 7	21.3 10	6.4 3	2.1 1	6.4 3	6.4 3	47
22	3.7 2	0 0	9.3 5	5.6 3	16.7 9	24.1 13	3.7 2	5.6 3	22.2 12	1.9 1	1.9 1	5.6 3	54
30	0 0	0 0	0 0	2.9 1	0 0	0 0	8.6 3	5.7 2	0 0	37.1 13	31.4 11	14.3 5	35
31	0 0	0 0	0 0	3.8 1	3.8 1	3.8 1	11.5 3	19.2 5	15.4 4	7.7 2	11.5 3	23.1 6	26
32	0 0	0 0	0 0	6.9 2	10.3 3	10.3 3	6.9 2	24.1 7	20.7 6	3.4 1	0 0	17.2 5	29

Table 5. Transition frequencies and probabilities for all May days, 1988-2003. First number in each cell is transition probability (%) and second number is frequency of occurrence (days).

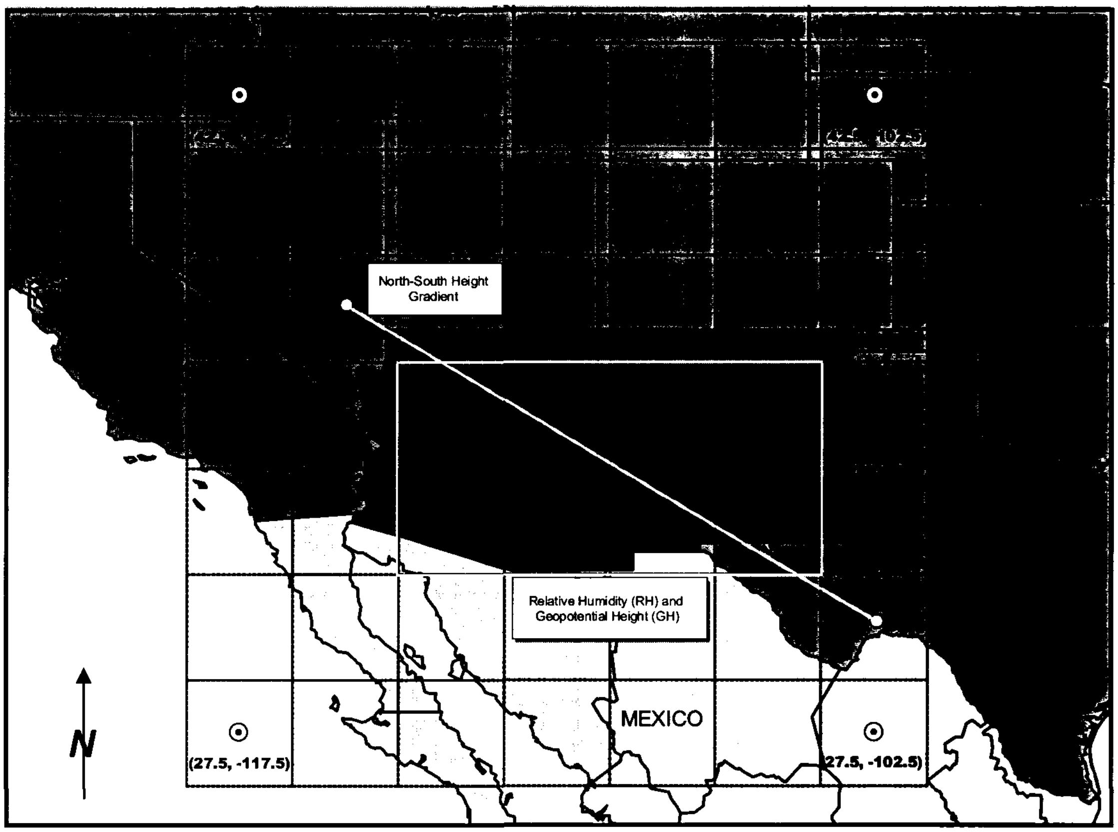

Figure 1. Study area showing location of RAWS sites (black dots) and NCEP-NCAR Reanalysis grid cells used in SOM classification. Diagonal white line represents transect along which geopotential height gradients were calculated and white box highlights the eight grid cells used in calculation of average 700mb relative humidity values (RH) and geopotential heights (GH). Reanalysis data grid points are located in the center of each grid cell (latitude and longitude shown for corner grid points).

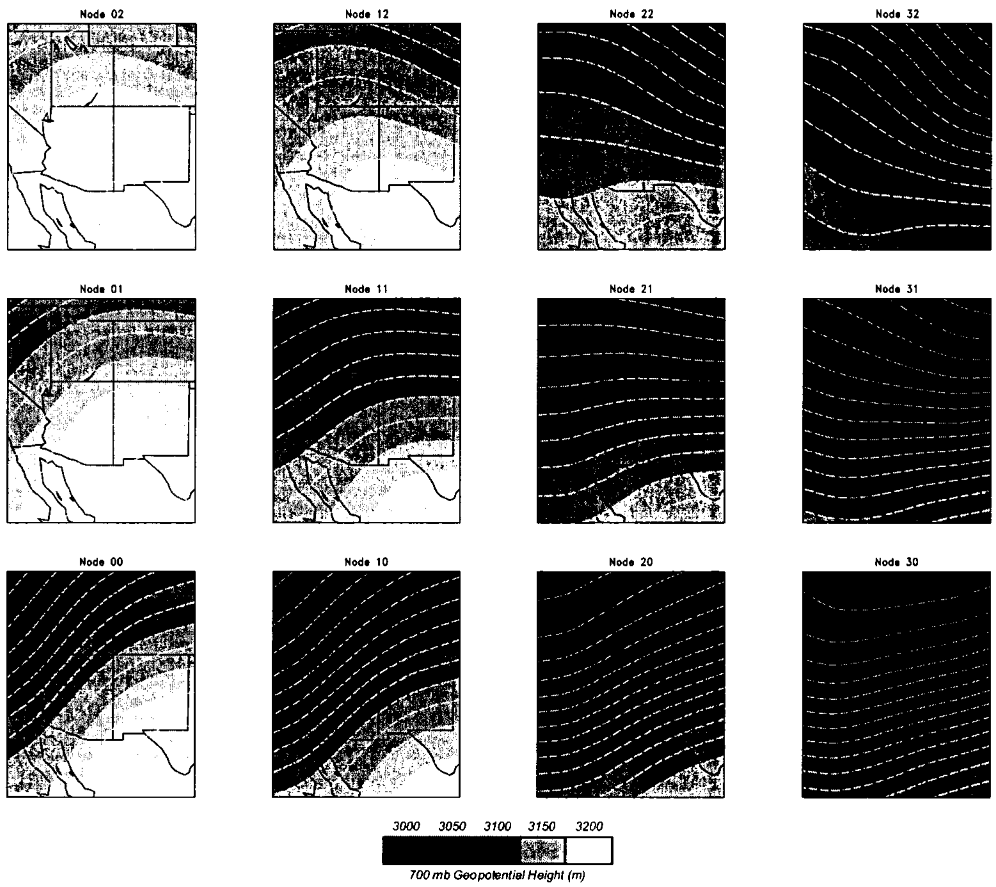

Figure 2. SOM classification of daily gridded Reanalysis 18Z 700mb geopotential heights for the period of 1988-2003. Highest height contour is in Node 02 (3190 m) and lowest contour is in Node 30 (3010 m). Contour interval is 10 meters for all nodes.

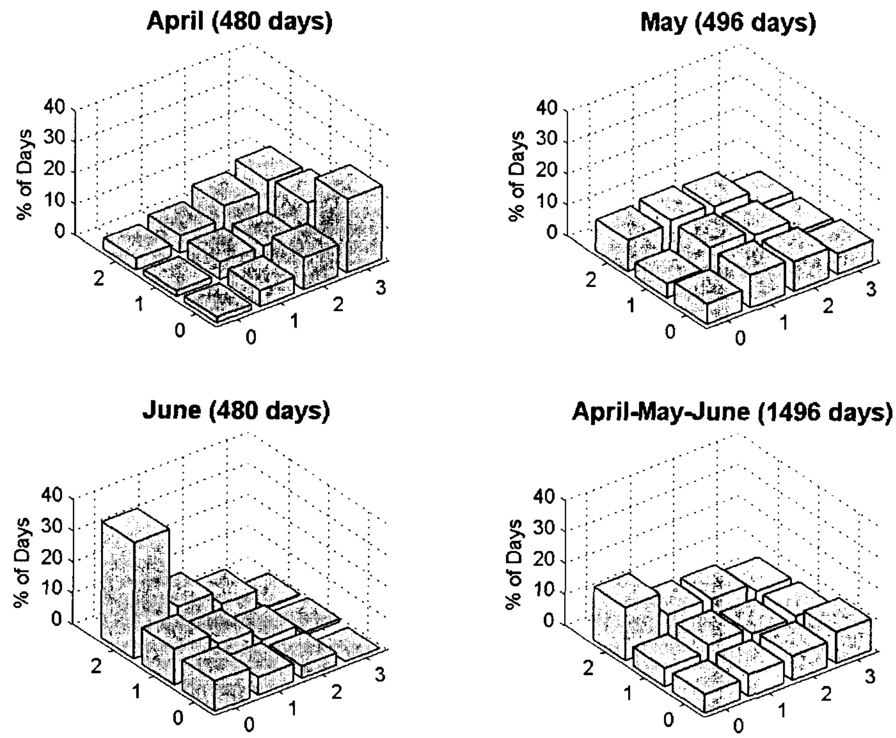

Figure 3. Frequency of occurrence of different SOM classified weather types. Organization of nodes is identical to Figure 2.

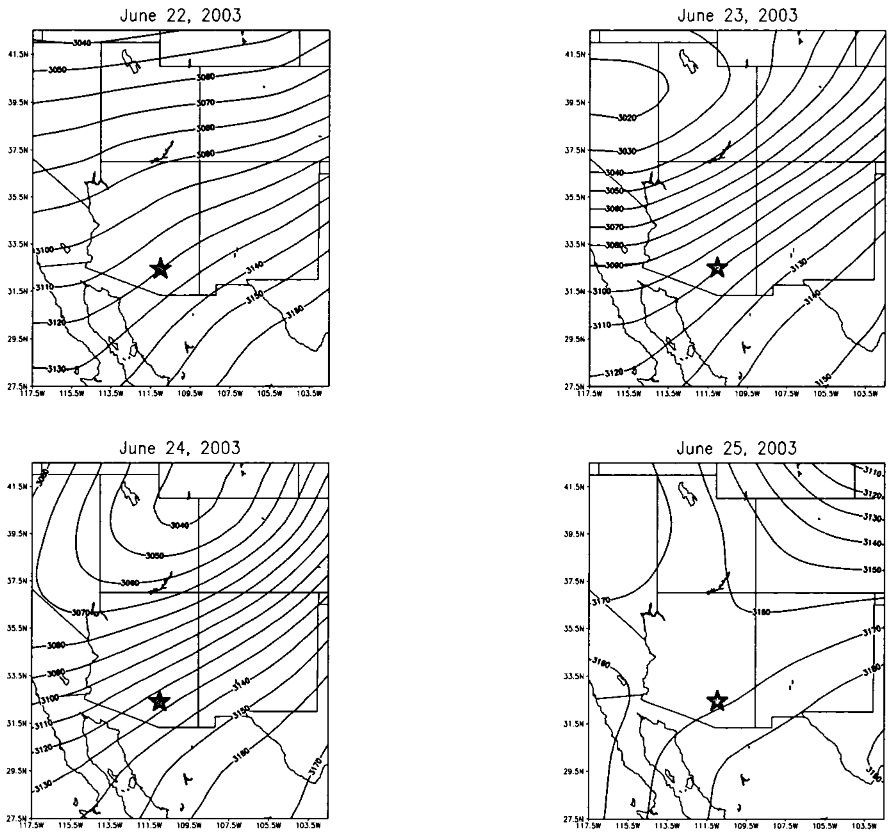

Figure 4. Daily (18Z) 700mb geopotential height plots of Reanalysis Data for a four day period during the Aspen wildfire (grey star) in southern Arizona in June of 2003. The wildfire was especially active on June 23rd, burning more than 8,500 acres in one day.

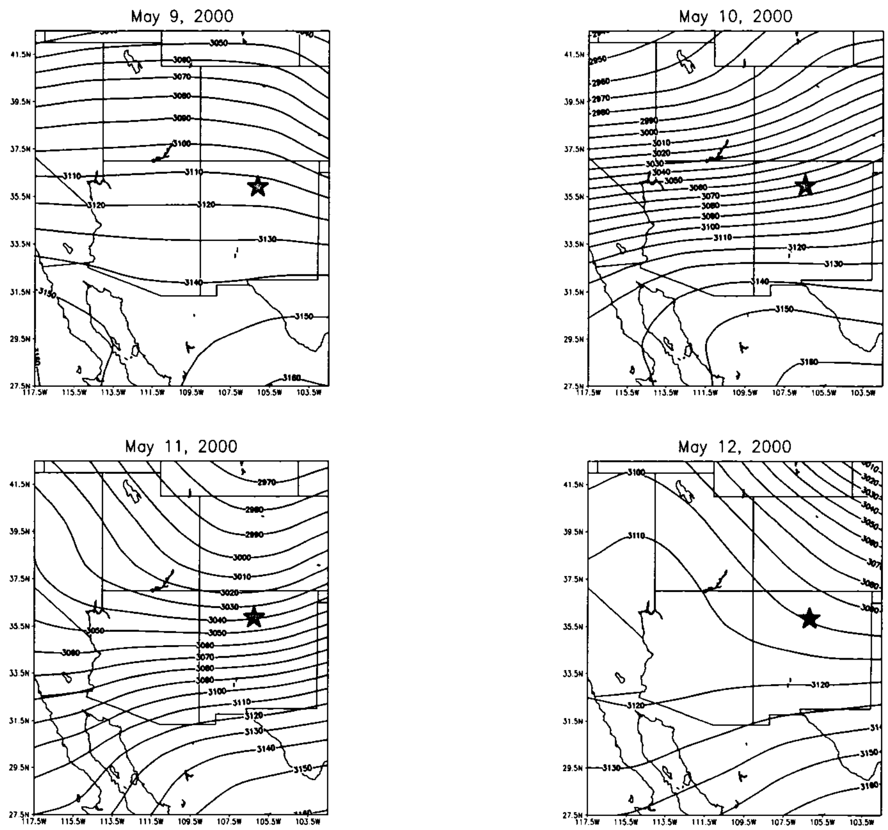

Figure 5. Daily (18Z) 700mb geopotential height plots of Reanalysis Data for a four-day period during the Cerro Grande wildfire (grey star) in northern New Mexico in May of 2000. May 10th and 11th were the most active days of the Cerro Grande event with over 8,000 acres burning on the 10th and 19,000 on the 11th.

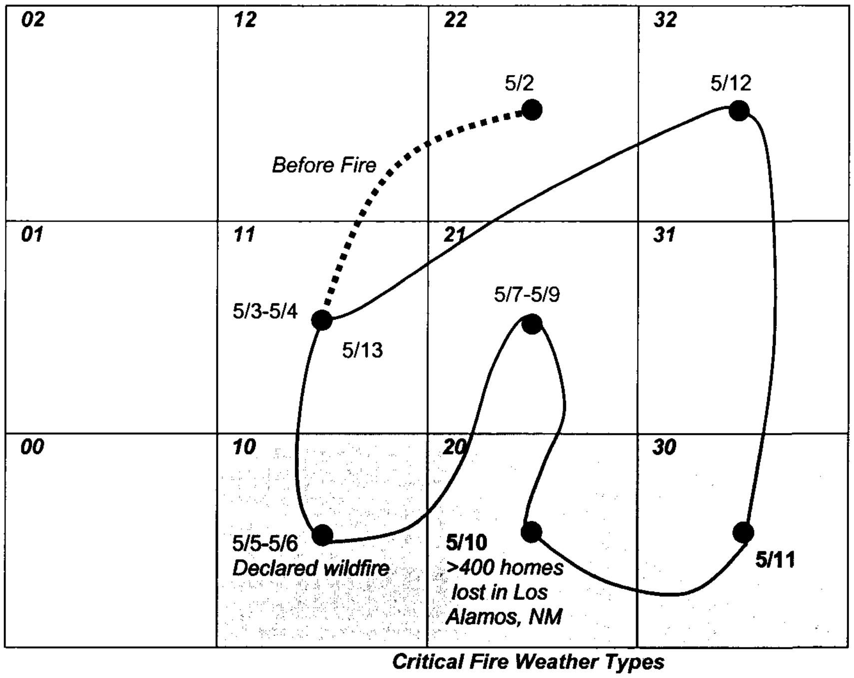

Figure 6. Sequence of daily weather types prior to and through the first week of the Cerro Grande WildFire. Dates in bold indicate most active fire days.

APPENDIX C

INTERANNUAL TO DECADAL CHANGES IN EXTREME FIRE WEATHER EVENT FREQUENCIES ACROSS THE SOUTHWESTERN UNITED STATES

MICHAEL A. CRIMMINS

(To be submitted to Journal of Applied Meteorology)

Abstract

Low-frequency changes (decades to years) in precipitation related to the El Nino-Southern Oscillation and the Pacific Decadal Oscillation are known to influence wildfire variability across the southwest United States. Little work has been done to identify whether daily fire weather variability, also important to wildfire activity, is influenced by these same climatic phenomena. This study identifies the synoptic climatological conditions associated with extreme fire weather events in the Southwest and constructs an extreme fire weather frequency dataset for the period of 1958-2003 using a logistic regression technique. Interannual changes in extreme fire weather day frequencies are not linearly correlated with either ENSO or PDO, but do show significant deviations from expected values when grouped by PDO phase (positive or negative) and further sub-grouped by ENSO state (La Nina, El Nino, or neutral). A higher number of extreme fire weather days occur during the negative phase of the PDO, especially when accompanied by a La Nina event.

Introduction

Climatological connections to wildfire variability exist through a variety of mechanisms operating on different temporal scales. Low frequency (years to decades) changes in precipitation regimes that modulate fuel production and fuel conditioning have been linked to wildfire variability in several studies (Simard et al. 1985, Swetnam and Betancourt 1990, 1998, Westerling and Swetnam 2003, Crimmins and Comrie 2004). Shorter-term (days to weeks) changes in synoptic circulation regimes have also been identified as important climatological influences on wildfire activity (Brotak and Reifsnyder 1977, Johnson and Wowchuk 1993, Nash and Johnson 1996, Flannigan et al. 2003, Westerling et al. 2004). Changes in daily fire weather conditions (windspeed, temperature, relative humidity) that occur through low frequency teleconnection patterns all are climatic components related to wildfire variability. Little work has been done to examine how these components are connected and how they may co-vary through time.

The relationship between wildfire and climate is rather unique across the southwest United States. Identified fire-climate relationships in areas of Arizona and New Mexico dominated by xerophytic forests show that antecedent climate conditions months to years prior to fire seasons can be as important as the actual fire season conditions (Swetnam and Betancourt 1998, Crimmins and Comrie 2004). Normal springtime (April, May and June) fire season conditions are climatologically hot and dry across Arizona and New Mexico. Above normal temperatures and below normal precipitation would do little to change already harsh conditions during the spring. Precipitation anomalies in seasons to years prior appear to promote the growth and accumulation of fine fuels that exacerbate wildfire activity during the fire season. Several studies have shown that the sequencing of El Nino events (wet) and La Nina events (dry) can promote the growth of fuels and then subsequently dry them out over a period of years (Swetnam and Betancourt 1990, 1998, Crimmins and Comrie 2004).

Short-term transitions to synoptic patterns that promote extreme fire weather conditions are also important in controlling seasonal wildfire variability across the southwest U.S. A discrete synoptic pattern characterized by a strong height gradient and broad southwest flow across the Southwest can elevate fire danger by bringing extremely windy conditions and low relative humidity values to the region (Schroeder 1969, Crimmins 2004). Wind events that occur during the spring fire season are particularly dangerous due to the background hot and dry conditions. Wildfires can quickly grow to large sizes when coincident with these wind events (e.g. Cerro Grande Wildfire, Crimmins 2004).

This study examines the interannual changes in extreme fire weather event frequencies with respect to known teleconnective phenomena already identified as important to southwestern U.S. climatic variability (e.g. ENSO; Redmond and Koch 1991 and PDO; McCabe and Dettinger 1999). Several recent studies (Gray et al. 2003, 2004) suggest that North Atlantic sea surface temperature variability may also impact western U.S. teleconnection patterns, but will not be examined in this study. An extension of the record of extreme fire weather frequencies is constructed using synoptic circulation indices and logistic regression modeling. Increasing the period of record strengthens the analysis of interannual variability in extreme fire weather frequencies. Identification of interannual trends in extreme fire weather frequencies will help improve our understanding of the connections between climatic and wildfire variability across the southwest U.S.

Data and Methods

Extreme Fire Weather Days

The daily fire danger ratings used as predictands in the logistic regression model were calculated from daily weather observations at 15 remote automated surface weather stations (RAWS) (Fig. 1). Daily data were only available from 1988-2003 due to the relatively recent implementation of the RAWS network. Initially 33 stations from across Arizona and New Mexico were considered for inclusion in the study. Short periods of record and missing data forced the exclusion of 18 stations. The final 15 stations included in the study represent the best spatial coverage of stations for the longest period of time.

Daily fire danger levels were determined by calculating the daily Fosberg Fire Weather Index (FFWI) values for each of the 15 stations. This index is essentially a non-linear filter that is extremely sensitive to changes in wind speed and relative humidity levels (Fosberg 1978, Goodrick 2002). High winds and low relative humidity values result in high FFWI values (Fosberg 1978). A statistical study by Haines, et al. (1983) found the FFWI to be a strong and significant predictor of wildfire activity when compared to historical records in the northeastern United States. The daily FFWI values from the 15 RAWS sites were combined into one regional time series by first converting the individual station time series into z-scores and then averaging them. It is understood that averaging the individual time series created a loss of information, but the regional signal was the desired component of the variability in daily fire danger. Sub-regional variability in daily fire danger does exist, but it is not addressed in this study.

The single, regional time series of FFWI z-scores was converted to rank-percentiles with the highest values being the highest percentiles. The 90th percentile was chosen as the breakpoint to determine extreme fire weather conditions. This is a common threshold used by the fire management community to identify extreme fire weather conditions (Fosberg et al. 1993, Schlobohm and Brain 2002). The final time series used as the predictand in the logistic regression model consisted of a binary variable indicating occurrence (1) or non-occurrence (0) of an exceedance of the 90th percentile threshold.

Reanalysis Data

Time series of daily (18Z) Reanalysis data were extracted and used as predictors in the logistic regression model. Monthly average grids were used to develop geopotential height anomaly composites. Reanalysis data are produced by the National Center for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) (Kalnay et al. 1996). These data represent model reconstructions of various atmospheric fields from daily observations at a grid resolution of 2.5 degrees. They provide a spatially and temporally consistent global dataset and are widely used in all types of climatological studies. The time series use 700mb level variables because of their proximity to the higher elevation areas of the Southwest. The study period was confined to the period of 1958-2003, when confidence in Reanalysis variable fields is highest (Kalnay et al. 1996).

Logistic Regression Modeling

A logistic regression model was used to develop an extended record of daily extreme fire weather frequencies back to 1958. The observational record of the current fire weather-monitoring network only extends back to the late 1980's and is not sufficient for a long-term climatological analyses. Model specification was done with Reanalysis grid time series to capture upper level (700mb) circulation characteristics important to driving to surface fire weather conditions. Several studies have identified synoptic circulation patterns that are associated with extreme, surface fire weather conditions (Schroeder 1969, Brotak and Reifsnyder 1977, Johnson and Wowchuk 1993, Takle et al. 1994, Crimmins 2004). Figure 2 shows a 700mb geopotential height anomaly composite of 141 extreme fire weather days occurring in April, May and June for the period of 1988-2003. A steep height gradient and anomalously low relative humidities characterize the synoptic environment over the study area during these extreme fire weather days. Three components were used to capture this synoptic signature in the regression model. A north-south gradient, east-west gradient, and regional average relative humidity (Fig. 1) were used as predictors to predict the occurrence or non-occurrence of a 90th percentile exceedance day. Daily odds-ratio values produced by the logistic regression model were examined to determine exceedance days. Days with odds-ratio values greater than 0.5

were counted as exceedance days. Final output consists of monthly (April, May and June) totals of predicted exceedance days for the period of 1958 to 2003.

Pacific SST Indices

Relationships between extreme fire weather event frequencies and ENSO and PDO variability were examined through the use of sea surface temperature (SST) indices. The PDO index developed by Mantua et al. (1997) was used to characterize the state of the north Pacific region. Index values represent the leading principal component of monthly North Pacific sea surface temperature variability (Mantua et al. 1997). The Oceanic Nino Index (ONI) was used to capture the state of the equatorial region of the Pacific Ocean. The ONI is a three-month running mean of the Extended Reconstructed sea surface temperature (ERSST.v2) anomalies from the Nino3.4 region (5°N-5°S, 120°-170°W) based on the 1971-2000 base period (CPC 2004). Trenberth (1997) proposed the use of Nino3.4 SSTs as a standard measure of ENSO variability because it most effectively captures the Pacific warm pool during El Nino events.

Both the ONI and PDO are SST based indices ensuring commensurate persistence and atmospheric response time lags. The assumption is that these SST based indices will reflect changes in forcing mechanisms that will eventually affect atmospheric circulation and afford forecasting lead times. This is done as an alternative to using the traditional atmospheric circulation indices associated with ENSO and PDO (Southern Oscillation Index [SOI] and North Pacific Index [NP]). The atmospheric circulation index values are highly correlated with the SST-based index values when lagged by one season. December-January-February (DJF) ONI values were correlated with March-April-May (MAM) SOI values at r=-0.897 while DJF PDO and MAM NP values were correlated at –0.687.

Spearman rank (ρ) correlations, χ^2 tests, and anomaly composites were all used to assess relationships between the SST indices and the frequency of extreme fire weather events. The local statistical significance of composite anomaly patterns was determined using the bootstrapping percentile method (Efron and Tibshirani 1993). Each composite grid cell was resampled with replacement 400 times to develop an artificial distribution. Significant differences of the anomaly from zero (no anomaly) were then determined at the 0.1 and 0.05 levels.

Results and Discussion

Extreme Fire Weather Frequency Modeling

Three time series derived from reanalysis data points were used to specify the logistic regression model. A composite of 700mb geopotential height anomalies and relative humidity anomalies for 141 April-May-June FFWI 90th percentile exceedance days was developed to determine the circulation anomaly associated with critical fire weather days (Fig. 2). This pattern is consistent with other studies of critical fire weather patterns across the southwest United States (Schroeder 1969, Crimmins 2004). Examination of the geopotential and relative humidity anomalies in Figure 2 show a steep height gradient and humidity anomalies across Arizona and New Mexico. A north-south and east-west gradient value were entered into the logistic regression model to capture variations in this height gradient pattern and a regional average relative humidity was used to discriminate variations in daily humidity anomalies (Fig. 1). The parameter estimates of these three variables were all highly significant ($p<0.001$) and the overall model was highly significant ($p<0.001$) indicating that the model was well specified. The receiver operating characteristic (ROC) curve produced an 'Area Under Curve' value of 0.93281 indicating that the model is well balanced between producing a low number of false positive values relative to false negative values at a range of probability thresholds (Swets 1998).

The model is well specified, but does not perfectly fit the input data. A pseudo-R^2 value can be calculated relative to an idealized, saturated model but does not represent percent variance explained like a traditional R^2 value. The present model has an R^2 value of 0.45, which represents a reasonable fit. The output of a logistic regression model is a probability of the predictand occurring relative to the values of the predictors. A threshold probability of 0.50 was used to determine the occurrence of an exceedance day. This appears to be a reasonable threshold upon examination of the predicted versus observed frequencies (Fig. 3). Even with a relatively low threshold probability the model tends to under-predict yearly exceedance frequencies when AMJ are considered together (Fig. 3). Closer examination of the individual months shows that the model performs best for the month of May. The correlations (r) between observed and predicted exceedance day frequencies for April, May and June were 0.35, 0.91, and 0.45 respectively. Only the May correlation ($r=0.91$) was significant ($p<0.001$). Model confidence is highest for May days and most exceedance days occur during May (43% of total AMJ exceedance days), so subsequent analyses will be confined to the month of May.

Modeled May exceedance day frequencies for 1958-2003 are shown in Figure 4, along with monthly Pacific Decadal Oscillation (PDO) index values (5 month running average) and Oceanic Nino Index (ONI) values. Frequencies are highly variable with values ranging from zero to eight exceedance days over the 46-year study period. The median value is 1.5 and the range is 8, indicating substantial positive skew.

Subtle patterns are evident when comparing the May exceedance day frequencies with the PDO time series (Fig. 4). PDO values were generally negative for the early part of the record with a shift towards positive values occurring around 1976-77. Two substantial but short-lived shifts to negative PDO values occurred in 1989 and 1999 during the later part of the record from 1977-2003. May exceedance day values were highly variable during the negative PDO phase from 1962 to 1976. This period had some of the highest predicted exceedance day frequencies for the entire study period, but also had six years with zero predicted exceedance days. The shift to positive PDO values in 1976 marked a period of lower variability and also lower exceedance day values. May exceedance day frequencies never rose higher than 3 days from 1981 to 1989. The shift to negative PDO values from 1989 to 1991 was accompanied by dramatic increases in predicted exceedance day frequencies.

The above discussion relates interannual variability in north Pacific sea surface temperatures with changing frequencies of May extreme fire weather days. Well known teleconnection patterns originating from equatorial SST anomalies impact winter temperature and precipitation across the southwest U.S. (Redmond and Koch 1991, Gershunov 1998, Cayan et al. 1999, Sheppard et al. 2002). These teleconnections appear to be limited to the winter season for temperature and precipitation, but may extend into the spring and modulate the occurrence of critical fire weather circulation patterns. Transitions between El Nino (positive ONI) and La Nina (negative ONI) conditions occur about every four years during the early period from 1961 to 1976 (Fig. 4). These transitions may help explain the high variability in exceedance day frequencies from year to year during the same period. The pattern of high and low exceedance day counts during the early part of the record may be related to ENSO-induced atmospheric teleconnections.

χ^2 *Testing of Group Frequencies*

No significant correlations were found when Spearman rank correlations were calculated between May exceedance day frequencies and seasonally averaged ONI and PDO indices (prior winter and spring season including May). The patterns in Figure 4, however still suggest a relationship between the datasets. There may be non-linear interactions that will not be resolved by a linear correlation analysis. An alternative analysis is to evaluate the general state that each index is portraying (e.g. El Nino, neutral, or La Nina) and form categories. This method was employed by Gershunov and Barnett (1998) to develop sea level pressure composites of general PDO and ENSO states. This analysis will use a similar approach and evaluate the frequency of May exceedance days by PDO phase, ENSO state, and subgroups representing the combination of both (e.g. PDO+ and El Nino). The groupings are shown in Table 1. ENSO and PDO states from the winter months preceding the May in the question are used. This was done with the expectation that changes in sea surface temperature reflected by the indices would take time to manifest atmospheric circulation anomalies into the spring and that the SST anomalies would persist into spring. Evaluating the lagged relationship between the SST states and the May exceedance frequencies also affords a potential forecasting tool. If relationships exist, the winter SST state could be used to project the potential extreme fire weather activity for the upcoming spring. El Nino and La Nina events are based on the Climate Prediction Center method of a 0.5 °C threshold in the ONI where La Nina events are >-0.5°C and El Nino events are >0.5°C (CPC 2004). PDO state is based on the NDJFM mean.

χ^2 tests were performed between the expected and observed proportions of exceedance to non-exceedance days for several different groupings based on ENSO and PDO states (Table 2). The total number of observed May exceedance days for both PDO states was significantly ($p<0.01$) different from the expected number. Fewer than expected occurred during Mays where the winter PDO was positive and more than expected occurred during the negative PDO state. None of the ENSO-based groupings had significant deviations of the observed versus expected frequencies. The observed frequencies were higher than expected during La Nina events and lower during El Nino events, but not significantly different. Grouping on ENSO and PDO states together helped to further discriminate the relationship between May exceedance days and Pacific Ocean states. Two subgroups had differences in observed and expected frequencies that were highly significant ($p<0.05$). Interestingly, they were both La Nina events but associated with different PDO states. Mays associated with La Nina events during PDO+ had a less than expected number of days while La Nina-PDO- had more. Neutral-PDO – also had more days than expected contributing to the overall relationship between PDO- and higher exceedance day frequencies. El Nino-PDO+ had fewer than expected days helping to explain the PDO+/fewer exceedance day relationship.

These results suggest that Mays that follow PDO- winters had a higher frequency of extreme fire weather days, especially if a La Nina event was underway. The opposite was true for Mays that were preceded by PDO+ winters and both El Nino and La Nina events. ENSO and PDO states have rarely been implicated in explaining springtime climatic variability across the southwestern United States. The strongest teleconnection patterns in the southwest U.S. associated with ENSO and PDO are found during the winter with precipitation and temperature (Gershunov and Barnett 1998, Gutzler et al. 2002, Brown and Comrie 2004). The present study deals with very subtle changes in extreme fire weather events that most likely would have very little influence on mean monthly climate values. The relationships identified in above the χ^2 analyses are not evident when examined with linear methods like correlation analysis.

Composite Analysis

A composite analysis was performed to examine circulation anomalies that may help explain the shifts in May exceedance day frequencies associated with the different composite groups. Composites of 700mb geopotential height anomalies for PDO+ and PDO- years are presented in Figure 5. The patterns are consistent with the results of the χ^2 test between the PDO+ and PDO- groups. A ridge-trough-ridge pattern is present on the PDO- composite, which is similar to the exceedance day composite presented in Figure 2. The opposite pattern (trough-ridge-trough) is present on the PDO+ composite. Patterns on both composites have significant anomaly areas, with the north central United States having the most consistent anomaly area that is highly significant. The anomalies are weak, but do indicate a more favorable pattern for producing exceedance days during PDO- than PDO+.

Subcomposites grouped by PDO and ENSO state are presented in Figure 6. The highly significant χ^2 value La Nina groups both have highly significant geopotential height anomalies across the southwest U.S. The La Nina-PDO- composite shows a pattern with ridging over the Pacific and troughing over the western United States. This is consistent with the composite exceedance day pattern depicted in Figure 2. The La Nina-

PDO+ composite shows a very different pattern with significant positive height anomalies extending from the mid-Pacific into the southwest U.S. This pattern reflects a strong and persistent expansion of the subtropical high into the western United States and retreat of the polar jet, which may block the troughing events necessary for extreme fire weather conditions across the Southwest.

The El Nino-PDO+ and Neutral-PDO- groups also had significant ($p<0.1$) χ^2 values. The El Nino-PDO+ composite shows a weak and generally insignificant anomaly pattern across the United States. A weak trough-ridge pattern can be made out, but only the upper Midwest has significantly positive height anomalies associated with the ridge. The weak negative height anomaly off the California coast and positive anomalies over the north central U.S. suggest a pattern that is counter to the western U.S. troughing associated with exceedance days. This group has a lower than expected number of exceedance days, but the anomaly pattern is weak and does not indicate any very persistent features that would definitively explain the reduction in observed exceedance days.

An opposite ridge-trough-ridge pattern is present on the Neutral-PDO- composite. Significant positive height anomalies are found over Alaska and the southeast United States with very weak and insignificant troughing between these areas over the western U.S. This pattern in general is favorable for troughing over the western U.S. associated with exceedance days. This group had 23 exceedance days relative to the 15.4 expected

(χ^2 p=0.06) and may be due to the upstream ridging over Alaska. The significant, positive height anomalies over Alaska may induce the downstream trough-ridge pattern.

Neutral-PDO+ and El Nino-PDO- both had insignificant χ^2 values and anomaly patterns that are neither favorable nor unfavorable for producing exceedance days across the southwest U.S. The Neutral-PDO+ composite has trough-ridge-trough pattern with significant negative height anomalies south of the Aleutian Islands and over the eastern United States. Weak, but significant, positive anomalies occur only in central Canada. No height anomalies exist over the southwest U.S. indicating a lack of persistent circulation features for this area.

The El Nino-PDO- composite was similar to the El Nino-PDO+ composite with subtle shifts in the highest and lowest height anomalies. The negative height anomaly off of the California coast was significant, but shifted further west towards Hawaii. Positive height anomalies shifted toward the northwest U.S. and negative height anomalies dominated the area south of Hudson Bay, Canada. The positive height anomalies over the northwest U.S. are north of the Pacific negative anomalies indicating the possibility of a weak, split jet stream.

The anomaly patterns associated with each PDO phase are made up of different numbers and types of ENSO events. El Nino conditions were present for 10 of the 23 years in the PDO+ composite while 11 of the 23 years in the PDO- composite were La

Nina conditions. This is especially evident with the PDO- composite (Fig. 5). The ridge-trough pattern in the La Nina-PDO- composite is very similar to the overall PDO- composite, but is stronger and is a significant anomaly. This tendency towards more La Nina events during the negative PDO phase and El Nino events during the positive phase helps explain the overall shift to more May exceedance days during PDO- and less during PDO+.

Teleconnection Patterns

It is unclear what the exact mechanisms are that either limit or promote the development of the steep gradient troughing pattern characterized by the daily exceedance composite in Figure 2 during the transition season month of May. The neutral and El Nino subcomposites of PDO+ have negative height anomalies off of the California coast, which may be remnants of the wintertime Aleutian Low. A strong Aleutian Low is associated with the positive phase of the PDO and typically shifts east during El Nino events (Gershunov and Barnett 1998, Niebauer 1998, Overland et al. 1999). Composite analysis of several El Nino events performed by Overland et al. (2001) showed that the strong, wintertime Aleutian Low ended quickly in April, but negative height anomalies persisted into June over the north Pacific south of the original low center. These anomalies may be due to changes in SST patterns over the north Pacific induced by the Aleutian Low that persist into the spring. The negative anomalies don't appear to be strong enough to represent persistent, blocking features, but may be a weak forcing mechanism for ridging over the western U.S. counter to the critical fire weather pattern in Figure 6.

The positive height anomalies over the southwest U.S. during La Nina-PDO+ do appear to represent a blocking pattern. The broad influence of the subtropical high would tend to push the baroclinic zone further north and limit long or shortwave trough development over the western U.S.. La Nina events were relatively rare during the positive PDO phase of the study period with only four years in the La Nina-PDO+ group. There appears to be relatively strong agreement in the height patterns between the four years, but they account for only 9% of the total years during the study period.

The La Nina-PDO- and neutral-PDO- represent 78% of the total years comprising PDO-. Both of these subcomposites have positive height anomalies over the eastern Pacific region and troughing over the western U.S.. Burnett (1994) found that upstream ridging over the eastern Pacific was a consistent feature associated with the development of troughing over the southwest U.S.. Weak, wintertime Aleutian Lows are associated with the negative phase of the PDO. The weaker than normal Aleutian Low may condition north Pacific SSTs that directly or indirectly promote positive height anomalies that persist into the spring.

The constructive phasing suggested by Gershunov and Barnett (1998) with negative PDO-La Nina and positive PDO-El Nino events having the most stable teleconnection patterns appears to only be valid for the La Nina-PDO- group in this study. This group has the most exceedance days of any group and also has a significant ridge-trough pattern similar to the exceedance day composite pattern. The El Nino-PDO+ does not have a strong anomaly pattern that would help explain its fewer than expected exceedance days. The destructive pairing of La Nina and PDO+ actually has the strongest anomaly pattern and the pattern explains the fewer than expected observations in this group.

PNA and the May Exceedance Days

The general circulation anomalies represented by the PDO+ and PDO- composites are very similar to the PNA pattern which is characterized by a quadripole pattern with positive height anomalies over central Canada and Hawaii and negative height anomalies over the Gulf of Alaska and the southeast United States during its positive phase (Wallace and Gutzler 1981, Barnston and Livezey 1987, Leathers et al. 1991, Leathers and Palecki 1992). The PDO+ composite is most like the positive phase of the PNA while PDO- is like the negative PNA pattern. The exact mechanisms that drive the PNA pattern are not fully understood and change throughout the year, but have been related to ENSO variability with positive correlations between El Nino events and the positive PNA pattern (Yarnal and Diaz 1986, Hoerling and Ting 1994). This relationship is strongest in the winter months, but may exist in a weaker state into the spring. The bias of more El Nino events during the positive PDO phase may help explain the overall PDO+ composite. The PNA pattern alone does not help explain interannual variability in May exceedance day frequencies. May PNA index values are not correlated with May exceedance values (ρ=-0.094). A scatterplot of May PNA versus May exceedance day frequencies supports this lack of correlation (not shown), but reveals that many of the highest frequencies are associated with PNA values that are close to zero. The lack of a strong positive or negative PNA pattern and blocking features may allow for transient wave activity to produce troughing events that propagate across the Southwest. Regardless, the PNA pattern does not appear to be an important component in explaining interannual changes in exceedance day frequency.

Connections to Southwestern Wildfire Variability

Much research has documented the relationship between ENSO variability and changes in southwestern U.S. precipitation regimes during the winter months (Redmond and Koch 1991, Gershunov 1998, Cayan et al. 1999). El Nino (La Nina) events tend to bring above (below) normal precipitation to the Southwest during the winter months of DJFM. Recent research has also shown that the stability of this teleconnection is dependent on the phase of the PDO (Gershunov and Barnett 1998, Gutzler et al. 2002, Brown and Comrie 2004). The negative (positive) phase of the PDO tends to bring more La Nina (El Nino) events and an extended number of years with below (above) normal winter precipitation (Gray et al. 2003).

Regional-scale wildfire variability across the Southwest has been linked to the low-frequency climate variability inherent in the ENSO teleconnection patterns discussed above. Swetnam and Betancourt (1998) used ENSO to help explain periodic wildfire events in xeric forests across Arizona and New Mexico following sequences of El Nino and La Nina events. They hypothesized that wet winters associated with El Nino events were promoting the growth of fine fuels and suppressing fires while subsequent dry, La Nina winters helped to condition fuels. The sequence of climatic conditions that promote fuel growth and fuel drying would culminate in fire seasons with high total area burned.

The results of this study indicate that the low frequency wet-dry cycles associated with ENSO may not be the only climatic components modulating fire season activity across the southwest U.S.. Changes in the frequency of regional-scale extreme fire weather events appear to change with the same low-frequency components related to ENSO and PDO. La Nina events that typically bring dry winters to the Southwest also are related to a higher frequency of extreme fire weather events in May when the PDO is in the negative phase. Changes in the frequency of extreme fire weather conditions appear to be more dependent on the longer term shifts related to the PDO. The last several decades were characterized by the positive phase of the PDO, several of the strongest El Nino events on record, and exceptionally wet winters across the Southwest. This period has brought unprecedented surges in biomass across the U.S., exacerbating already high fuel loadings (Swetnam and Betancourt 1998). A return to the negative PDO phase would mean not only an extended period of drier conditions, but also a higher frequency of extreme fire weather conditions during the fire season. This combination could lead to catastrophic wildfire seasons with a shift to a more consistent negative PDO phase.

Conclusions

Low frequency changes in north Pacific SSTs related to the Pacific Decadal Oscillation appear to modulate the frequency of May regional scale extreme fire weather events across the southwest United States. Extreme event frequencies were significantly different from expected for both positive PDO and negative PDO years. More May events (69) occurred during negative PDO conditions than during positive PDO conditions (32).

Subgroups of PDO phases (positive and negative) based on ENSO state provide further insight into the connection between Pacific Ocean SST anomalies and southwestern U.S. critical fire weather patterns. La Nina events during the negative phase of the PDO had the highest total number exceedance days of any subgroup. 700mb geopotential height anomaly composites identified a significant ridge-trough pattern over the eastern Pacific-western United States that is favorable for the development of extreme fire weather conditions over the Southwest.

In general La Nina and neutral ENSO conditions during PDO- had positive height anomalies over the eastern Pacific that may either not block the development of trough events over the western U.S. or actually enhance them. This pattern appears to be favorable for developing the steep geopotential height gradients across the Southwest necessary for extreme fire weather conditions. El Nino events during both phases of PDO had weak negative height anomalies and were associated with fewer than expected exceedance days, only El Nino-PDO+ had significantly different observed days from expected. La Nina events during the positive PDO phase produced a strong and significant positive height anomaly across Arizona and New Mexico that may serve to block the formation of trough events. This subgroup was associated with only two exceedance days when 8.8 were expected.

The higher than expected frequencies associated with La Nina-PDO- events and the negative PDO phase in general have important ramifications for the southwest U.S. The exceptionally wet period from 1977-1998 associated with extreme El Nino events and a generally positive PDO phase may switch soon to a more consistent negative PDO phase. This shift may not only bring drier winter conditions as expected but increasing extreme fire weather activity during the spring. The combination of long-term fuel accumulation spurred on by the wet period of 1976-2001, below normal precipitation in upcoming winters and more frequent hot, dry, and windy spring days could mean a substantial increase in wildfire activity in upcoming fire seasons.

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	PDO Positive	PDO Negative
El Nino	1958, 1992, 1978, 1983, 1970, 1977, 1998, 1988, 2003, 1987	1969, 1964, 1995, 1966, 1973
La Nina	2001, 1996, 1985, 1984	1972, 1962, 1976, 1971, 1974, 2000, 1965, 1989, 1999, 1968, 1975
Neutral	1997, 1961, 1960, 1982, 1980, 1993, 1981, 1986, 1994	1991, 1967, 2002, 1963, 1990, 1979, 1959

Table 1. Composite group memberships by PDO phase and ENSO state (1958-2003).

	Observed	Expected	χ^2 Value(p)
PDO +	32	50.5	6.91 (0.009)
PDO -	69	50.5	6.91 (0.009)
EN	24	32.9	2.36 (0.124)
LN	38	32.9	0.66 (0.417)
NE	39	35.1	0.38 (0.538)
PDO +/EN	14	22	2.76 (0.096)
PDO +/LN	2	8.8	4.83 (0.028)
PDO +/NE	16	19.8	0.59 (0.442)
PDO -/EN	10	11	0.02 (0.888)
PDO -/LN	36	24.2	5.68 (0.017)
PDO -/NE	23	15.4	3.52 (0.06)

Table 2. χ^2 tests of the observed versus the expected number of May exceedance days based on the composite group (PDO = Pacific Decadal Oscillation, EN = El Nino, LN = La Nina, NE = Neutral).

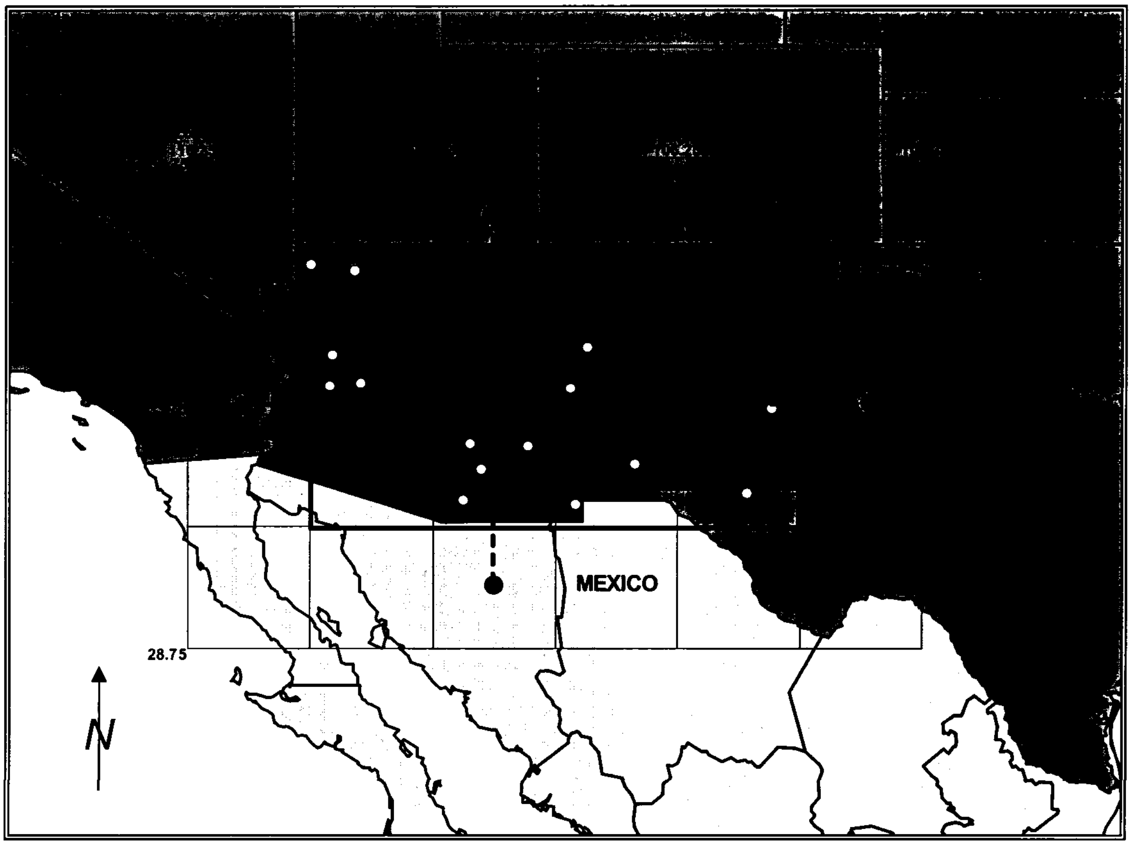
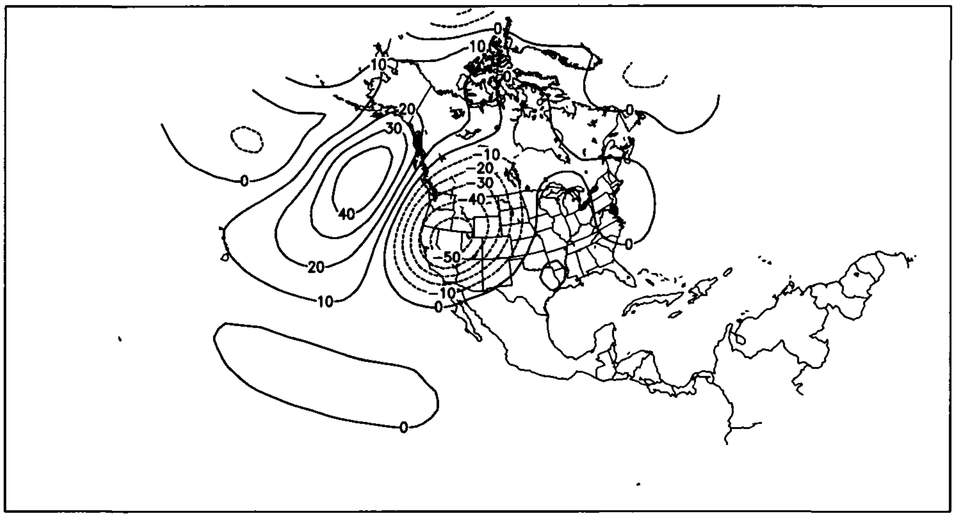
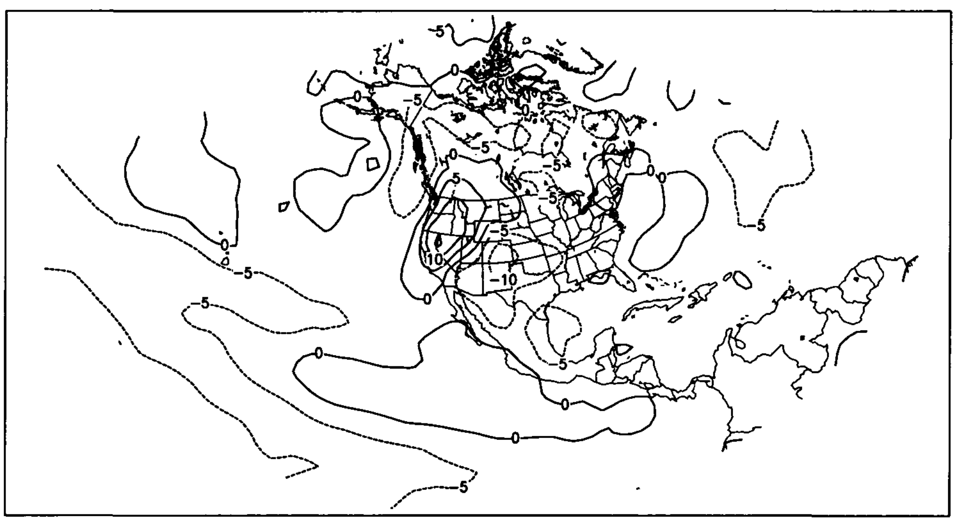


Figure 1. Study area with RAWS sites in Arizona and New Mexico shown (white circles). Grid (thin lines) represents location of Reanalysis data points (center of grid cells). Dashed lines divide where north-south and east-west gradient time series were developed (black circles). Dark outline of grid cells over Arizona and New Mexico highlights Reanalysis data points used in calculation of average regional relative humidity time series.



700mb geopotential height anomaly (contour interval: 10m)



700mb relative humidity anomaly (contour interval: 5%)

Figure 2. Anomaly composites of all FFWI 90th percentile days in AMJ from 1988-2003 (n=144 days)

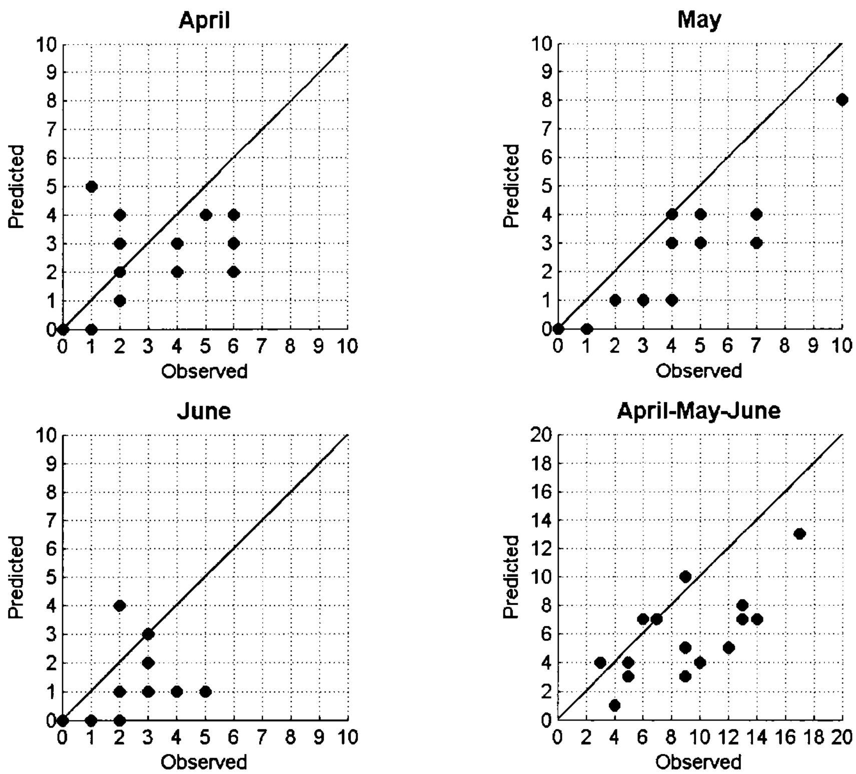


Figure 3. Observed versus predicted exceedance day frequencies between 1988-2001.

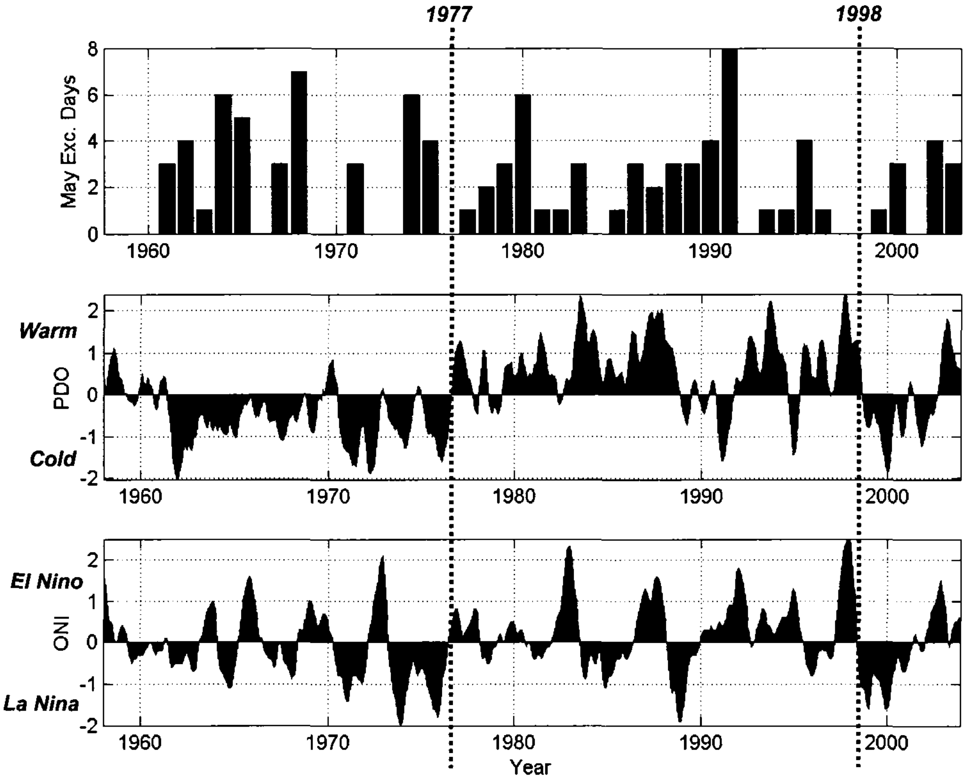
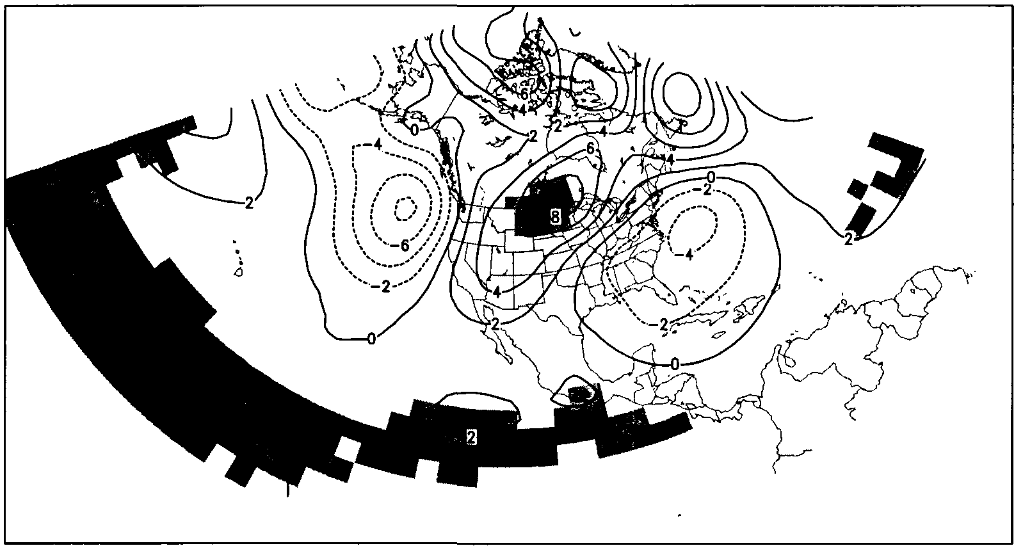
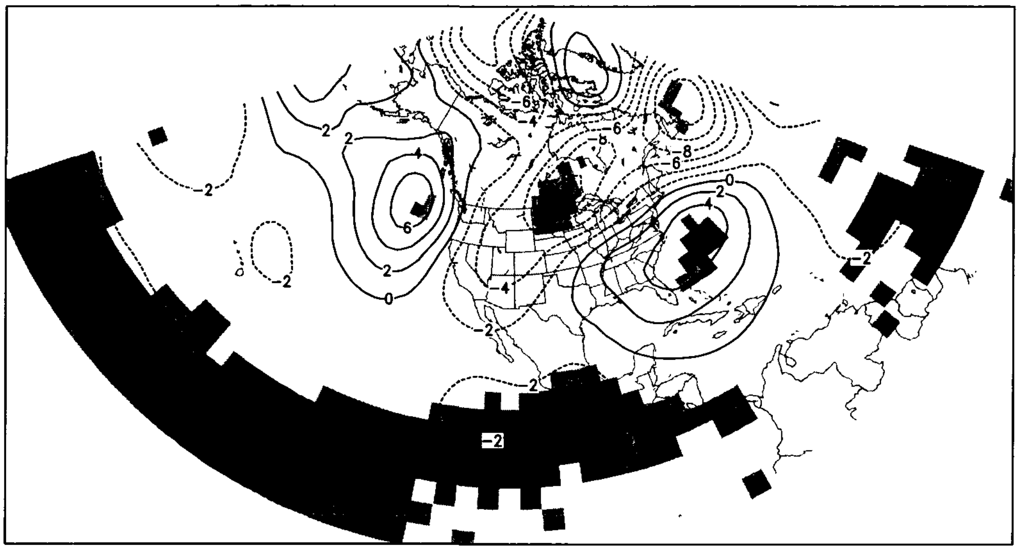


Figure 4. Reconstructed May exceedance day frequencies (top) and monthly Oceanic Nino Index (ONI) and Pacific Decadal Oscillation (PDO) values. Dashed vertical lines represent major shifts in north Pacific sea surface temperature patterns.



PDO Positive (n=23)



PDO Negative (n=23)

Figure 5. May 700mb geopotential height anomalies based on the PDO phase grouping (solid lines: positive anomaly, dashed lines: negative anomalies, contour interval: 2m). Dark shading indicates significance at 0.05 level and light shading indicates significance at 0.10 level.

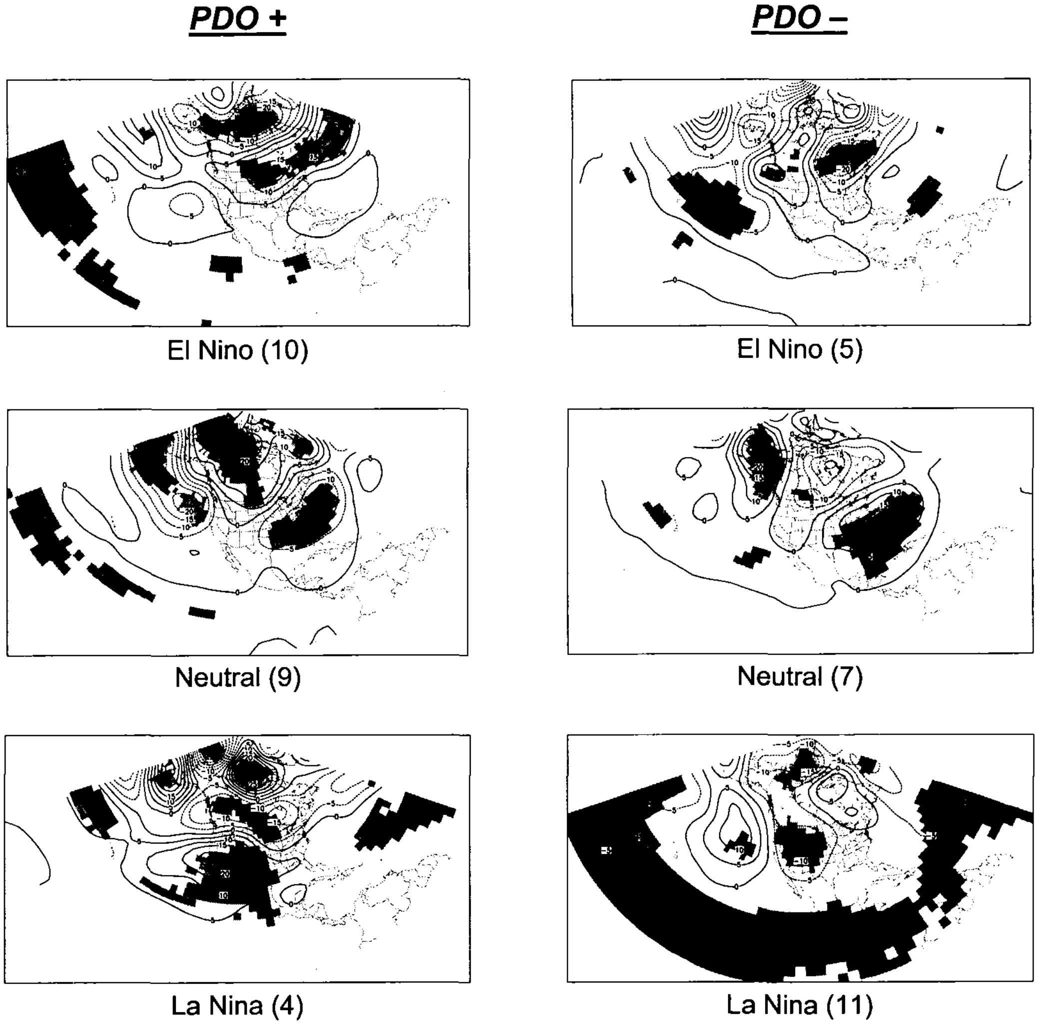


Figure 6. May 700mb geopotential height anomaly composites by sub-group. (solid lines: positive anomaly, dashed lines: negative anomalies, contour interval: 5m). Dark shading indicates significance at 0.05 level and light shading indicates significance at 0.10 level. Numbers in parentheses represent number of years used in each composite group.