University of Nevada, Reno

The Southwest Monsoon and the Relation to Fire Occurrence

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in
Atmospheric Science

Charlene R. Mohrle

Dr. Timothy Brown/Thesis Advisor

December 2003

ABSTRACT

In southeastern Arizona, a decline in climatological fire starts occurs in early July. The decline coincides with the arrival of the Southwest Monsoon, a seasonal climate phenomenon impacting southeastern Arizona. Corresponding changes in atmospheric elements such as relative humidity and dew point in conjunction with the monsoon could be some of the mitigating factors. Determining the extent of the monsoon's role in fire occurrence has not been well quantified or documented in either the climate or fire communities. The problem becomes quite complex given the interannual spatial and temporal variability in both the monsoon and fire occurrence. The changes in atmospheric conditions stemming from the monsoon result in both fire producing and fire mitigating effects.

This study examines the applicability of two existing definitions of the monsoon onset to fire occurrence and quantitatively assesses fire and atmospheric moisture elements occurring within the monsoon season. Historical fire occurrence data and weather data from Remote Automatic Weather Stations in southeastern Arizona are analyzed in an effort to improve understanding of this fire-monsoon relationship.

ACKNOWLEDGMENTS

I could say this research project was one of the most difficult things I have ever done in my life, but does anyone ever say it was a piece of cake? The difficulty, in terms of a higher level of education, to me, is a given. Instead, I will say that it has been a huge learning experience. Not only in the area of academic research but in my personal life as well. I, as other students, have somehow discovered how to deal with life's curve balls while completing graduate school and that is an accomplishment, to me.

When Tim Brown, my advisor, first took me in as a graduate student, he knew the risks in taking someone who was changing careers and who did not have a strong computer background. He has allowed me to experience a whole different world that at first I wasn't sure that I would fit in. He has shown me what the word persistence really means. At times when I wanted to throw in the towel, he persevered and amazed me with new outcomes that resulted by not giving up. It is from him that I have learned that research is not about specific deadlines. Sometimes, satisfactory results cannot be had within a finite amount of time. And in the end, it is about being satisfied with the overall results and knowing that you did all that you could. This is what he taught me and I believe that persistence is a virtue that I can apply to many aspects of my life beyond just research.

Another person that is largely responsible for my success is Beth Hall, my cheerleader, consultant and friend. I honestly feel that I would not be here writing this today if it weren't for her. She offered many words of encouragement in the beginning when I was having second thoughts. Having been through this herself, she knew exactly how I felt and used her own past experience to give invaluable advice and support that I will never be able to thank her enough in one lifetime.

My graduate committee members, Franco Biondi and David Mitchell, demonstrated much patience and understanding in the unending changes of my thesis. I thank them sincerely for that and that they were willing to be on my committee and be involved in my research.

It is always daunting to move to another city to start a new life. When I first came to Reno, the lack of friends was sometimes overwhelming. My co-student, Hauss Reinbold and I come from different backgrounds but our sense of humor is oddly similar. I want to thank him for interjecting humor into situations, and for listening to my problems, which at times I'm certain sounded like a broken record.

Earlier, in my undergraduate years at the University of Northern Colorado, I had the opportunity to work with Nolan Doesken, assistant state climatologist for Colorado. My first research experience was through him at the Colorado Climate Center. He was also, unknowingly, my bridge to the Desert Research Institute and CEFA as he knew Tim Brown personally. When I was accepted into graduate school at UNR, he offered some advice that at the time didn't make sense. As I started graduate school, however, it became clearer what he was talking about and I continued to remember those words for the remainder of my time here.

In the last months of completing my thesis, I moved back to San Diego, and through Tim, I was able to have an office to complete my work at the Scripps Institution of Oceanography. I owe much thanks to both Tim and Dan Cayan for making this possible.

My dear husband, Markus, is the most understanding, devoted person in the world who knows the true meaning of unconditional love. I know that he has been frustrated at times with my decisions but has never once made me feel guilty for some of the sacrifices that he had to make. Instead, he has stood by my side, encouraged me to finish even if the decisions impacted his life unfairly. I love you, Markus, with all my heart and I hope that someday I will be able to show you the same understanding and support that you've shown me.

There are countless others that I owe much gratitude including my parents, my brother, my in-laws, my sister-in-law and my friends that stood by my decision to go back to school after fourteen years of nursing. At first they must have thought that I needed a mental exam but when they realized the seriousness of my plans, they were in full support from the beginning. Although they never had a choice of not staying with me through all this, my two cats, the best listeners in the world, were always supportive in their own feline ways.

I'm sure years from now I will look back on my graduate school experience in Reno with fondness and satisfaction that I had the fortitude, and the motivation even with personal sacrifices to achieve my goals. This experience has no doubt expanded my knowledge in the areas of research, atmospheric science, fire science, and computers, but most importantly, it has allowed me to learn of my own capabilities. The academic knowledge is evident in a master's degree but the personal revelations will define my life from here on and for that reason, they are even more important than knowledge. Thanks to everyone!

TABLE OF CONTENTS

TABLES

FIGURES

CHAPTER ONE

INTRODUCTION

The southwestern United States (U.S.) is a region known for historically active fire seasons. Some of the more notable, nationally well-publicized fire events have been in Arizona and New Mexico. Climatic processes are one of the dynamic components driving fire regimes that are unique to this area. The existing research on climate and fire relationships has been mostly linked to the larger scale climate changes such as El Niño-Southern Oscillation (ENSO). Swetnam et al. (1990) has provided conclusive evidence using tree ring growth analysis that a wet El Niño winter followed by two, dry La Niña winter years are correlated to extensive wildfire occurrences in the southwestern U.S. (CLIMAS 2000).

On a more regional scale, a significant component of the climate system that could be impacting fire regimes in addition to the larger scale climate processes is the Southwest Monsoon. This seasonal climate phenomenon has been the subject of many atmospheric science studies but research of its association to fire is virtually non-existent.

In southeastern Arizona, a sharp decline in climatological fires begins around July 7th and levels around July 18th (Figure 1.1). After July 28th, the number of fires continues to decrease but not as abruptly. The timing of the initial decline coincides with the average onset of the Southwest Monsoon as defined by the Phoenix National Weather Service Forecast Office (NWSFO; around July 7th). In a time series comparison of fires in the four corner states (New Mexico, Arizona (excluding southeastern Arizona), Utah and Colorado) and southeastern Arizona, the two climatologies reveal intriguing differences in their patterns. The curves in Figure 1.1 represent the 5-day running mean of fires, both human and lightning caused combined. With the four corners states encompassing a larger region, the sample size is larger and so the scale for the frequency of fires is smaller for southeastern Arizona. Regardless, there does appear to be a drop in the number of fires occurring after July 7th for southeastern Arizona that is earlier, more abrupt and more prolonged than the initial drop in fires for the four corners states.

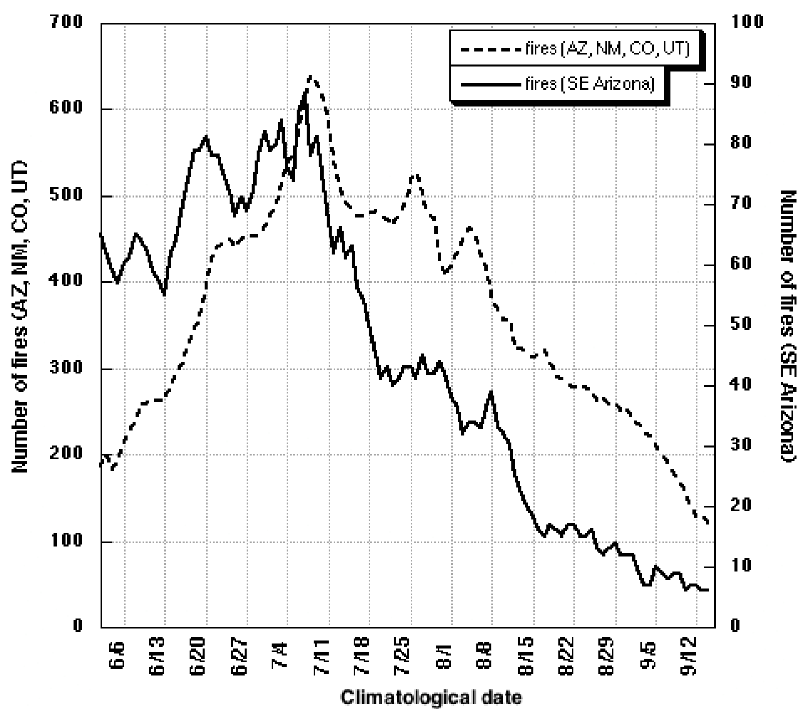

Figure 1.1. 5-day running mean fire (combined cause) climatology time series for southeastern Arizona and Arizona (excluding the southeastern part), New Mexico, Utah and Colorado combined for June 1st through Sept 11th.

On average, the effects of the Southwest Monsoon are felt to a large extent in southeastern Arizona. These effects are associated with increasing atmospheric moisture conditions that could affect fire occurrence in this area.

The climatological increase from the 23-year period of 1980-2002 in the atmospheric moisture elements dew point and minimum relative humidity (RH) is graphically displayed in the time series shown in Figure 1.2. Superimposed with the atmospheric elements is the corresponding fire start (both human and lightning caused) time series for southeastern Arizona.

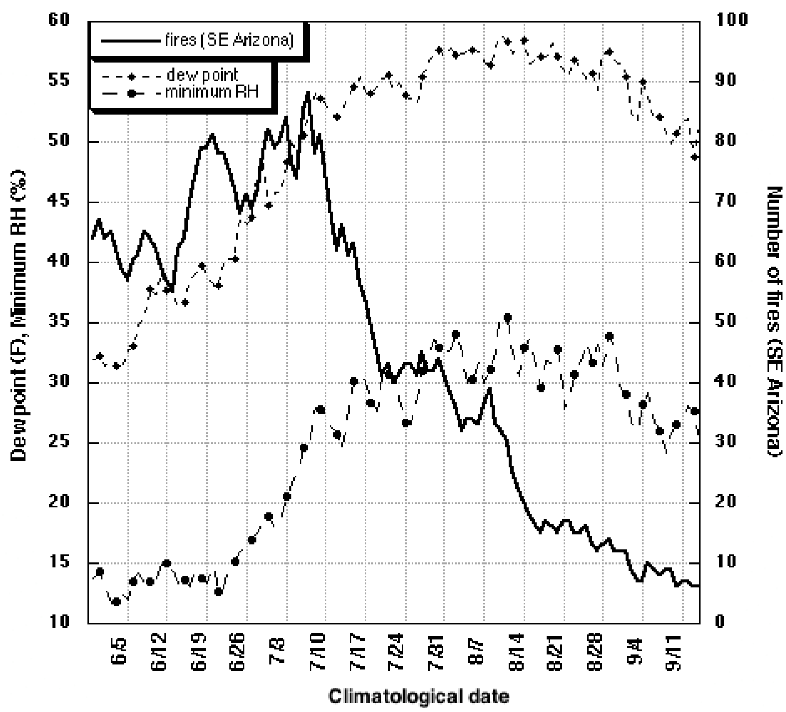

Figure 1.2. Total number of fires (solid line), average daily dew point (diamonds with dashed line), and average daily minimum RH (circles with dashed line) for southeastern Arizona for the period 1980-2002.

The curves in Figure 1.2 suggest an inverse relationship between atmospheric moisture (i.e., dew point, minimum RH) and fire occurrence beginning around July 8th, just one day from the average onset as defined by the Phoenix National Weather Service Office (NWSFO). These observations lead to the question: Is there a relationship between decreasing fires and increasing moisture associated with the onset of the Southwest

Monsoon? A superficial glance at these synchronized climatologies in Figure 1.2 would certainly suggest there could be an association. The Spearman Rank correlation coefficient between the two variables of moisture and fires is –0.575. This indicates a moderately strong negative correlation, but it does not verify that one factor is physically causing the other.

The objectives of this study are to determine the applicability of two existing Southwest Monsoon onset definitions to fire occurrence, and to quantitatively assess fire and atmospheric moisture elements occurring within the monsoon season.

This study describes linkages between atmospheric moisture elements and fire occurrence in order to provide fire weather forecasters and fire management with quantitative information about the relationship between the monsoon and southwestern wildland fires. The outcome should be an improved understanding of the 'firesoon', a self-selected term referring to the combination of fire and climate elements resulting from the seasonal climate phenomenon. The results will serve as a foundation for future research pertaining to meteorological/fire relationships in concert with other relevant variables and for other monsoon-impacted parts of the southwestern region of the U.S.

CHAPTER CONTENTS

Though research connecting southwestern U.S. wildland fire activity and the Southwest Monsoon are minimal, existing research on the larger climate processes and fire are discussed in Chapter 2. A basic understanding of the Southwest Monsoon properties, and characteristics and their relevance to fire activity is provided as well.

Chapter 3 describes the data sets used for fire occurrence and historical meteorological data from Remote Automatic Weather Stations (RAWS) for the study region. The refining, synthesizing and processing of the final data sets are described in detail.

The climatology and interannual/intra-seasonal variability of both fire and moisture elements in southeastern Arizona is presented and addressed in Chapter 4. The relevance of the extreme variability to fire occurrence and the complications that can develop is discussed.

Chapter 5 assesses the application of the definitions of the monsoon onset to fire occurrence and quantifies the relationship of fire occurrence and moisture elements in order to determine potential moisture thresholds.

The final results, a summarization of these chapters, the conclusions from this study, and potential future work is provided in chapter 6.

CHAPTER TWO

BACKGROUND

The majority of climate and fire research for the southwestern U.S. has tended to focus on larger-scale climate variability (i.e., El Niño-Southern Oscillation (ENSO)). But there is a basic understanding of Southwest Monsoon properties that can be investigated in the context of fire, even if the mechanisms and causes of interannual and intra-seasonal variability of both monsoon and fire are not well understood.

1. Climate Variability and Fire Occurrence

A fair amount of research has been done on the link between interannual and decadal scale climate anomalies (i.e., those associated with ENSO) and fire regimes in the southwestern U.S. The Southwest tends to experience wetter than normal winters during El Niño years and drier than normal winters during La Niña years (e.g., Swetnam et al. 1990). Swetnam et al. (1990) has correlated sequences of a wet El Niño winter followed by two dry La Niña winters resulting in an above average fire season for the successive summer after these two dry winters. It is speculated that high winter precipitation in the first year produces fine fuel growth, while the following dry years allow the vegetation to become very dry, thus creating widespread fire potential conditions. An example of this pattern was the severe fire season of 2000. A strong El Niño occurred in 1998 and was followed by two relatively strong La Niñas in 1999 and 2000. Other contributing factors to the severity of the fire season in concert with climate conditions may include changes in forest ecosystems from fuel load accumulations that have been induced by suppression practices (Swetnam et al. 1990).

The climate community recognizes the importance of connecting the smaller seasonal climate features such as the Southwest Monsoon and fire occurrence (CLIMAS 2000). In the southwestern U.S., an area largely impacted by the monsoon, the interactions between atmospheric processes at the global and regional scale are complex and not well understood. Much of the difficulty in the understanding of the monsoon lies within these complex interactions. The varied topography in the southwestern U.S. is also a contributor to the extreme spatial and temporal characteristics of the monsoon. As a result of these factors, forecasting and modeling the monsoon remains problematic (CLIMAS 2000).

2. Description of Southwest Monsoon

The Southwest Monsoon (also called the North American Monsoon System or the Mexican Monsoon depending on the regional perspective) is a well-established component of the climate system in the southwestern U.S. Mechanisms involve a change in upper level wind patterns from westerly to southerly as the subtropical high ridge shifts northward from Mexico to the Southwest U.S. This is graphically displayed in Figures 2.1 and 2.2. The seasonal prediction of exactly when or precisely where this change will occur remains elusive.

The seasonal reversal in wind direction brings moisture and precipitation, usually in the form of thunderstorms, into the southwestern U.S. A thermally induced low-pressure area typically develops over southern Arizona that augments the moisture transport into the region (Higgins et al. 1997). Arizona and New Mexico are on the northernmost fringes of the monsoon but its impact can be felt from the Sierra Nevada Range in the west to the Colorado and Wyoming Rockies. In terms of geographic extent of rainfall amounts, the monsoon impact lessens with increasing northward distance from northwestern Mexico (Douglas et al. 1993).

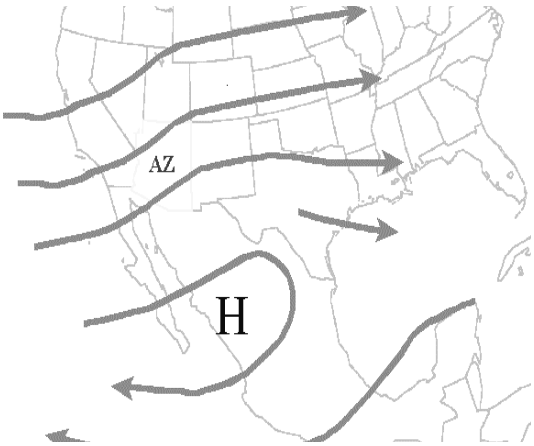

Figure 2.1 Westerly flow at 500mb in June

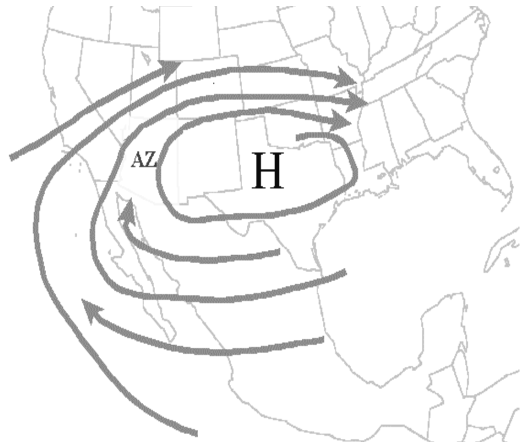

Figure 2.2 South/southeasterly flow at 500mb in July

(source: Tucson National Weather Service, http://www.wrh.noaa.gov/tucson/monsoon/mexmonsoon.html)

3. Moisture transport

There is little agreement in the climate community on the moisture source location for the monsoon. The disagreement is centered on the contributions from the Gulf of California (GOC; Adams et al. 1997) and the Gulf of Mexico (GOM; Douglas et al. 1993). National Center for Experimental Prediction – National Center of Atmospheric Research (NCEP-NCAR) reanalysis studies have indicated that moisture in lower levels of the atmosphere (below 850 ha) originates from the northern GOC and upper level moisture arrives from the GOM (Higgins et al. 1997). If atmospheric moisture is found to have an association with decreasing fire occurrence, then moisture source regions are most likely one of the keys to an improved understanding of the fire-monsoon relationship in the southwestern U.S.

The monsoon's regional effects can exhibit substantial spatial variability. High-resolution mesoscale model simulations have revealed a primary role of the north-south Sierra Madre Occidental (SMO) mountain range of northern Mexico as a moisture pathway into the interior of southwestern U.S. (Fawcett et al. 2002). This study showed the primary moisture source for lower levels west of SMO is the GOC and east of SMO is the GOM. Daytime land surface heating generates strong onshore, moist winds that originate over the GOC towards the western slopes of the SMO. This occurs on the eastern side as well with winds from the GOM moving up the eastern slopes of SMO. Strong, southeasterly flow advects a large amount of moisture into west Texas and eastern New Mexico. At night, a strong lower level jet (LLJ) influenced by topography occurs west of the SMO but not directly over the GOC (Fawcet et al. 2002). This LLJ would likely feed moisture into southeastern Arizona. On the eastern side, southerly and southeasterly flow, also influenced by topography and the nocturnal Great Plains LLJ, converge with winds from the GOM and transport moisture into western Texas and southeastern New Mexico.

These findings certainly suggest the bulk of moisture is transported at night via lower level jets into various regions of the southwestern U.S. It also helps to explain the spatial differences observed in atmospheric moisture conditions. Similar results to the model study were found using observed data from rawinsonde, geostationary satellite imagery and monthly mean rainfall to determine geographical extent of summer rains for the southwestern U.S. (Douglas et al. 1993).

4. Properties of the Southwest Monsoon

The primary known features resulting from the monsoon are increased atmospheric moisture, and increased precipitation in the form of moisture-laden thunderstorms for particular areas of the Southwest (Higgins et al. 1997; Douglas et al. 1993; Fawcett et al. 2002). Precipitation and moisture are both essential inputs for determining fuel moisture content in the National Fire Danger Rating System (NFDRS), a system of various indices to provide indicators of fire behavior, fire potential and fire danger (Bradshaw et al. 1978). Both dew point and relative humidity are indicators of atmospheric moisture and are used in two definitions of the monsoon onset discussed below.

Another property having significance in the context of fire activity is the occurrence of lightning that results from dry or wet monsoonal thunderstorms. The lower level atmospheric moisture content appears to be significant in determining if dry or wet lightning will occur. Rorig et al. (2002) found for the Pacific Northwest and the northern Rockies that the 85kPa dew point depression and the 85-50 kPa temperature difference appears to be successful in discriminating between dry and wet lightning days. The changes in atmospheric conditions stemming from the monsoon result in both fire producing (i.e., dry lightning) and fire mitigating (i.e., atmospheric moisture, rainfall) effects.

5. Monsoonal Characteristics

The latitudinal shifts in the subtropical high ridge over the southwestern U.S., and surges of moist air from the Gulf of California, that can account for a large amount of intra-seasonal variability of the monsoon, are associated with the interannual variability of the onset, strength, and duration of the monsoon (Carleton 1990; Hales 1972). The prediction of these characteristics, however, is not yet close to a high degree of reliability, in part because these mechanisms are not fully understood (Mitchell et al. 2002).

Basically used as indicators, there are a few definitions to designate the onset of the monsoon. The Phoenix NWSFO definition is considered ‘official’. In the 1960’s, a meteorologist and a state climatologist from the Phoenix NWSFO developed a definition that was originally designed for Phoenix but eventually became widely used by other meteorologists to identify the onset for Arizona. The intent was to use this definition in an operational sense. It was based on the relationship that a dew point of 55 degrees correlated to an inch of precipitable water, which is sufficient for producing measurable precipitation. Through trial and error, it was determined that a 3-day duration was needed to minimize ‘false’ onsets from non-monsoon related weather that may occur early in the summer (Phoenix NWSFO website-
http://www.wrh.noaa.gov/Phoenix/general/55degree/index.html). The inherent problem with this definition is using a single location to delineate a change in meteorological conditions that is spatially and temporally variable. Thus, if various locations throughout the monsoon-impacted region were to use this definition, the onset should vary.

A second definition, designed solely for fire purposes, uses relative humidity as the defining variable for the onset. The Southwest Geographic Area Coordination Center

(SW GACC) in Albuquerque, New Mexico uses 5 out of a 7-day period with 20% or higher minimum relative humidity as the onset for various selected weather stations distributed throughout Arizona and New Mexico. These Remote Automatic Weather Stations (RAWS) will be discussed further in the next chapter.

Unlike the single location for the Phoenix NWSFO definition, the minimum RH onsets are geographically representative of the spatial variability associated with the monsoon. Though this definition is not published or documented in a scientific paper, it can be found on the Southwest GACC website (http://www.fs.fed.us/r3/fire/swapredictive/swaoutlooks/swaoutlooks.htm).

Precipitation has been used more to indicate the strength of the monsoon in terms of seasonal statewide totals (Mitchell et al. 2002) but it is also used to indicate the onset. Higgins et al. (1997) developed a precipitation index by averaging daily accumulations of observed precipitation at each grid point (2.5 X 2.5 degree) of the rectangular region (112.5º-107.5ºW; 32º-36ºN). They used the years 1963-1994 for most of Arizona and western New Mexico. Historical onsets were defined as 3 consecutive days of +0.5 mm of daily precipitation. Among their findings was an abrupt monsoon onset in Arizona compared to a gradual transition in New Mexico.

A recent study by Mitchell et al. (2002) has quantitatively related sea surface temperatures (SST's) in the Gulf of California to the onset, amount and regional extent of monsoonal rainfall. These findings suggest that relatively heavy rainfall in Arizona typically occurs about 3-days after the northern GOC SST's reaches or exceeds 29º C. Results from this study indicate that GOC SST's do play a role in the timing, and the rainfall distribution in the southwestern U.S. The results also lend support to physical justification for the dissimilarities in the observed monsoon impacts for Arizona and New Mexico.

There is a lack of information regarding indicators of monsoonal strength and duration. Some studies have suggested an early onset of the monsoon to result in above-average total monsoonal rainfall (i.e., strong monsoon) (Higgins et al. 1997). But the localized and irregularity of precipitation events in complex terrain can cause precipitation totals to be spatially variable.

The duration of the monsoon is the least understood of all of the monsoonal features. Further research into this characteristic can be potentially significant to fire suppression and fire use activities in the Southwest. Designation of the end of the monsoon is difficult since weather patterns gradually transition into a wintertime pattern instead of reverting to pre-monsoon values.

The changes in climatological properties associated with the monsoon such as dew point, relative humidity, precipitation, winds, and lightning from dry or wet thunderstorms are directly and indirectly related to fire occurrence. The result of these monsoonal properties is a change in atmospheric conditions that can be identified with the definitions of the monsoon onset. Applicability of the dew point and minimum relative humidity definitions to fire occurrence in southeastern Arizona is assessed quantitatively in chapter 5. Invariably, the interannual and intra-seasonal variability of the monsoonal characteristics will introduce complexity into this study.

CHAPTER THREE

DATA

This study would not be possible without the existence of historical fire start data from the federal agencies, daily weather data from RAWS and lightning from the National Lightning Detection Network™ (NLDN) data set. This chapter focuses on data acquisition, quality and the necessary synthesis before analyses are performed.

1. Fires

Figure 3.1 highlights the region of fire and meteorological analyses in southeastern Arizona. The fires used in this study were located within 50-mile radii around each RAWS. Fire occurrence data were obtained from the U.S. Forest Service (USFS) based on Form 5100-29 reports that are locally compiled and then electronically transferred to the National Interagency Fire Management Database (NIFMID), and Department of Interior Form-1202 reports that includes Bureau of Land Management (BLM), Bureau of Indian Affairs (BIA), National Park Service (NPS), and Fish and Wildlife Service (FWS). For purposes of separating fires, only fires with known causes were included (e.g., lightning, arson, campfire). Fires occurring within the time frame of May 1st to September 15th were used. The fires in Figure 3.1 show preferential locations of occurrence. Most of the fire activity is clustered along the mountainous areas of the Mogollan Rim in central eastern Arizona and the mountainous areas in west-central, and northern New Mexico.

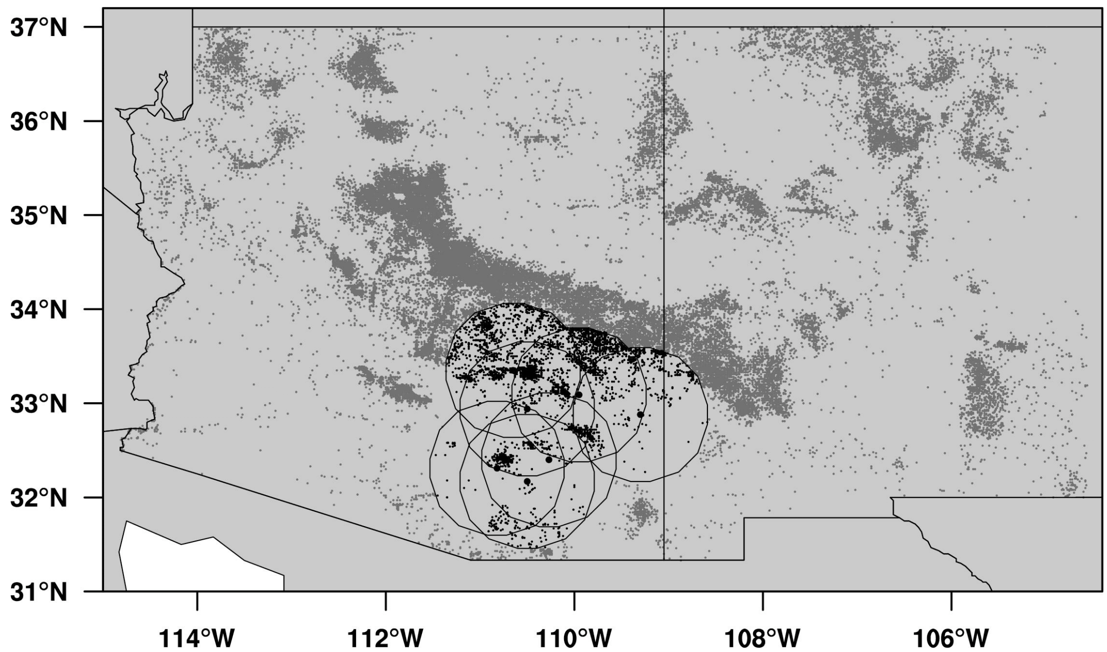

Figure 3.1. Map showing all federal fires (gray dots) in Arizona and New Mexico, and fires used in the study (black dots) within the 50-mile radii of selected RAWS locations (large black dots) in southeastern Arizona.

Some state land fires were collected from the federal website, Coarse-Scale Spatial Data for Wildland Fire and Fuel Management (http://www.fs.fed.us/fire/fuelman/index.htm). This website has a National Fire Occurrence database that was compiled by researchers from the Rocky Mountain Research Station, Fire Sciences Laboratory. Acquisition of additional state and/or private land fires from Arizona was unsuccessful. According to Arizona state office personnel, there is no existing record of fire data or at least of data in any form that would have been acceptable for this study. Unfortunately, the state fires that were successfully obtained from the USFS website had to be excluded due to the uncertainty of the cause codes. The cause codes need to be reliable for the purposes of separating the natural and non-natural caused fires (Brown et al. 2002). The state land fires before their exclusion had comprised about 20% of the total fire data set that included state and federal fires.

Because of potentially serious data quality issues, the fires were subjected to a coarse assessment (Brown et al. 2002) to ensure that the location, date of occurrence, fire type, fire cause, agency, and size were available and accurate. This included the use of Arcview/GIS (Geographic Information Systems; http://www.esri.com) to visually confirm the accuracy of each fire location. Fires of any size, within the specified boundaries of analyses were extracted if they occurred during the period 1980-2002 (May 1st through September 15th), of which most of the readily available data is accessible.

In some of the analyses, large fires were assessed and compared to the results using all sized fires. A large fire was defined as equal to or larger than 40 ha (approximately 100 acres). The large fire maps on the National Interagency Fire Center (NIFC) website (http://firemapper.sc.egov.usda.gov/modisrr/lg_fire2.php) defines a large incident as a wildfire of 100 acres or more occurring in timber, or a wildfire of 300 acres or more occurring in grass/sage.

The 1km Current Cover Type (version 2000) fuel model map (http://www.fs.fed.us/fire/fuelman/) was used to estimate the vegetative fuel associated with the start location of each fire. For purposes of this study, only fires occurring in timber or shrub vegetation were extracted. The cover types not used were grass, agriculture, and wetland type locations.

There are a total of 4741 fires in southeastern Arizona that occurred within the time period of June 1st to September 15th for the years 1980-2002. These are fires located within the 50-mile radius rings around each RAWS in Figure 3.1. The percentage of these fires that are lightning caused versus human caused are evenly split at 50%. Timber fires comprise a smaller fraction of the total than shrub fires at around 36% and 64% respectively. For the 1st part of the analysis in Chapter 5, the methodology considers fires 45-days before and 45-days after the onset dates. Because of early onsets in some years, this approach necessitated the inclusion of fires prior to June 1st. The total 90-day period was chosen with the onset date as the midpoint for the reason of maximizing sample size for fires. For this particular analysis because of the additional days, the total number of fires is 6829 with the percentage of natural fires at 37% and human fires 63%.

2. RAWS

RAWS are strategically located in remote, fire-prone areas, and can provide a good representation of fire weather conditions. The necessary weather data was extracted from RAWS historical datasets from the Western Regional Climate Center (WRCC) for the years 1980-2002. The use of data from ASOS (Automated Surface Observing System) or co-op stations (National Weather Service managed) was not considered for this study. The RAWS network is required to meet NFDRS standards to support interagency fire danger assessments and predictions (http://www.fs.fed.us/raws/standards/), whereas ASOS, located at airports and co-op stations, which uses volunteers, are not.

Specific criteria were used in the selection of RAWS sites for analysis. This became a double-edged sword as the need to retain as many sites as possible due to the large differences in each station's environmental characteristics such as elevation, and fuels was weighed against the necessity to disregard sites with questionable or large gaps in data. In order to develop a climatology given the short period of record available, there needed to be at least 11 years of consistent and relevant weather data during the time period of 1980-2002. Non-existing or insufficient fire data preceding 1980 precludes the use of earlier years. Regardless, many RAWS were not active prior to 1985 though some manual stations prior to automation may have been. No more than 30 days (about one third of the season) for the summer period of June 1st to September 15th was allowed to be missing or that year was disregarded. Strictly requiring more than 11 years of sufficient data to the criteria would have limited the number of RAWS and caused the final results to be less reliable due to a very small number of available stations. Figure 3.2 is a map of southeastern Arizona RAWS sites with the number of existing years with sufficient data from 1980-2002 given. The squares represent the final selected RAWS that have 11 or more years. Some of the sites shown in Figure 3.2 had no years of sufficient data for this analysis. The final number of RAWS was reduced to 7 from a possible 20 due to data deficiencies. The instances of missing data were much too common and remained one of the biggest impediments in this research. Some of the contributing factors to poor data quality and data gaps are blocked transmissions and equipment malfunction (Brown et al. 2001).

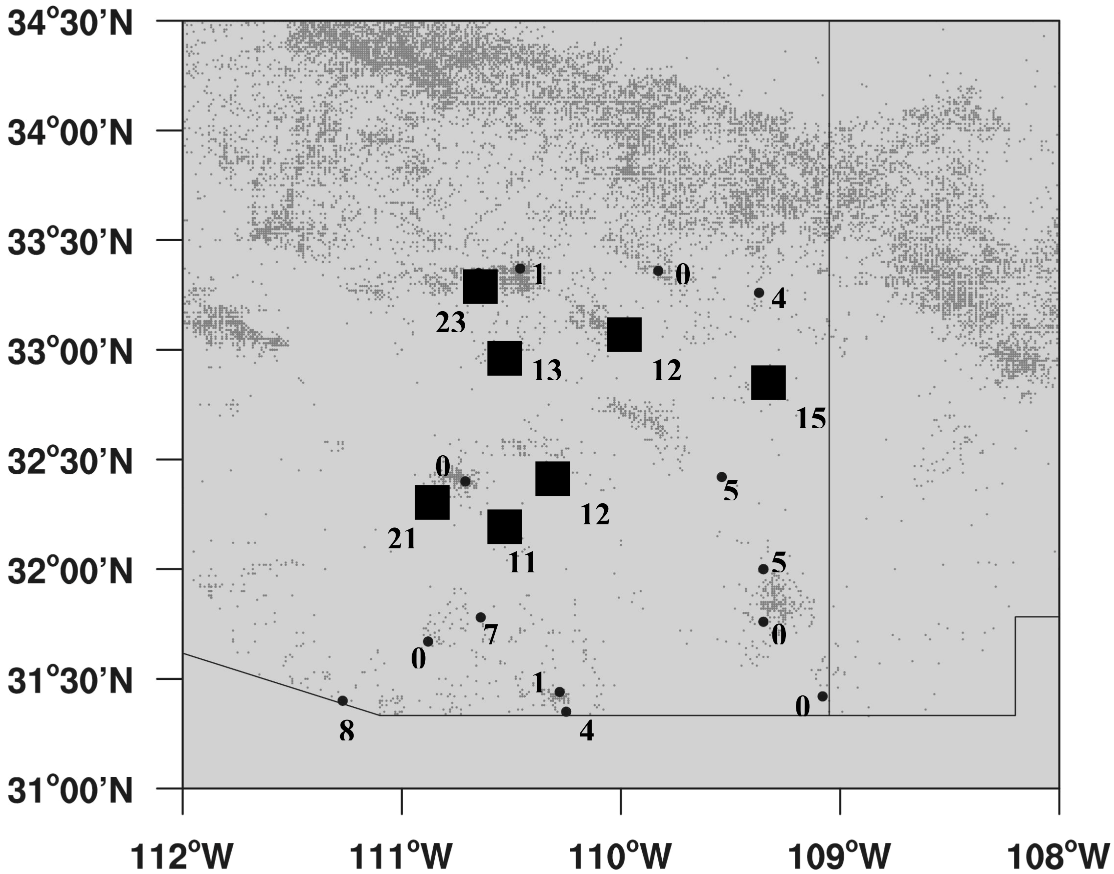

Figure 3.2 Map of fires (gray dots) with SE Arizona unusable RAWS (solid circles) and final RAWS after criteria selection (solid squares). Also shown is the number of years of quality (based on this study's criteria) data for each RAWS.

The meteorological values used in the study are from the daily 1300 (UTC) observations, along with the maximum and minimum values for the 24-hour period. The relevant variables used were maximum and minimum relative humidity, and maximum and minimum temperature. From these values, the daily dew point was calculated. The equations used for the dew point calculation was provided by Greg McCurdy from the Western Regional Climate Center (WRCC) and are given in Appendix A. The Phoenix NWSFO onset uses the 24-hour average of hourly dew points, whereas the dew point that is calculated for this study is the daily median value (1300 observation) computed from the 7 regional RAWS. A simple cross check examination using one RAWS site (Roosevelt, nearest to Phoenix, AZ) for the summer of 2000 (available from the WRCC website, http://w3wrcc.dri.edu/wraws/azF.html) was done to compare the 24-hour average dew point values to the 1300 dew point values that was calculated from the WRCC equation mentioned above. They were found to be consistent, and never varying by more than 1 degree (F°).

3. Lightning

Another meteorological element with important relevance to fire occurrence that was incorporated into this study is lightning. Cloud-to-ground lightning data including the date and location were provided by Vaisala-GAI from their NLDN system. Details regarding NLDN may be found in Cummins et al. (1998). The readily available years for study are from 1990-2000 (though more recent data are available from Vaisala-GAI). Strikes occurring within the same regional boundaries as for the extracted fires were examined for the seasonal period June 1st through September 15th.

4. Other Variables

Precipitation and wind are both meteorological elements with significance to fire danger and fire behavior. Precipitation has fire-mitigating properties and wind speed and direction are incorporated into the spread component in NFDRS (Bradshaw et al. 1978). However, there are some valid reasons for not including them in this study. Both wind and precipitation measurements are site specific rather than broad scale (Brown et al. 2001). Specifically in areas of complex terrain they can both be highly variable within a relatively short spatial distance. In an analysis of the Great Basin RAWS network, wind speeds had poor correlations between three pairs of closely spaced RAWS (Brown et al. 2001). Regarding precipitation, the resolution for the existing gridded daily average precipitation totals from Higgins et al. (1996) is 2.5 X 2.5 degrees for the southwestern U.S., and thus considered too coarse of a grid for the local area of interest.

5. Methodology

The relatively small sample size of fire occurrence in this region necessitated the grouping of RAWS rather than performing analyses for individual sites. A daily median dew point and minimum RH value for the entire summer period was determined using the 7 usable sites for each year of the study period. A 50-mile radius for each RAWS was applied to count fires that occurred only within these radii. As shown in Figure 3.1, some of the 50-mile rings overlap, but this approach demonstrates adequate spatial representation for southeastern Arizona. The fires that are within the overlapping areas are not counted more than once. The 50-mile distance from the RAWS was chosen because this is the furthest distance at which sufficient correlations existed between nearby RAWS for temperature (Brown et al. 2001). Beyond 50 miles, the standard errors get large suggesting an upper distance limit. In other words, it would become more difficult to accurately conclude a relationship between weather variables and fires that are greater than 50 miles in distance from each other.

A larger number of RAWS for this study would have been optimal. But unfortunately most of the sites within this region had non-existing or deficient data given the strict criteria. The spatial inconsistencies of historical precipitation and wind data from RAWS are also unfortunate, considering their relevance to fire occurrence. Data issues notwithstanding, the interannual and intra-annual variability of fire and meteorological elements, discussed in the next chapter, poses one of the most challenging problems in the attempt to relate fire occurrence to the Southwest Monsoon.

CHAPTER FOUR

CLIMATOLOGY AND VARIABILITY OF FIRE AND THE MONSOON

1. Climatology

The climatology of the two atmospheric moisture elements (i.e. dew point, minimum relative humidity) associated with the Southwest Monsoon is shown superimposed with the fire climatology for southeastern Arizona in Figure 4.1 (from chapter 1). The curves in Figure 4.1 imply from a climatological perspective an inverse relationship between these atmospheric moisture elements and fire starts. The number of fires in Figure 4.1 begins to decrease around July 8th as the dew point and minimum relative humidity continue to increase. This time series plot has initiated the question: Is there a relationship between moisture variables resulting from the Southwest Monsoon and fire occurrence?

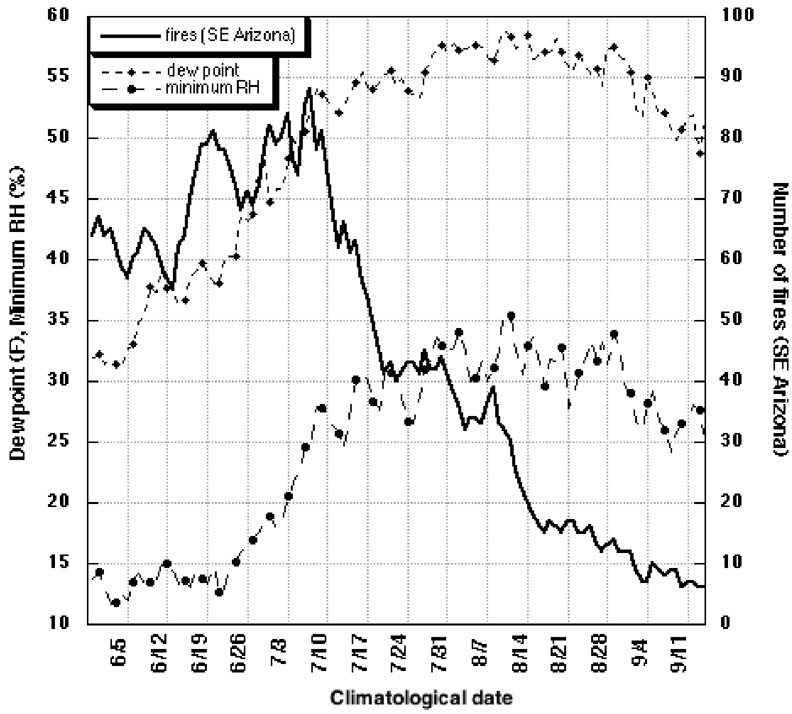

Figure 4.1. 5-day running mean climatologies of the daily number of fires (solid line), dew point (dashed line with diamonds), and minimum RH (dashed line with circles) for southeastern Arizona for years 1980-2002.

Based on the lightning climatology for southeastern Arizona shown in Figure 4.2, lightning strikes (the primary ignition source for natural fires) start to increase sharply at the end of June, peak in mid to late August, and abruptly drop in the beginning of September indicating the potential of natural ignition sources all through the summer season. This pattern corresponds to increasing monsoonal thunderstorm occurrence as the summer progresses.

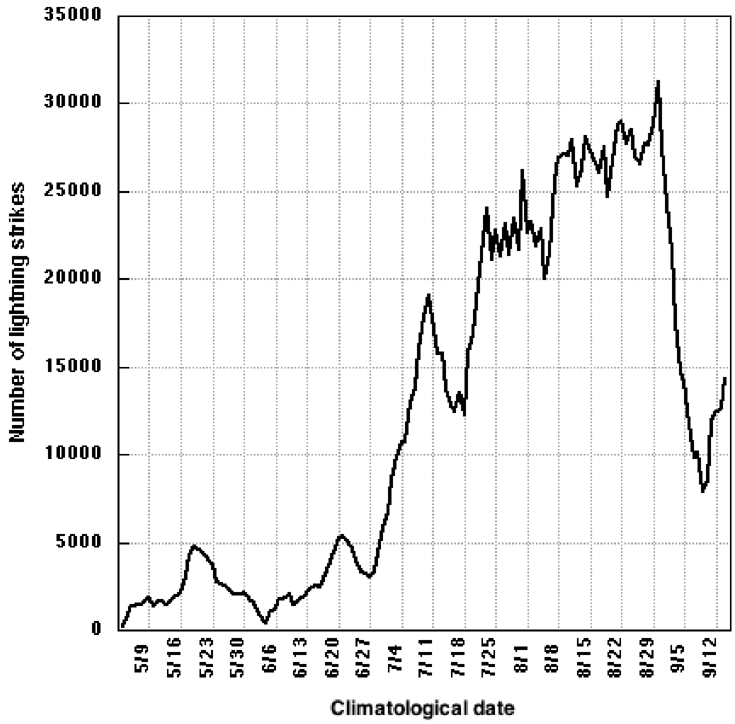

Figure 4.2. 5-day running mean of the lightning strike climatology for southeastern Arizona for the period 1990-2000.

Lightning is an obvious cause of natural fires, but non-natural or human fires are comprised of a variety of causes such as campfire, arson, smoking and railroad sparks. When weather and climate conditions are persistent enough to dry out fuels, the potential for fires will exist regardless of whether from natural or human causes. If fire occurrence and size patterns were shown to be qualitatively different for various fuel types given the dry conditions, the source of ignition would be more important to consider. For this reason, fires were separated by their primary cause – lightning and human.

Figure 4.3 is the non-natural and natural fire climatologies for southeastern Arizona. Both curves were smoothed using a 5-day running mean. After a peak around July 3rd and 4th, there is a sharp decline in non-natural fires that continues until mid July. From there, it gradually declines for the rest of the summer. The timing of the initial decline is within a few days of the average onset as defined by the Phoenix NWSFO definition. After July 4th, natural fires continue to increase with a broad peak until mid-July. After this time, they decrease somewhat but remain elevated and never reach the level of non-natural fire occurrence for the remainder of the summer. In view of this finding, analyses of fire and meteorological relationships will be done separately for natural and non-natural caused fires. Natural fires continue, but decrease before the number of lightning strikes peak suggesting that other influential factors not related to lightning are playing a part.

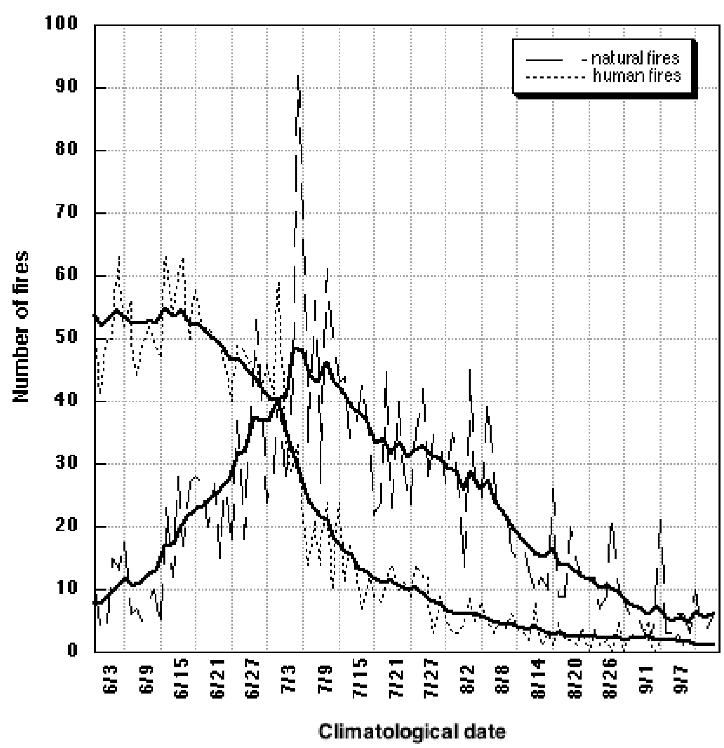

Figure 4.3. Number of natural fires (lengthened dash line) climatology, and non-natural fires (shortened dashed line) climatology with 5-day running mean curves for SE Arizona.

2. Interannual Variability

a. Fires

The fire community, in particular, is keenly aware of the large differences between one fire season and the next in terms of not only the number of fires, but also the area burned. There are a multitude of physically dynamic factors such as fuel characteristics, larger scale climate impacts (i.e., ENSO) and the available fire suppression resources that can produce these yearly differences (Swetnam et al.1990). Figure 4.4 is the annual number of fires (natural and non-natural) counted from 1980-2002 for the time period of June 1st to September 15th for southeastern Arizona. This plot not only schematically presents the interannual variability, but also the substantial differences between natural and non-natural fires observed within the same year. The two years with the highest non-natural fire counts (1998 and 2001) are twice the number of natural fires for those same years. The year 2001 saw the highest total number of fires around 475.

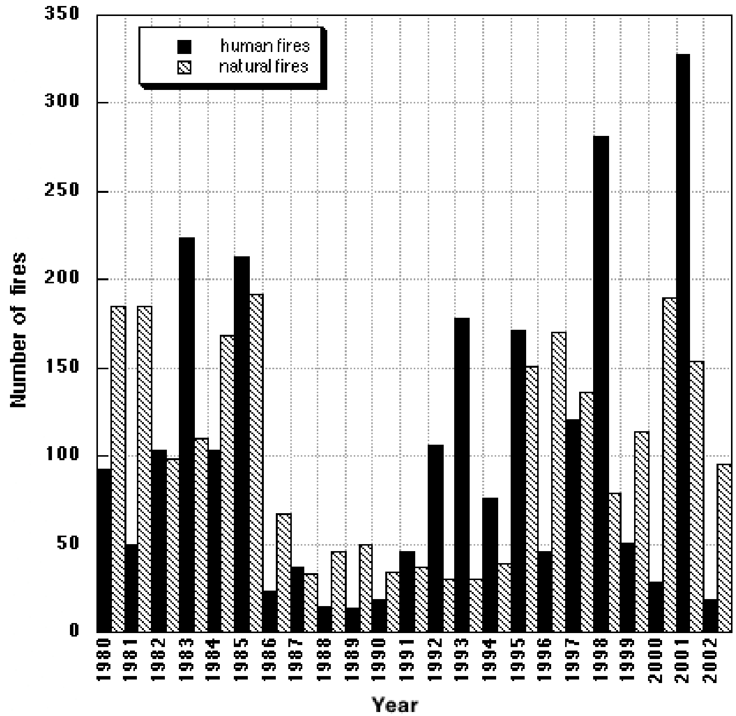

Figure 4.4. Annual number of natural fires (striped) and non-natural fires (solid) for southeastern Arizona for the climatological period June 1st through September 15th

For this area and time period, the most active year in terms of the number of *non*-natural fire starts was 2001. The number of natural fire starts is relatively high for this year as well, but still less than half of the non-natural fires. The most notable pattern observed in Figure 4.4 is the rather inactive period for both natural and non-natural fire counts during the years 1986-1991. Non-natural fires increased again after 1991 but natural fires continued to be relatively fewer until 1995. The average number of annual fire starts, found by totaling the number of natural and non-natural fires separately and dividing by 23 years is 104 for natural fires and 102 for non-natural fires. The similar averages are not surprising considering the total number of fires is about the same for both causes (natural fires – 2392; human fires - 2349). What these numbers do not reflect is the greater annual variability observed for human caused fires illustrated well in Figure

4.4. The standard deviations of 90.1 fires for human caused and 60.5 fires for natural caused highlight this difference.

The annual area burned is shown in Figure 4.5. The relatively high number of non-natural fires that was observed in 1985 and 1995 are reflected in the large amount of area burned for both years. But 2001, an extremely active years in terms of natural *and* non-natural fire counts, was basically small in the amount of area burned. Apparently both human and lightning ignitions were plentiful, but other mitigating factors such as increased suppression resources, or changing meteorological conditions were also present. Out of the 23 years, 1995 was the worst year in terms of the total area burned. In addition, the fire counts for both causes for that same year were also relatively high. For the area burned, the average for natural fires is 6585 acres and for non-natural fires is 8473 acres. The total number of acres for all 23 years is 151475 acres for natural fires and 194887 acres for non-natural acres. The human started fires on average have been larger in terms of area burned than natural started fires.

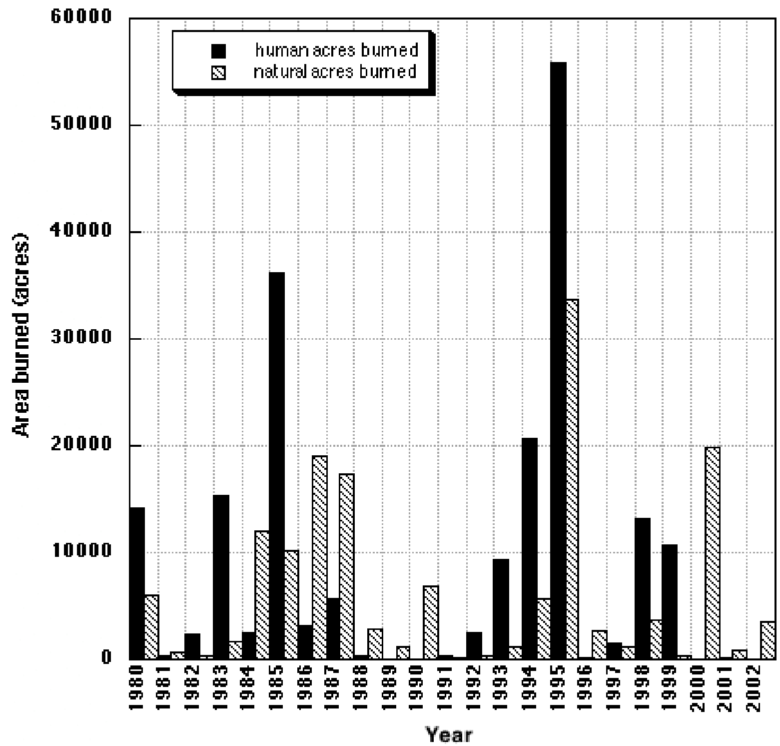

Figure 4.5 Annual area burned for natural fires (striped) and non-natural fires (solid) for southeastern Arizona for the climatological period June 1st through September 15th.

Figures 4.4 and 4.5 illustrate that over the last 23 years, for southeastern Arizona, the average number of fire counts has been essentially equal for both causes of fires even with the observed greater annual variability for non-natural fires. However, human fires have contributed more to the total area burned. Lightning trends can explain the interannual variability of natural fire counts but cannot account for the interannual variability of human fire counts. Other meteorological conditions, however, such as the lack of precipitation, high temperatures or increased winds that would result in dry fuels could give human ignition sources an equal chance at initiating a fire as lightning.

The plots of annual fire counts and annual area burned (Figure 4.4 and 4.5) show that natural fire activity (numbers and area) in 2000 was high with no appreciable human fire activity. On the contrary, 2001 was very active in terms of the number of fires, but these fires did not burn a large amount of area. The most severe year for southeastern Arizona for area burned was 1995 with an abundance of ignitions from both human and lightning sources.

b. Atmospheric Moisture

A plot of the yearly number of high moisture days can show the strength of the monsoon in terms of atmospheric moisture. Figure 4.6 was constructed to highlight strong or weak monsoon years in this context. During June 1st to September 15th, the number of days that were within a 3 consecutive day period of 55 degrees (F°) dew point or higher (i.e., Phoenix onset) was counted for each year from 1980-2002. These are shown by the striped bars. Another count based on the SW GACC definition (the number of days that were within a 7-day period having at least 5 of those days at 20% minimum RH or higher) for the same seasonal time period and number of years were also counted and shown as solid bars.

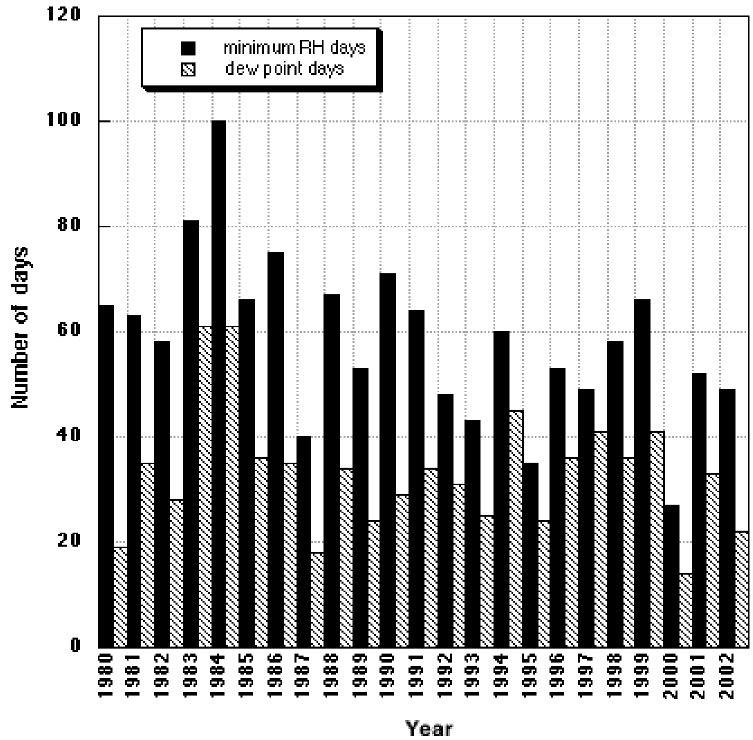

Figure 4.6 Annual number of days at or above 55 degrees for 3 consecutive days (striped) and annual number of days at or above 20% minimum RH for 5 out of 7 days (solid) for the climatological time period June 1st to September 15th.

To begin with, every year saw a higher number of days at or above the minimum RH definition than the number of days at or above the dew point definition. Atmospherically, the RH definition is observed more frequently than dew point definition. The yearly minimum RH and dew point patterns appear to be synchronous in Figure 4.6. In other words, if the number of minimum RH days was high then the dew point days were relatively high for that particular year as well. This is expected because both elements are sufficiently related and represent atmospheric moisture conditions. The differences between the two are not constant, however, in that some years the difference is larger than for others. This is most likely a result of their subtle nuances. Relative humidity changes diurnally with temperature and therefore has the tendency to fluctuate considerably within a 24-hour period. Additionally, using the median value from the collective group of RAWS may supply a small contributing factor to these differences.

The years 1983 and 1984 could be identified as 'strong' monsoon summers, or at the very least, monsoon seasons with numerous, intense and/or extended moisture surges. This finding is consistent with the average statewide precipitation (June-August) for Arizona indicating 1983 as a year with slightly above average precipitation and 1984 as the wettest Arizona monsoon between 1975 and 2001 (Mitchell et al. 2002). Out of all the years, 2000 was the most deficient in days with higher atmospheric moisture. Although natural fire occurrence in 2000 was high, non-natural fire occurrence was not. Both of the years 1987, and 1995 are the two weakest monsoon seasons based on the number of days of higher dew point and minimum RH values. In 1987, the fire counts were exceptionally low, but some of the natural fires that did ignite apparently became quite large. As mentioned already, the 1995 summer was the most severe in terms of area burned from both causes.

The annual variation in atmospheric moisture characteristics can be further illustrated by plotting the yearly onset dates (Figure 4.7) using the existing definitions of the onset discussed in detail in Chapter 3. The southeastern Arizona (SEAZ) dew point onset date is found from applying the 'official' definition (i.e., 55 degrees or higher dew point for 3 consecutive days) using historical dew point data from RAWS. The SEAZ minimum RH onset date is found applying the SW GACC definition of the onset (i.e., 5 out of 7 days with 20% minimum RH or greater) using historical minimum relative humidity data from RAWS.

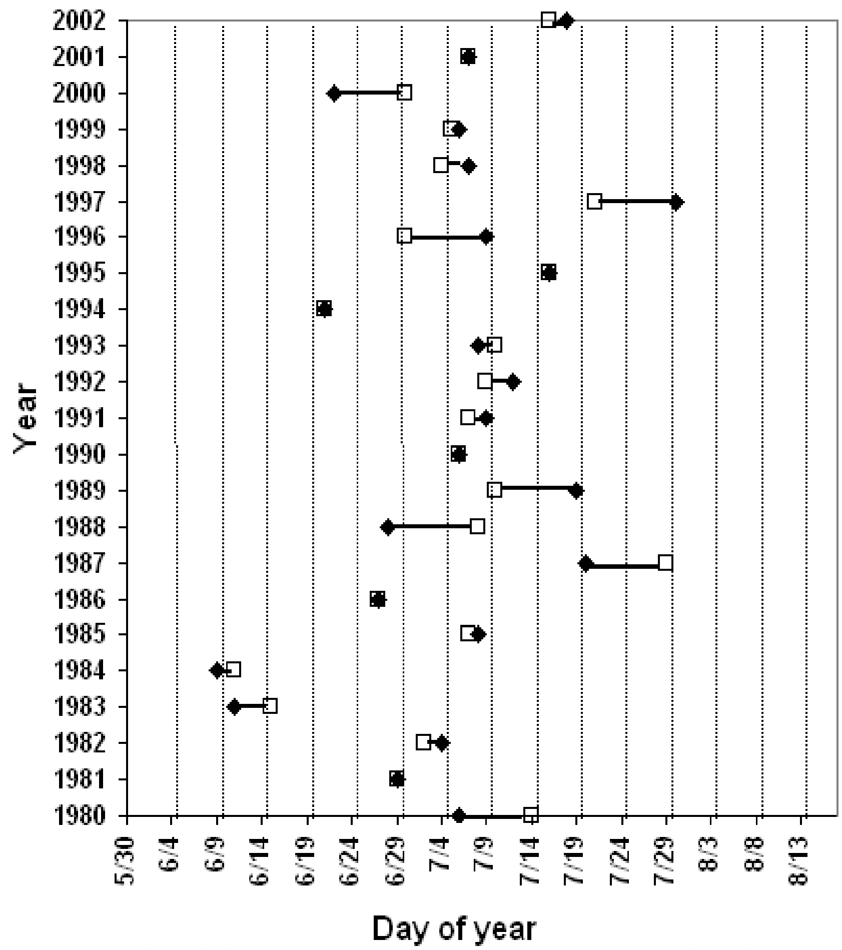

Figure 4.7 Onset dates for SEAZ dew point (open squares) and minRH (solid diamonds) onsets for southeastern Arizona

Figure 4.7 shows not only the yearly variability for the two definitions, but also the notable differences between the unique onsets for the same year. The earliest date for the SEAZ dew point onset was observed on June 11th, 1984 and for the SEAZ minimum RH onset, June 9th, 1984. The latest date for the SEAZ dew point onset was observed on July 29th, 1987, and for the SEAZ minimum RH onset, July 30th, 1997. Only a few years had a sizeable difference between the two definition onsets for the same year. The biggest difference is no more than 11-days between the dew point and minimum RH onset.

SEAZ dew point and minimum RH onset dates were more often in agreement than not which signifies localized consistencies between dew point and minimum RH.

c. Lightning

Lightning from the monsoon is extremely important in the context of fire in that it provides natural ignition sources. The interannual variability of lightning should bear some resemblance to the variability that was shown for the moisture elements since lightning is directly associated with moisture laden thunderstorms. Intuitively, the same years with a higher (lower) number of moisture days should be high (low) as well for lightning strikes because lightning is produced from thunderstorms that would not be possible without the availability of atmospheric moisture. Most of the years from 1990 to 2000 illustrate this complementing pattern in Figure 4.8. In 2000, the high number of lightning strikes was reflected quite well in the large number of fires and area burned by lightning started fires (Figure 4.4, and 4.5, respectively). From 1996 to 2000, there are a higher number of strikes that coincides with the higher natural fire counts for those same years (shown in Figure 4.9). Interestingly, these summers had only an average number of higher moisture days, and the area burned by natural fires was rather low to average with the exception of 2000. Figure 4.10 shows the lack of correspondence between lightning strikes and natural area burned for most of the years during 1990-2000. These particular plots (Figure 4.9 and 4.10) help support the argument of years with numerous lightning strikes equating more to years with a high number of natural fires, but not necessarily to years with large areas burned by natural fires.

Table 4.1 gives the Spearman Rank correlations between the numbers of lightning strikes, natural fires, dew point/minimum RH days and the area burned by natural fires. Note the correlations that incorporate the number of lightning strikes are only for the years 1990-2000. The highest correlations were between the number of lightning strikes and the number of natural fires (.58), and between the number of dew point days and the number of strikes (.44), although neither correlation was exceptionally strong. The lowest correlation is between the number of strikes and the area burned from natural fires (.08).

Table 4.1 Spearman Rank correlations for number of lightning strikes, natural fire area burned, number of natural fires and number of dew point days (number of days within a 3 consecutive day period of 55 degrees dew point or higher).

	Number of Strikes	Area burned from natural fires	Number of natural fires	Dew point days
Number of strikes	-	0.081	0.5841	0.4455
Area burned from natural fires	0.081	-	0.2312	-0.1835
Number of natural fires	0.5841	0.2312	-	0.1497
Dew point days	0.4455	-0.1835	0.1497	-

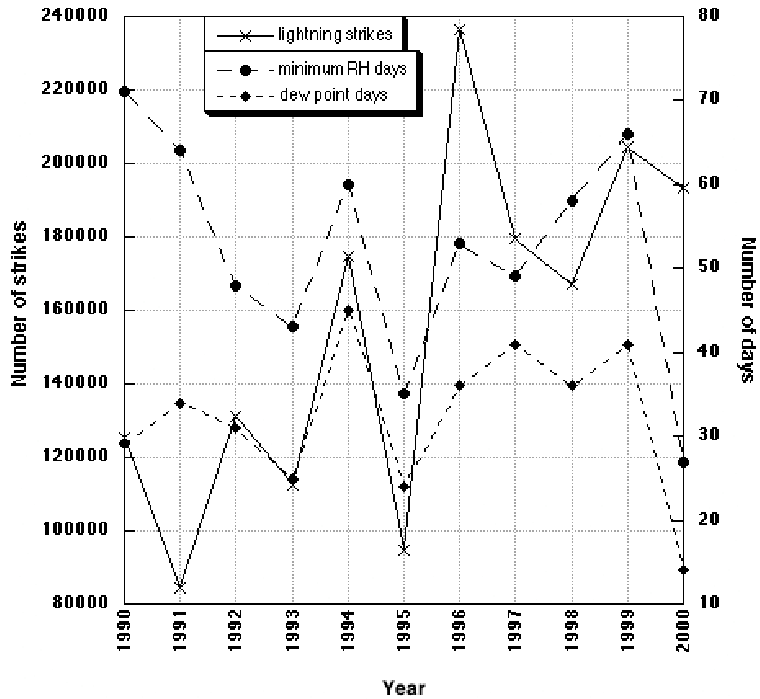

Figure 4.8 Annual number of lightning strikes (crosses) and the number of minimum RH (circles) and dew point (diamonds) days from June 1st to September 15th for the years 1990-2000 in SE Arizona.

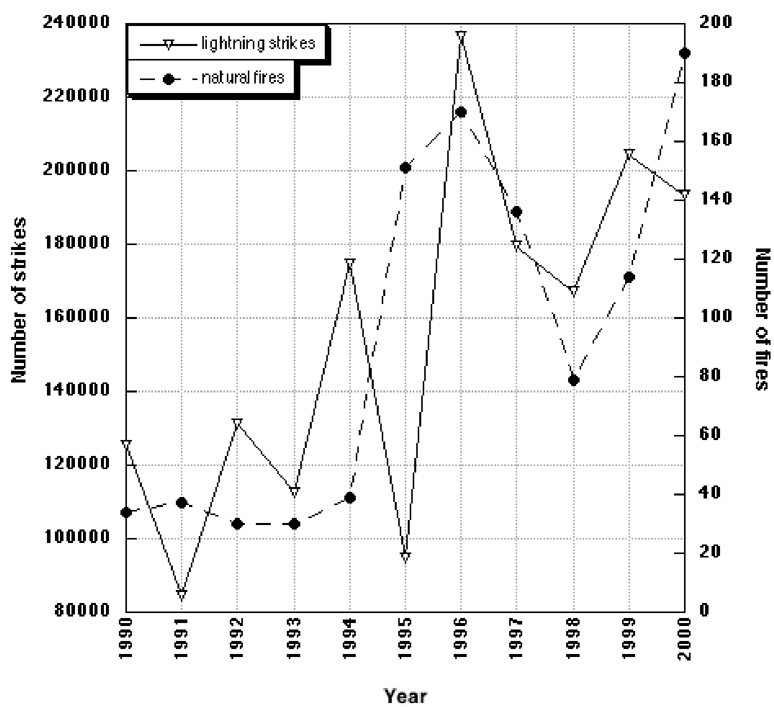

Figure 4.9 Annual number of lightning strikes (triangles) and the number of natural fires (circles) from June 1st to September 15th for the years 1990-2000 in SE Arizona.

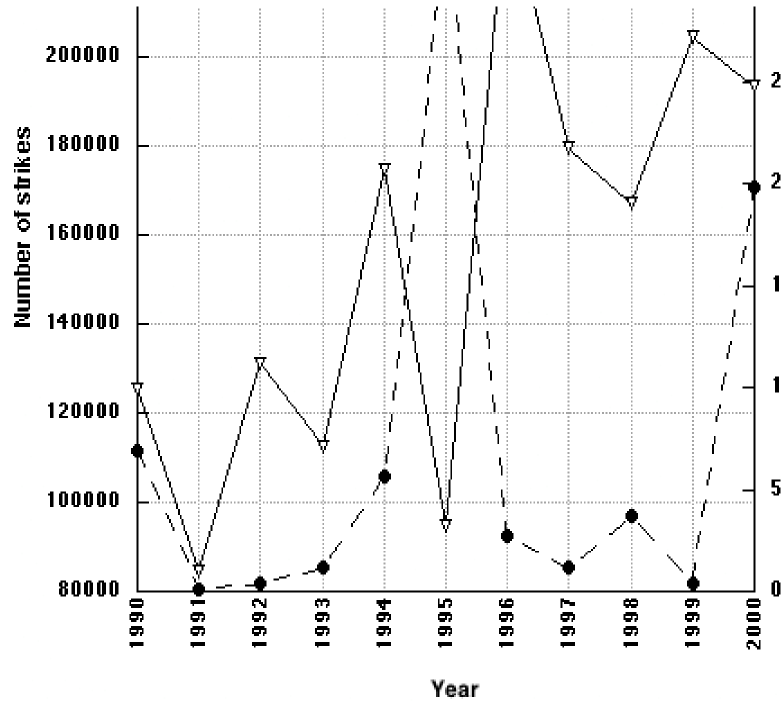

Figure 4.10 Annual number of lightning strikes (triangles) and the area burned from natural fires (circles) from June 1st to September 15th for the years 1990-2000 in SE Arizona.

3. Intra-seasonal variability

The intra-seasonal variability of atmospheric elements is a manifestation of the seasonal irregularity of the monsoon. Figures 4.11, 4.12, 4.13, and 4.14 portray the intra-seasonal variability of the number of natural fires, number of non-natural fires, dew point values and the number of lightning strikes for the years 1984, 1995, 1998 and 2000, respectively. These specific years are representative of both average and outlying patterns.

Natural fire time series for these example years are plotted in Figure 4.11. A 5-day running mean smoother was applied to minimize variance. Even with the smoothing, the series are quite erratic, though distinct features are discernible. Natural fire activity for the summer of 1984 was early, intense and remained elevated until mid July. This distinct pattern is not evident in the other 3 years. Although natural fire activity began in early June for 2000, there was a lull for most of July before it intensified again at the end of the month. Only the natural fire time series of 1984 and 1998 resemble the natural fire climatology (Figure 4.4) with peaks around the 2nd week of July. In contrast, the years 1995 and 2000 both have peaks for the number of natural fires in late July and early August.

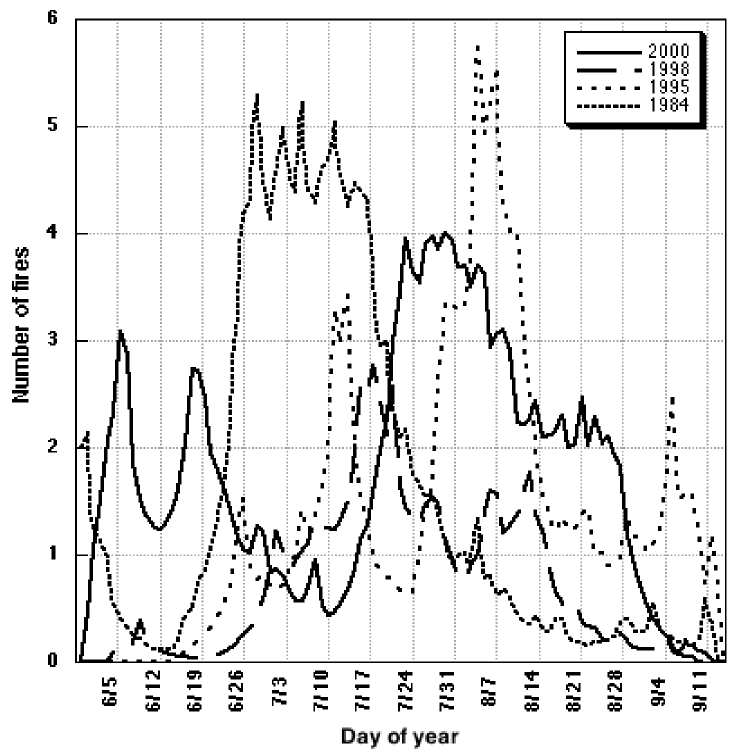

Figure 4.11 *Natural* fire 5-day running mean time series for the years 1984, 1995, 1998 and 2000.

The time series for the non-natural fire activity for the same years are illustrated in Figure 4.12. Except for 2000, all of the years' patterns show a decline at the end of June and beginning of July that closely resembles the non-natural fire climatology (Figure 4.3). For unknown reasons, the fires modestly increased later in the summer in 1995.

Although 2000 was an active fire season for lightning started fires, it was not problematic for human started fires at least within this regional context.

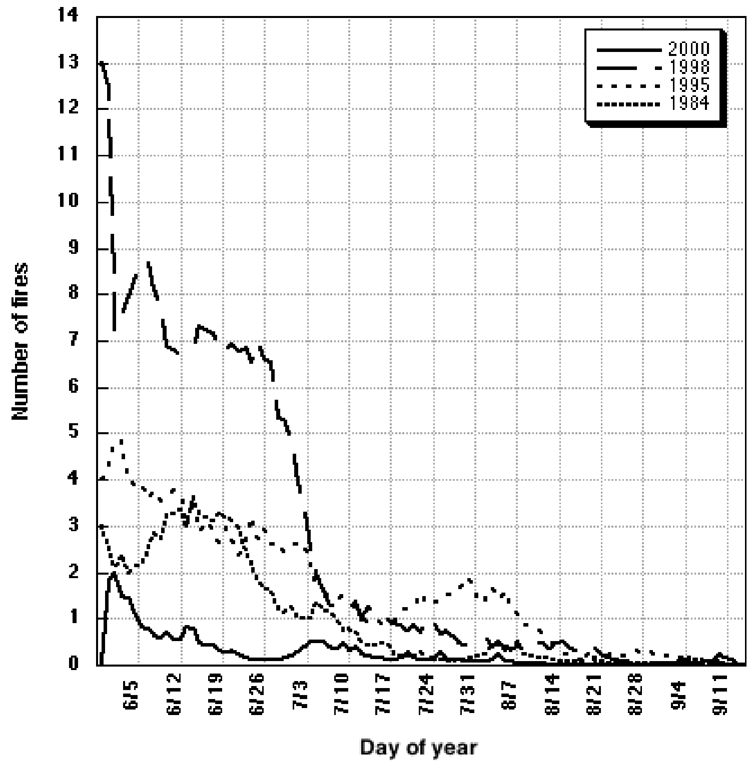

Figure 4.12 *Non-natural* fire 5-day running mean time series for the years 1984, 1995, 1998 and 2000.

The individual years' time series for dew point in Figure 4.13 are comparatively distinct until early August. After the beginning of August, the individual years' series show much less difference in the dew point values than earlier in the summer. The summer of 1984 exhibits the most seasonal consistency in dew point with an early increase that is not seen in the other years. In fact, using 1984 as the earliest and 1995 as the latest dew point increase out of the four years (i.e., monsoon onset), there is about a 3-week difference. This is not all that surprising since onset variability was evidenced in the plot of historical onset dates from Figure 4.7. Considering that the 1984 summer was one of the wettest monsoons for Arizona (July-August), the elevated and steady dew point trend is logical. Although the increase in moisture occurred later in the season for 1998 in comparison to other years, the precipitation totals for the summer were still within climatological average.

The years 1995 and 2000 are entirely a different story. The monsoon never fully materialized in 1995, and indeed this was considered a very dry year (i.e., low precipitation totals) for Arizona (Mitchell et al. 2002). The summer of 2000 began deceptively with a relatively early increase in moisture that was subsequently followed by a decline that never recovered until much later in the summer. The large fluctuations illustrated in the individual dew point series (Figure 4.13), notably before August, are likely the result of the occasional to frequent monsoon moisture surges (Hales 1972) that can occur not only before, but also after the onset. Moisture surges are one of the primary causes of intra-seasonal variability of the monsoon and are difficult to predict (Carleton 1990).

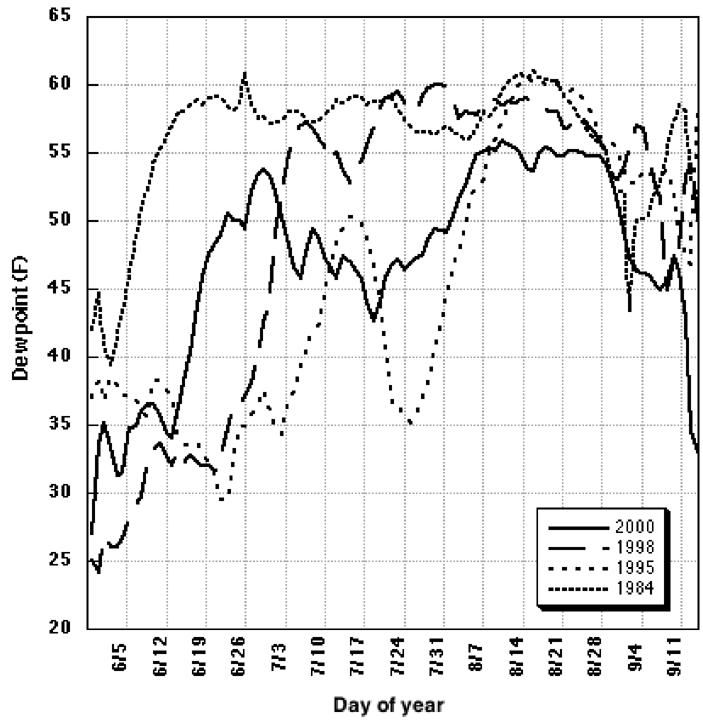

Figure 4.13 Dew point 5-day running mean time series for the years 1984, 1995, 1998 and 2000.

These years have shown that dew point can be significantly variable throughout the monsoon season as a result of periodic surges of moisture. The Spearman Rank correlation between dew point and number of lightning strikes from Table 4.1 shows a correlation of 0.4455, a moderately strong relationship. Based on this, the lightning strike time series should follow a similar pattern to the dew point series. Figure. 4.14 depicts the lightning strike time series for the years 1995, 1998 and 2000. The year 1984 was not available from the lightning dataset and therefore is not included. All three years follow a similar pattern of a peak in lightning strikes around mid to late August. The year 2000 shows an early increase in strikes that are consistent with an early increase in dew point. Interestingly, 1995, a year with a large amount of area burned from both natural and non-natural caused fires, did not have an abundant amount of lightning strikes.

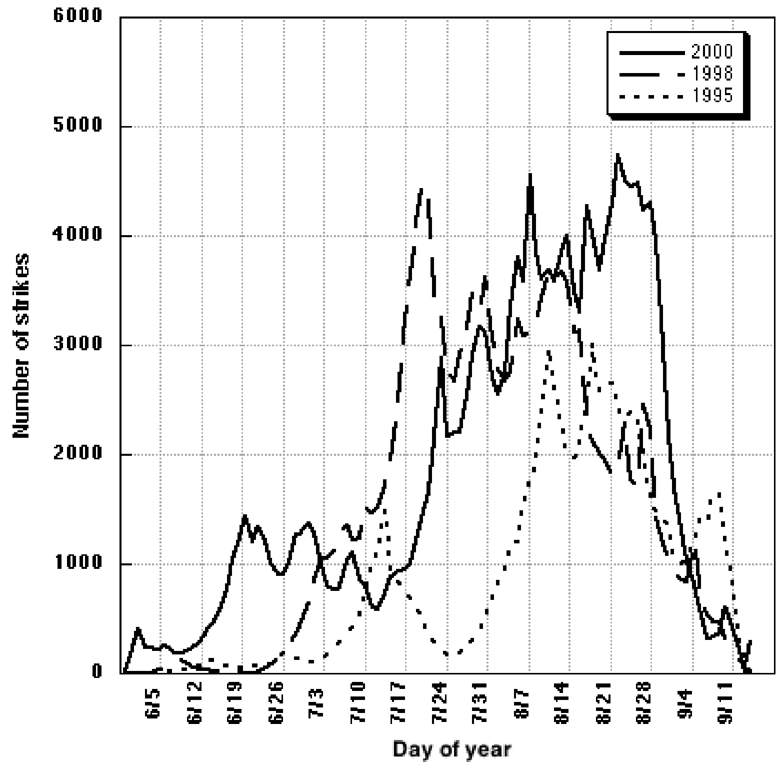

Figure 4.14 Lightning 5-day running mean time series for the years 1995, 1998 and 2000.

The climatology, interannual, and intra-seasonal variability of the meteorological elements associated with the monsoon and of the natural and non-natural fire occurrence in southeastern Arizona has been addressed in this chapter. It was shown that the onset definitions define the interannual variability of the monsoon, but does not significantly account for the intra-seasonal variability that can result from moisture surges within the defined monsoon season.

The year-to-year variability of fire occurrence is associated to some extent with larger scale climate effects such as ENSO. Swetnam et al. (1990) found reasonable correlations for an active fire season in the Southwest that is preceded by two successive dry La Nina winters that followed a wet El Nino winter. However, ENSO accounts for only a portion of the interannual variability. Other well-defined factors remain to be discovered.

For effectively everywhere, yearly climate variability, dynamical factors such as natural fuels accumulation and reduction, human land use and management impacts on vegetation, and fire suppression and management strategies are likely contributors to interannual variability. But specifically for the southwestern U.S., the monsoon plays a significant role in the interannual and intra-seasonal variability of fire occurrence and atmospheric elements.

CHAPTER 5

ANALYSIS/RESULTS

The following analyses were conducted to explore the concept of increasing atmospheric moisture resulting from the Southwest Monsoon impacting fire occurrence in southeastern Arizona. The applicability of the 'official' definition (Phoenix) and the Southwest Geographic Area Coordination Center definition (GACC) of the onset are both assessed in the context of human and natural fire occurrence. The first approach evaluates the effectiveness of these definitions by calculating 'after onset' fire percentages. Although some analyses were done for no onset, the second approach essentially focuses on fire counts and moisture values occurring within the monsoon period as defined by the two definitions to investigate potential moisture thresholds.

1. After onset fire percentages using definitions of monsoon onset

As previously mentioned, the Phoenix definition uses a dew point of 55 degrees or higher for 3 consecutive days and the GACC definition uses 5 out of a 7-day period with a 20% or higher minimum relative humidity as the onset. The GACC definition was founded by fire weather meteorologists and is based on physical relationships between relative humidity and fire potential. Phoenix NWSFO meteorologists produced the dew point definition as merely a guideline for the monsoon's arrival without any association to fire activity in the southwest U.S. Fires, regardless of cause or fuel type, are not expected to cease completely when the monsoon begins. However, the fire community generally anticipates a decrease in fire size and numbers. Fire suppression resources could then be available for prescribed fire, fire use opportunities and relocation to assist in other fire active regions. The monsoon can potentially establish atmospheric conditions (i.e., precipitation, increased cloud cover) that are favorable for shifting fire management tactics from primarily suppression efforts to fire use planning.

The methodology for this part of the analysis is described below. For each year, starting from June 1st, the onset was found using the appropriate definition from the median minimum RH and dew point values from the 7 regional RAWS. June 1st is justified because historically, the Phoenix onset has never occurred before June 16th (http://www.wrh.noaa.gov/Phoenix/general/monsoon/index.html). Furthermore, higher moisture conditions on or before June 1st could be a result of late spring synoptic storms that are unrelated to the monsoon.

Using each yearly onset, the percentages were calculated by dividing the number of fires and area burned in the 45-day period after the onset by the total number of fires and area burned for the 90-day period using the onset as the midpoint. The percentages incorporate all 23 years of historical federal fire occurrences and weather data. The onset dates used here were plotted as the SEAZ Phoenix and GACC onset dates from Figure 4.8 (from chapter 4).

Table 5.1 provides the percentages of the number of human, and natural fires that occurred as well as the area burned *after* the GACC or Phoenix onset date. Fires are separated by fuel type and by large fires (≥100 acres; ≥40 hectares).

The percentages in Table 5.1 will not add to be 100% because they are based on *separate* totals of the number of and area burned by timber, shrub and timber/shrub combined and for human and natural fires. Furthermore, these percentages represent fire occurrence after monsoon onset. Before monsoon onset percentages are not provided.

Table 5.1 After onset percentages of natural and human fires and area burned for timber and shrub (T & S) combined, and timber and shrub separately. Large fires are defined as ≥ 40 ha.

	Natural fires		*Human fires*	
	GACC	**Phoenix**	**GACC**	**Phoenix**
T & S, all size, fires	58.2%	60%	18.7%	18%
area burned	47.3%	47.1%	14.5%	14.1%
Timber, all size, fires	57%	59.3%	24.1%	25.7%
area burned	37%	37.3%	20.5%	20.5%
Shrub, all size, fires	60.2%	61.2%	18.3%	17.4%
area burned	54.5%	54.2%	14.2%	13.8%
Large fires, T&S, fires	55.2%	55.8%	16.5%	15%
area burned	47.1%	46.8%	14.4%	14.1%

From the combined 23 years, over 61.2% and 60.2% of shrub natural fires occurred after the Phoenix and GACC onset, respectively. The percentages for total area burned from natural fires are somewhat lower than the number of natural fires, but remains high in comparison to any of the percentages for total area burned from human fires. For both the Phoenix and GACC definition, the area burned after the onset from natural timber fires is at least 20% lower than the number of natural timber fires. Natural *large* fire percentages were a little more than half for occurrence and slightly less than half for the area burned for both definitions.

The percentages for human caused fires indicate an alternate depiction of the monsoonal impact on fire occurrence. Compared to natural fires, the percentages for human fires are much lower for both the number of fires and the area burned. Out of all the percentages in Table 5.1, the lowest was 13.8% for area burned by shrub human fires. Large human fire occurrence percentages were nearly the same as the percentages for combined timber and shrub fires in terms of numbers and area burned.

Table 5.1 does reveal some key findings. Among the most interesting is the substantial difference in human and natural fire percentages. This is consistent with the dissimilarities observed for the human and natural fire climatologies plots (Figure 4.3). The early and abrupt decline for climatological human fire occurrence not seen in the natural fire occurrence would most likely be reflected in these differing percentages. A comparison of the Phoenix and GACC onset percentages for either human or natural fires reveals very similar percentages. This is likely due to many of the years having identical onset dates for the two atmospheric moisture definitions. There is a large difference noted between the relatively higher number of natural timber fires and the lower amount of area burned by natural timber fires. This could be because fires that are started by lightning may not spread in timber fuels as easily or quickly as in shrub fuels particularly after the onset. Given the right fuel conditions, however, crown fires in heavier timber fuels can spread just as rapidly as fires in finer shrub fuels. Although the percentage for the number of human timber fires was greater than the percentage for area burned by human timber fires, this difference was not nearly as large as observed for natural timber fires. The consistently observed lower percentages for area indicates that size, rather than the number of fires, is more likely impacted by the monsoon. Large human caused fires (≥40 ha) in both number and area burned are slightly less after the onset as well.

Based on these percentages, there is an indication that either the Phoenix or GACC definition could apply in terms of decreasing fire occurrence to human started fires, but clearly not to naturally started fires. If human caused fires are declining from an increasing atmospheric moisture impact then natural caused fires should be affected as well given a similar number of ignitions. But ignition availability for human started fires could very well be part of the underlying explanation.

The Table 5.1 percentages show that over the last 23 years, more than half of the natural fires occurred and almost half of the natural area burned after onset. The natural fire climatology (Figure 4.3) shows fires generally peak around the 2nd week of July with a slight decrease thereafter. But natural fires never decline to the level of human fire occurrence indicating the fires continue as a result of monsoon lightning. Although the post onset percentages are comparatively lower for human fire occurrence than for natural fire occurrence, the Phoenix and GACC definition do not provide a good indication of a monsoon – fire association. The next part of this chapter addresses this relationship further by exploring fire occurrence and moisture values during the defined monsoon seasons.

2. Analyses of moisture value thresholds for decreasing fire occurrence

In this section, potential moisture value thresholds for decreasing fire occurrence within the monsoon season are investigated. Since the median dew point, minimum

RH values and fire data is known for each day, these elements can be quantitatively linked. All 23 years from 1980-2002 of available data are used in this part of the analysis. The objective is to find a particular moisture value or range of values (i.e., dew point or minimum relative humidity) that exhibits a 'signal' in decreasing fire occurrence for the cases of no onset and with onset.

A description of the two fundamental plots illustrating how the results quantitatively link fire occurrence to dew point and minimum relative humidity is given below:

1) Histogram – Individual years' fire starts are totaled for the moisture value observed on the same day as the fire. For example, if on July 3rd, there were 10 fires that occurred and the 1300 dew point observation was 53 degrees then 10 is added to current sum of fire counts that had a dew point of 53 degrees during the specified time period of analysis. For the dew point, the range of values is 30 to 70 degrees (F°), and for minimum RH, the range is 15 to 60 percent.

2) Standardization – To allow for direct comparison between fire occurrence and dew point, minimum relative humidity values, the frequency of fire counts and total number of days of each 1 degree dew point, or 1% minimum relative humidity range (30 degrees to 70 degrees, 15 percent to 60 percent, respectively) are standardized and plotted along with the difference between these two curves. The range for dew point was restricted from 30 to 70 degrees because of the relatively low frequency of dew point occurrence for the lower

values. For the standardized values, the average of the total fire and dew point or minimum RH day counts from the entire range is subtracted from the fire and dew point or minimum RH count from each individual moisture value in the range. This number is then divided by the standard deviation of the total fire and moisture day count from the range of moisture values. In this approach, each dew point or minimum RH value within the range is given a standardized value. This is done to improve the visualization for comparison of the different data sets since all values become standard deviations. The equations for the standardized fire counts and dew point or minimum RH day counts are provided below:

$$S_F = \frac{N_F - \bar{x}_F}{\sigma_F}, \; S_D = \frac{N_F - \bar{x}_F}{\sigma_F}$$

where S_F = standardized value of fires, N_F= number of fires, $\bar{x}_F$ = mean of total fires, _$_F$ = standard deviation of the number of fires, S_D = standardized value of dew point/minimum RH days, N_D = number of dew point/minimum RH days, $\bar{x}_D$ = mean of total dew point/minimum RH days, _$_D$ = standard deviation of the number of dew point/minimum RH days.

A signal in a particular dew point or minimum RH value is manifested by an increasing or unchanged frequency in the occurrence of the moisture value and a corresponding decrease in fires for that specific moisture value. If the frequency of moisture value days and fires are decreasing concurrently, statistical rather than strictly physical or atmospheric influences could be the causal factor in the fire decrease.

Additionally, any decrease in fire frequency at a dew point or minimum RH value that is followed by a significant increase in fires for successively higher moisture values would be questionable. If the drop in fires is truly an effect of the monsoon moisture, then for higher dew point or minimum RH values, the fires should remain low. For this study, human and natural fires are examined separately.

Confining the time period of analysis (i.e., monsoon season) removes anomalous high moisture days with fires that may have occurred before the monsoon actually started. Nevertheless, the differences that could be revealed by comparing the results using the entire summer (without an onset) and the defined monsoon season (with an onset) for both dew point and minimum relative humidity may assist in identifying potential moisture value thresholds.

a. No defined onset analysis for dew point values (natural and human fires)

The number of natural and human fires regardless of size in southeastern Arizona is counted for each occurring dew point from June 1st to September 15th. Figures 5.1 and 5.2 show the frequency of the dew point days and the number of natural fires and the frequency of the dew point days and the number of human fires, respectively. For each dew point value, the bars represent the number of fires that occurred at that dew point value and then the number of days the dew point value occurred for the season.

Figure 5.1 shows the dew point frequency is fairly steady until the mid 40's, then increases and peaks in the mid to higher 50's. The range of dew point values with the higher dew point day counts is from 57 to 59 degrees. Natural fire frequency in Figure 5.1 shows a drop from 183 fires at 59 degrees to 104 fires at 60 degrees with the dew point day frequency remaining relatively unchanged from 59 to 60 degrees (110 days and 116 days, respectively).

With the dew point day frequency the same as for natural fires, Figure 5.2 shows the human fire frequency to be quite different. For human started fires, more of them occurred in the lower dew point range (30-44 degrees) even though there appears to be a second increase in the 50's dew point range that is far less than the peak in natural fires. Nevertheless, there is no unprecedented decrease in human fires for a particular dew point value.

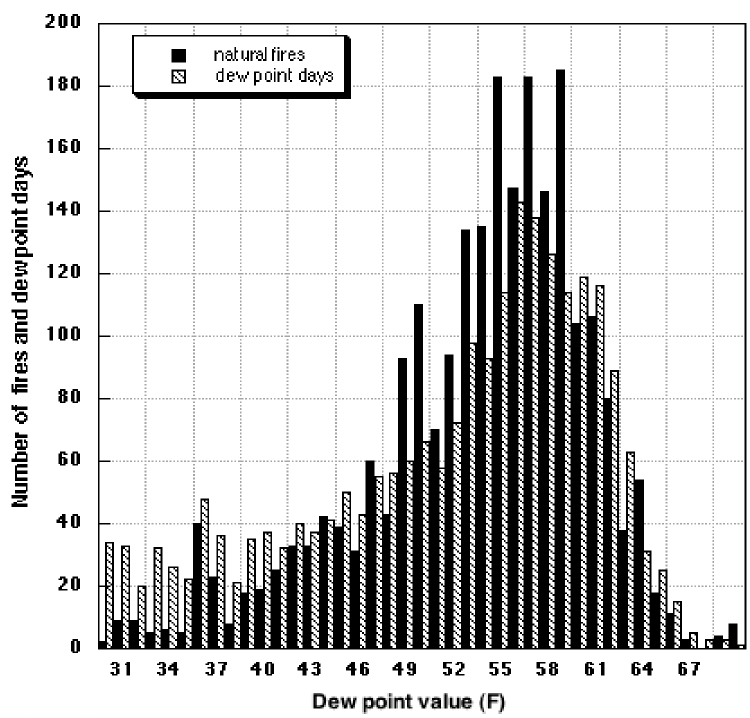

Figure 5.1 Bar plot of the number of natural fires (solid bars) and frequency of dew point day occurrence (striped bars) with no onset (June 1st through September 15th).

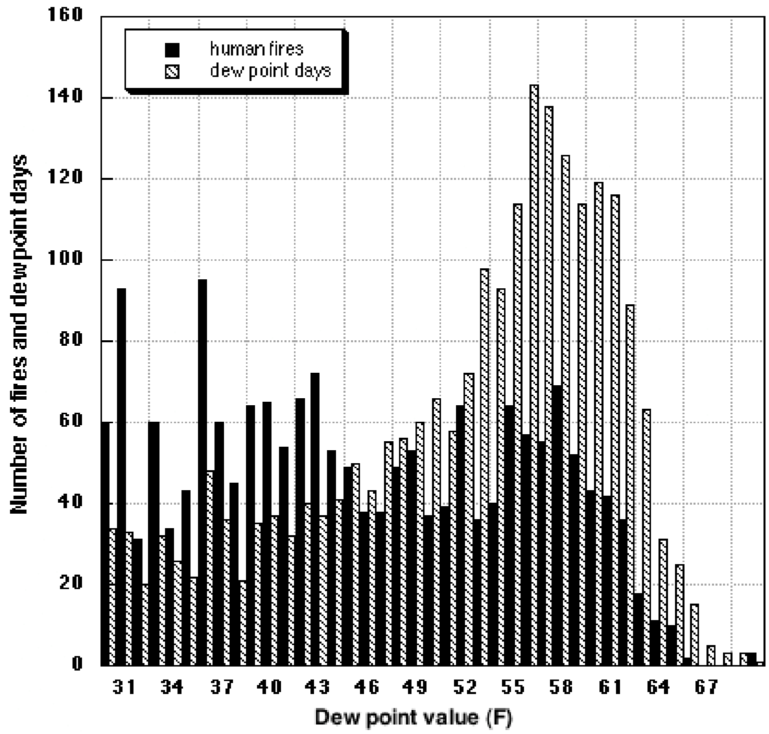

Figure 5.2 Bar plot of the number of human fires (solid bars) and frequency of dew point day occurrence (striped bars) with no onset (June 1st through September 15th).

The results from Figures 5.1 and 5.2 are re-expressed using standardization. In this manner, the units for the curves are consistent and so allows for a direct comparison in the fire and dew point day frequencies. Figure 5.3 and 5.4 are the standardized plots of natural fires with the dew point day frequency, and human fires with the dew point day frequency, respectively.

A moderate to large negative difference between standardized fire counts and dew point day frequency would give more validity to the 60-degree signal for natural fires (Figure 5.1). When the dew point day frequency exceeds the fire count frequency (ideal case), a negative difference is produced. The opposite (non-ideal case) would show a positive difference and would indicate the fire count frequency is greater than the dew point day frequency. Figure 5.3 shows negative differences for standardized natural fire counts without an onset starting at 56 degrees, however the number of natural fires remains high for that particular value. This is misleading because 56 degrees is the value that has the highest frequency of dew point day occurrence. So it is not a case that natural fires appreciably drop at 56 degrees, but that the dew point day occurrence counts are large. From 60 to 63 degrees, the standard deviation difference approaches –1.0. For this range of values, unlike 56 degrees, the fire counts decrease as the dew point day frequency remains unchanged. After 63 degrees, the number of dew point days significantly decreases in conjunction with the frequency of natural fire starts indicating the physical limitations at which these higher dew points are observed in the atmosphere (Figure 5.3). Essentially, 60 to 63 degrees is a range of dew point values that demonstrate a signal of decreasing natural fire occurrence.

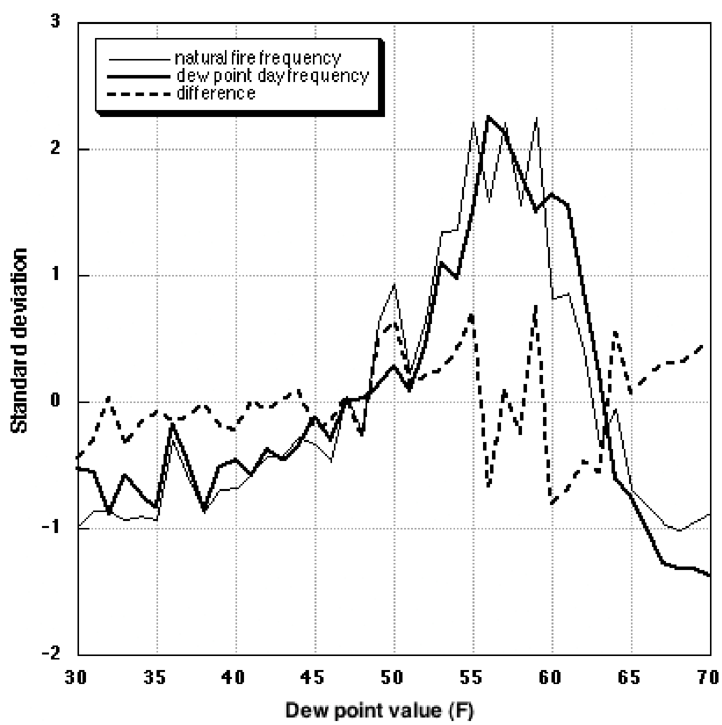

Figure 5.3 Standardized number of natural fires (thin line) and dew point day frequency (bold line) with no onset. The dashed line represents the difference between these two curves.

The dew point frequency for the standardized human fire counts in Figure 5.4 is represented in the same fashion as for natural fire counts in Figure 5.3. From 53 degrees dew point to 60 degrees there are large negative standard deviations. However, this is because the number of human fires from 53 to 60 degrees is lower in comparison to the number of natural fires for the same dew point values. The drop in human fire counts at 60 degrees is not as impressive as for the natural fire frequency for the same dew point value. Furthermore, except for 60 degrees, other dew point values in the 30-70 degree dew point range that show a decrease in human fire counts are followed by another increase in fire counts at higher dew point values.

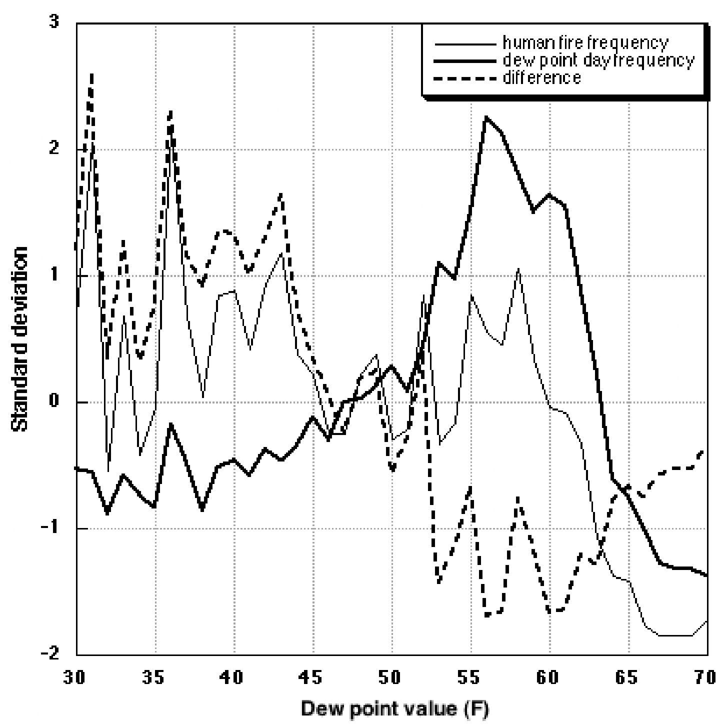

Figure 5.4 Standardized number of human fires (thin line) and dew point day frequency (bold line) with no onset. The dashed line represents the difference between these two curves.

b. Defined onset analysis for dew point values (natural and human fires)

The Phoenix onset dates that were used to calculate the post onset percentages in the first part of this chapter defines the seasonal period of fire and dew point day frequencies for each year. As a consequence, each season will now vary in length due to the interannual variability of the Phoenix onset. The season ending date is arbitrarily determined to be the last day that 55 degrees occurs plus 4 additional days or September 15th, whichever occurs first. This newly defined time period likely reduces the frequency of dew point day occurrence especially at lower dew point values.

Figure 5.5 shows the distribution of the natural fire counts and dew point day frequency occurring within the monsoon season to be quite similar to the natural fire and dew point day frequencies without a defined monsoon onset from Figure 5.1. The peak in natural fire counts and dew point days that is observed in the mid to upper 50's range for the analysis with no onset (Figure 5.1) is also shown for the analysis with an onset (Figure 5.5). The distinction between these plots (Figure 5.1 and 5.5) is the absence of natural fires in the lower dew point range and the overall lower number of natural fires for the onset analysis. The fire counts are not as high as the no onset counts because of the shortened time period of analysis. The natural fires drop from 59 to 60 degrees dew point with the dew point day frequency remaining largely unchanged (shown in Figure 5.5).

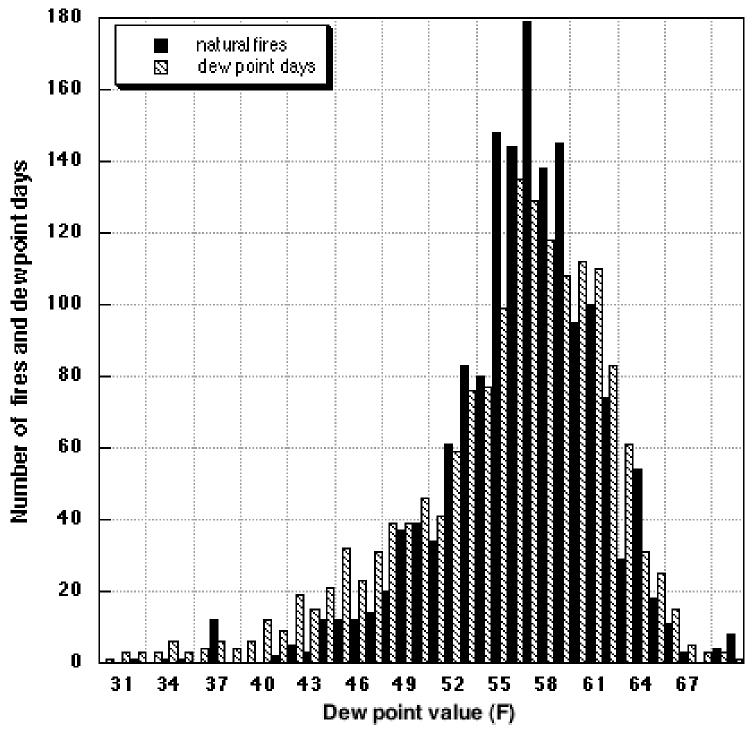

Figure 5.5 Bar plot of the number of the natural fires (solid bars) and frequency of dew point day occurrence (striped bars) using the Phoenix onset definition.

After 50 degrees dew point, the human fire counts with the Phoenix onset show that the number of fires and the frequency of dew point days follows a synchronously occurring bell shaped pattern (Figure 5.6). There is no significant drop in fire counts from one dew point value to the next. Rather, the human fires decrease in a stepwise fashion after a peak at 59 degrees dew point.

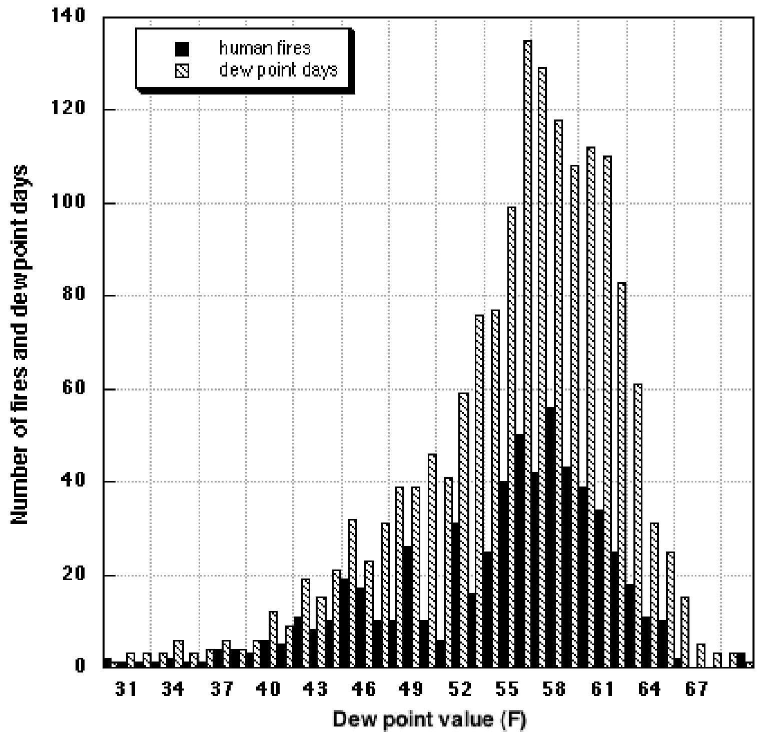

Figure 5.6 Bar plot of the number of the human fires (solid bars) and frequency of dew point day occurrence (striped bars) using the Phoenix onset definition.

The standardized curves for natural fire frequency within the monsoon season in Figure 5.7 show the standard deviation difference between the number of natural fire counts and dew point day frequency to be around –0.6, which is somewhat less than for the difference in the curves without a defined onset. When the time period is constrained to a specific time period after a pre-determined onset, it is clear that 60 degrees is not as strong of a signal for decreasing natural fire occurrence. This is statistically explained because the average of these two variables are no longer including days outside the bounds of the monsoon season.

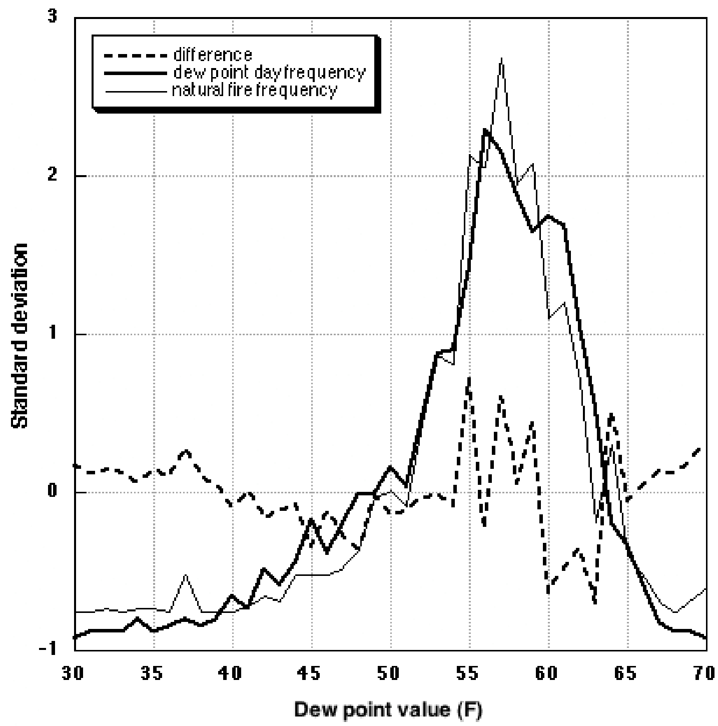

Figure 5.7 Standardized number of natural fires (thin line) and dew point day frequency (bold line) using the Phoenix onset definition. The dashed line represents the difference between these two curves.

The negative standard deviation differences from 53 to 60 degrees dew point that was observed in Figure 5.4 for the standardized human fire counts without an onset are not nearly as large as the differences for dew point values using an onset (Figure 5.8). In addition, the human fire frequency and dew point day frequency with an onset appear to closely correspond to each other from 54 to 70 degrees.

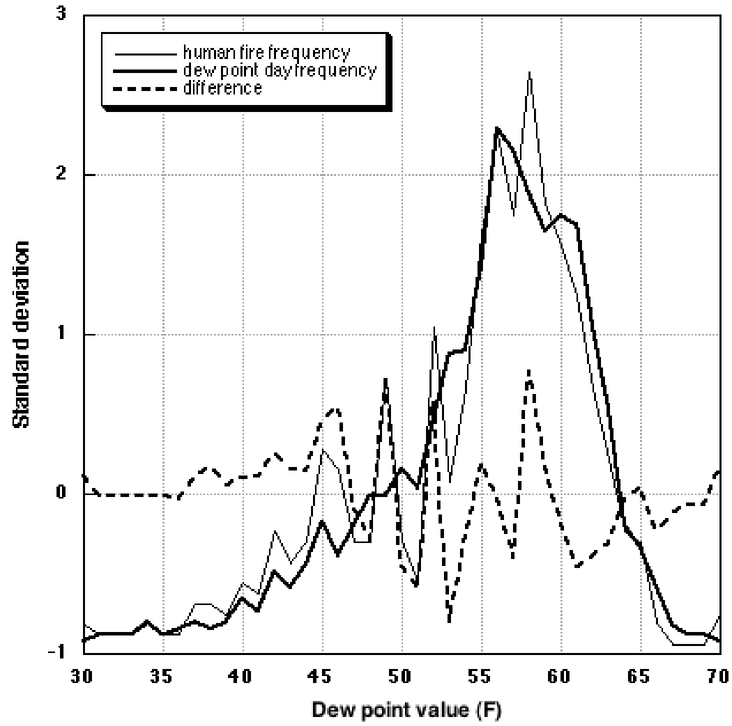

Figure 5.8 Standardized number of human fires (thin line) and dew point day frequency (bold line) using the Phoenix onset definition. The dashed line represents the difference between these two curves.

The lack of a signal in dew point for decreasing human fire occurrence during the monsoon season could be a consequence of decreased sample size since it was found that a low percentage of these fires occurred after the defined onset (Table 5.1). Natural fires show a signal at 60 degrees dew point as a potentially influencing factor in decreasing fire occurrence. This finding will be addressed in more detail later in this chapter. The same analysis is next applied to both human and natural fires with minimum relative humidity as the moisture variable.

c. No defined onset analysis for minimum RH values (natural and human fires)

The frequency of natural and human fires is counted for each occurring minimum relative humidity value in southeastern Arizona for the time period of June 1st to September 15th (i.e., no onset). Figure 5.9 displays the number of natural fires and the frequency of the minimum relative humidity (RH) occurrence. The largest number of natural fires occurs from around 17% to 28% RH with the greatest frequency of minimum RH occurrence observed for the same values. Although a drop in natural fires is observed at 25% RH, the simultaneous drop in minimum RH day frequency renders the signal highly questionable. Furthermore, the fires increase after 25% RH causing speculation that this drop is more than likely an outlier. Figure 5.9 also displays a decline in natural fires at 29% RH without a coinciding significant drop in the frequency of minimum RH days for the same RH value. However, from 30% to 32% RH, the fires increased by a third before gradually decreasing again. Some suspicious increases in the natural fire counts are observed for 43%, 50% and 57% RH. These fire increases for higher values reduces the likelihood of 29% minimum RH as a signal in decreasing natural fire occurrence.

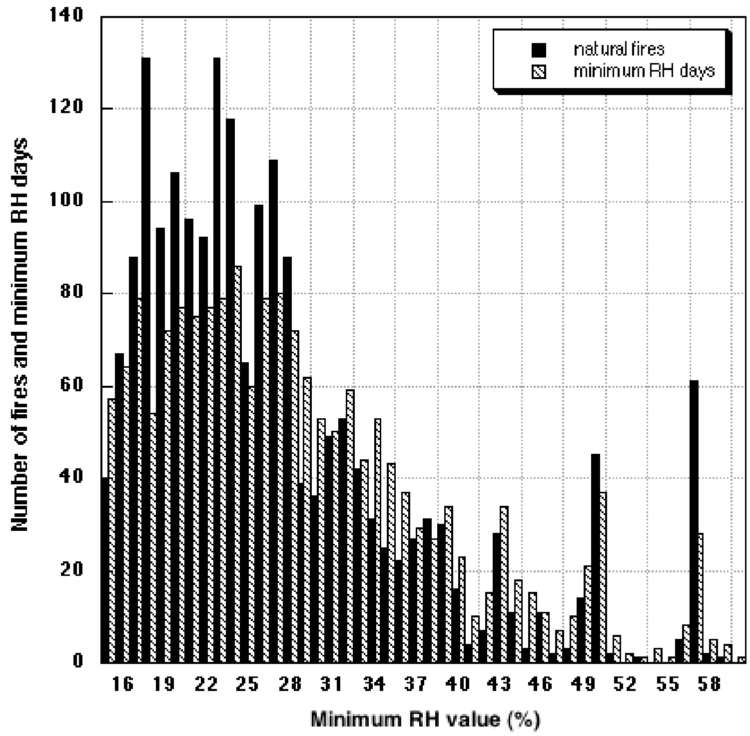

Figure 5.9 Bar plot of the number of the natural fires (solid bars) and frequency of minimum RH day occurrence (striped bars) with no onset (June 1st through September 15th).

The human fire frequency without the GACC onset is plotted in Figure 5.10 along with the frequency of minimum RH day occurrence. Similar to the patterns observed for human fire and dew point day frequency, the greater number of human fires is observed at the lower minimum RH values. There is a gradual decline in both the fire counts and minimum RH occurrence until around 29% RH. A sharp drop in the fire counts occurs at 30% RH without a coincidental decrease in minimum RH occurrence. There are increases in the number of human fires for the minimum RH values of 32%, 43%, 50%, and 57% RH that was also observed for natural fires.

The standardized results for natural fires and minimum RH day frequency depict a moderate standard deviation difference of nearly –1.0 at 29% minimum RH (shown in Figure 5.11). As expected, the standard deviation curves fluctuate greatly with the increased fire counts that were observed for the outlier percentages of 43%, 50% and 57% RH from Figure 5.9.

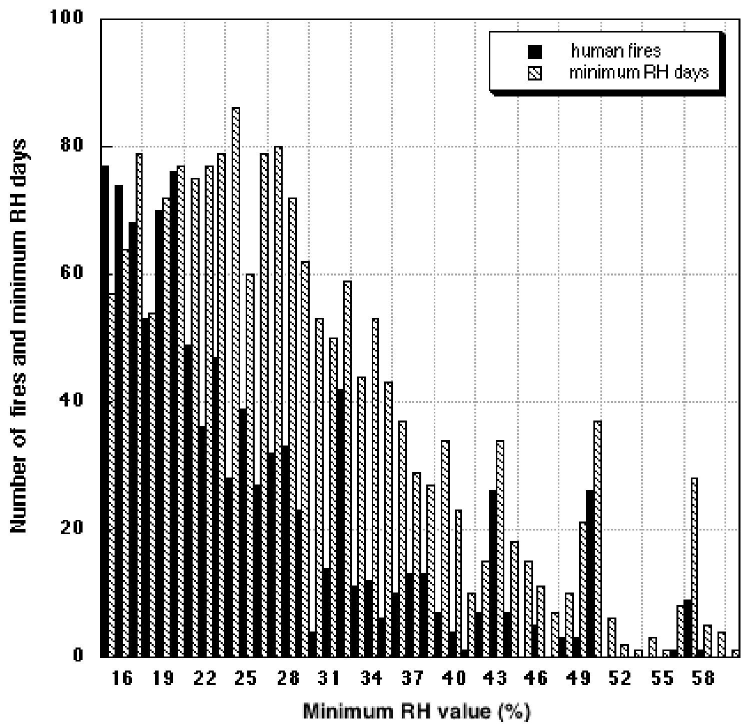

Figure 5.10 Bar plot of the number of the human fires (solid bars) and frequency of minimum RH day occurrence (striped bars) with no onset.

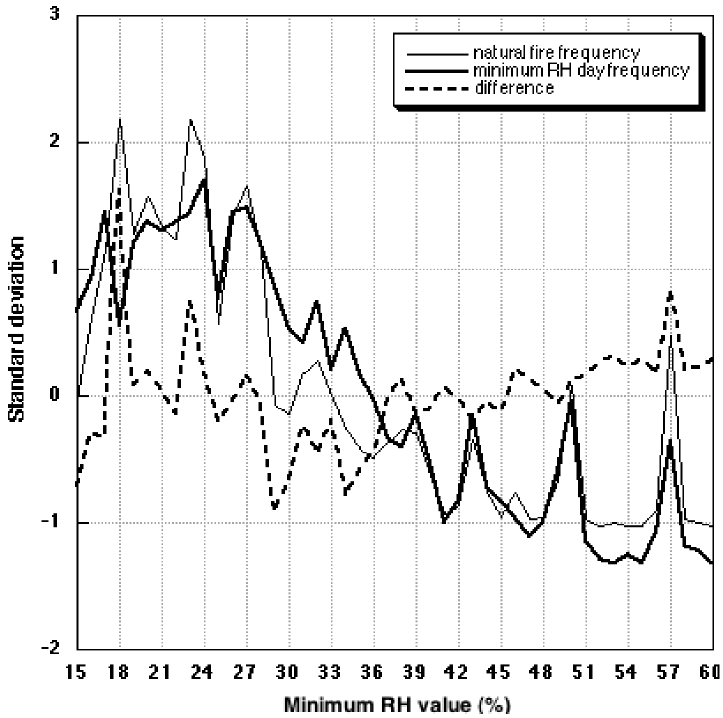

Figure 5.11 Standardized number of natural fires (thin line) and minimum RH day frequency (bold line) with no onset. The dashed line represents the difference between these two curves.

The outlying cases in human fires for the minimum RH values of 32%, 43%, 50% and 57% that were shown in Figure 5.10 (bar plot) are shown in Figure 5.12 (standardized) as well. The large spikes in the standard deviation curves for fire counts and minimum RH days easily identify these outliers (Figure 5.12).

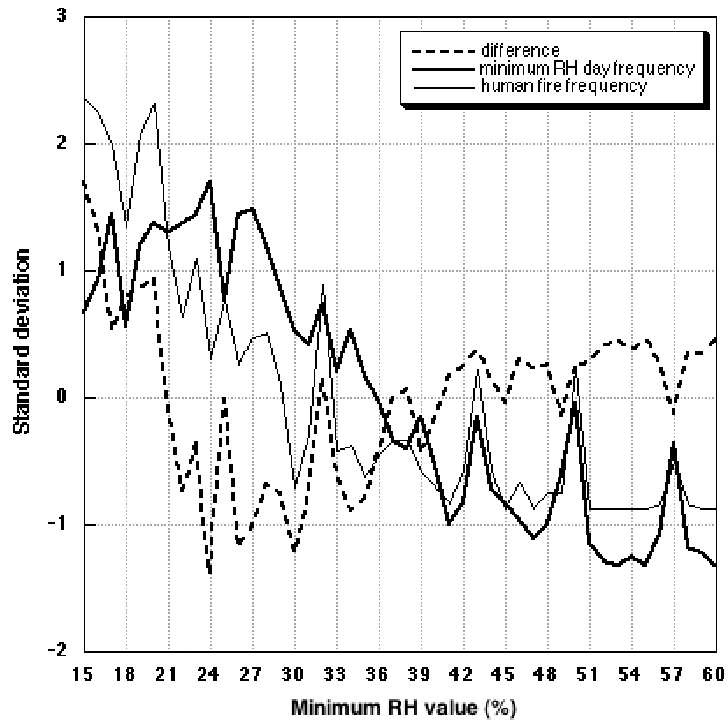

Figure 5.12 Standardized number of human fires (thin line) and minimum RH day frequency (bold line) with no onset. The dashed line represents the difference between these two curves.

Although the actual number of natural and human fires was not the same, both of the natural and human fire frequency plots (Figure 5.9 and 5.11) exhibit outlying cases for the same minimum RH values of 43%, 50% and 57% RH. It is also shown in these plots that for those particular values, the minimum RH day occurrence is relatively high in comparison to other values. Further computational investigation showed the increases in fire frequency (human and lightning caused) for the particular minimum RH values of 43%, 50%, and 57% are the result of active fire seasons in the years 1983 and 1984.

d. Defined onset analysis for minimum RH values (natural and human fires)

With the GACC onset, the time period of analysis is modified reducing the number of fires to be counted in the analysis. A drop in natural fires by more than half occurs from 27% to 29% RH with a subsequent increase in fires from 31% to 32% RH in Figure 5.13. A decrease in natural fires at those values was also seen in the analysis using no onset (Figure 5.9). The frequency of the minimum RH day occurrence does not appreciably change over these values. As expected, the same outlying cases in natural fires appear at 43%, 50% and 57% with the minimum RH occurrence increasing relative to those values.

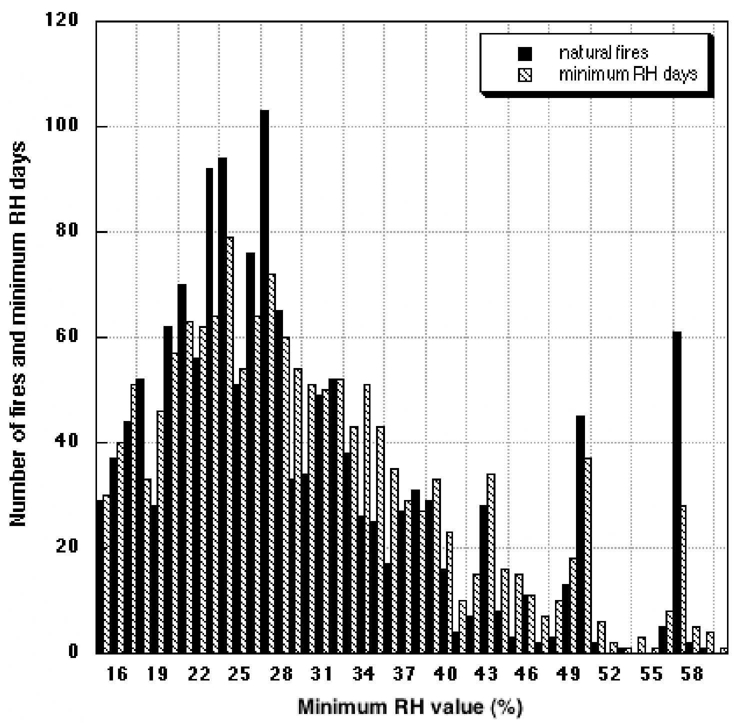

Figure 5.13 Bar plot of the number of the natural fires (solid bars) and frequency of minimum RH day occurrence (striped bars) using the GACC onset definition.

The minimum RH frequency for human fire counts in Figure 5.14 is unchanged from the natural fire counts in Figure 5.13. The patterns of minimum RH occurrence demonstrate a gradual increase and peak in the mid-20 percent values. The human fires show relative uniformity until around 29% RH. After this value, the fires for the most part, decline but there are outlying cases noted for the values of 32%, 43%, 50% and less so at 57% RH. This pattern is largely observed for natural fires as well but the number of fires is greater for natural fire counts.

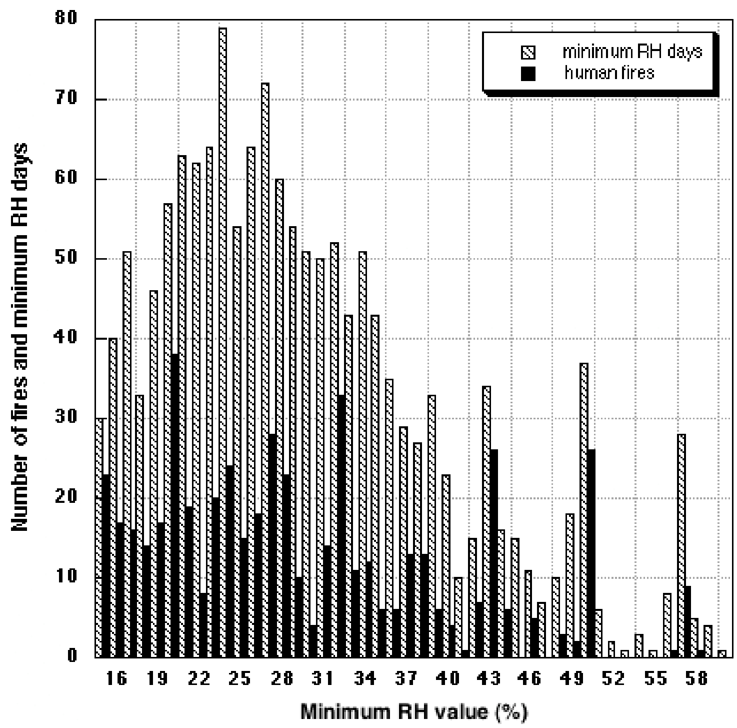

Figure 5.14 Bar plot of the number of human fires (solid bars) and frequency of minimum RH day occurrence (striped bars) using the GACC onset definition.

The standardized results for natural fires with an onset (Figure 5.15) show similarities to Figure 5.11 (standardized without an onset). The large variation in the standard deviation curves at specific RH values is reflective of the outlying cases that were illustrated in Figure 5.11. Constraining the time period of analysis to examine natural fires and minimum RH day frequency did not appreciably change the results.

Applying the GACC onset for human fire counts dramatically reduced the number of fires that occurred (shown in Figure 5.16). The human fires that were able to be included showed much more variation from one RH value to the next.

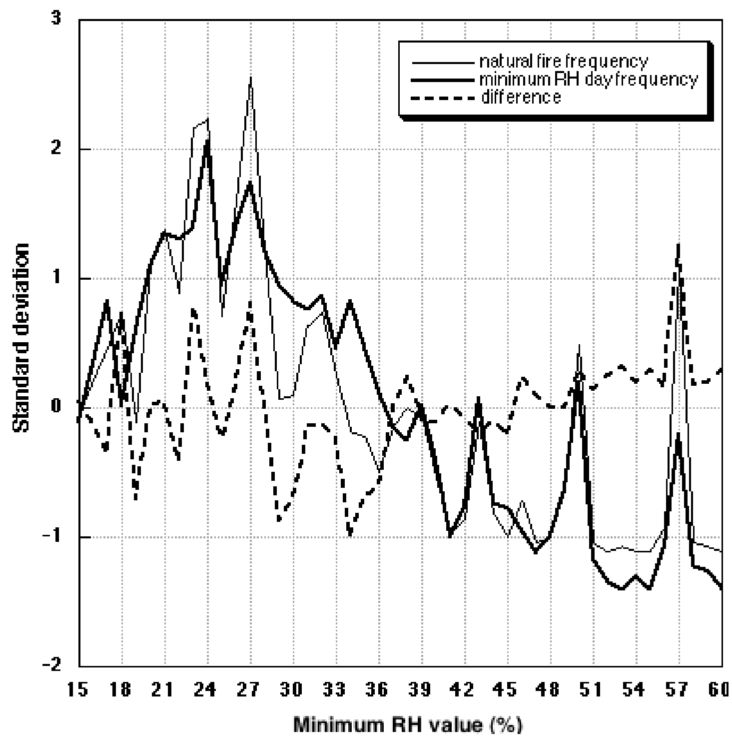

Figure 5.15 Standardized number of natural fires (thin line) and minimum RH day frequency (bold line) using the GACC onset definition. The dashed line represents the difference between these two curves.

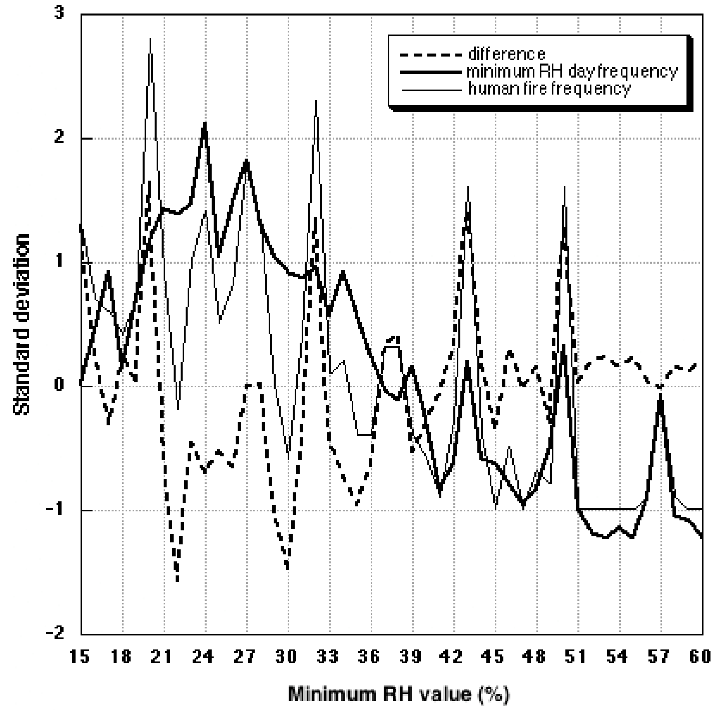

Figure 5.16 Standardized number of human fires (thin line) and minimum RH day (bold line) using the GACC onset definition. The dashed line represents the difference between these two curves.

This section examined fire counts and dew point, minimum RH values for time periods without an onset (i.e., June 1st to September 15th) and for annually varying monsoon seasons as designated by the Phoenix and GACC definitions of the onset. While the human fire analyses did not elicit a signal for dew point in decreasing fire occurrence, the natural fire analyses showed a potential signal for 60 degrees dew point. For human fires, there was no indication of a signal in minimum RH for decreasing fire occurrence. The analyses for minimum RH showed a potential signal of 29% minimum RH for decreasing natural fire occurrence, however the fire increases observed for the higher values of 31 and 32% RH reduced the validity of this signal.

This analysis was performed to assess possible signals in moisture values for a time period with no defined onset and with a defined monsoon season. For either case, no multiple day condition was applied to the fire counts. The next section assesses a range of moisture values using the onset dates for both the Phoenix and GACC definitions for 1, 2 and 3 consecutive days as conditions. This is done to investigate the relevance of multiple days of particular moisture values as a potential threshold for decreasing fires during the actual monsoon season.

3. Analyses of a Range of Moisture Values

Fire occurrence and moisture elements can be quantitatively assessed by calculating percentages of fires and frequency of moisture days for a range of moisture values. Natural fires will only be analyzed because human fires failed to show any signal in the previous analyses. The monsoon season time period of the counts are again defined by the annual onset from the Phoenix and GACC definitions. For dew points of 45 to 65 degrees, and minimum RH values of 15% to 45%, at 1, 2 and 3 consecutive days as conditions, percentages were calculated by dividing the number of fires and moisture days above this condition by the total number of fires and moisture days that occurred within the defined monsoon season without any condition.

An example will assist in clarification of this methodology. Suppose the condition is 58 degrees dew point for 2 consecutive days. For each year from 1980-2002, beginning from each year’s onset date, the number of natural fires and the frequency of dew point days are totaled. These totals are then combined for all 23 monsoon seasons. Subsequently, the natural fires occurring when the condition of 58 degrees or higher for 2 consecutive days is met are counted from all 23 monsoon seasons. Also, the number of days that 58 degrees or higher for 2 consecutive days is observed during the monsoon season is counted. These sums are divided by the total counts (fire and dew point day frequency) to calculate the percentage of fires and dew point days occurring at or above the specific condition. This process was applied to each dew point from 45 to 65 degrees and each minimum relative humidity value from 15 to 45 percent at 1, 2, and 3 consecutive days.

Preferably, any dew point or minimum RH value within the range showing a lower percentage of fires compared to the percentage of dew point or minimum RH days at that moisture value would be an ideal case since this finding would give more credibility to the particular dew point or minimum RH value as influential in decreasing fire occurrence. Figures 5.17 and 5.18 are the percentages for a 1-day condition for dew point and minimum RH respectively. Until a dew point of 59 degrees is reached, the fire count percentage is always greater than the dew point day percentage from Figure 5.17. After the curves intersect at 59 degrees, the fire count percentage is slightly lower than the dew point percentage but never more than a 2% difference. Still, it shows the ideal case after 59 degrees. The 1-day condition percentages (Figure 5.18) for natural fires and minimum RH days depicts a greater fire percentage than minimum RH until 24% RH at which point they intersect. From 24% to 37% RH, the minimum RH percentage is greater than the fire percentage (ideal case) but not exceeding more than a 6% difference.

The percentages for the 2-day conditions for dew point (Figure 5.19) are largely similar to the 1-day condition illustrated in Figure 5.17, but the intersection of the fire count and the dew point day percentage occurs at 58 degrees, 1 degree less than for the one-day condition. After 58 degrees, the ideal case of a greater number of dew point days than fires is present. The difference between the dew point and fire percentages for the 2-day condition is larger than the difference that was found after 59 degrees from the 1-day condition, but still not more than 5%. The 2-day condition percentages of minimum RH days and natural fire counts from Figure 5.20 are for the most part very similar to the 1-day condition. The minimum RH value at which the percentage curves intersect remains around 24% RH, and the percentage differences thereafter is no greater than 5%.

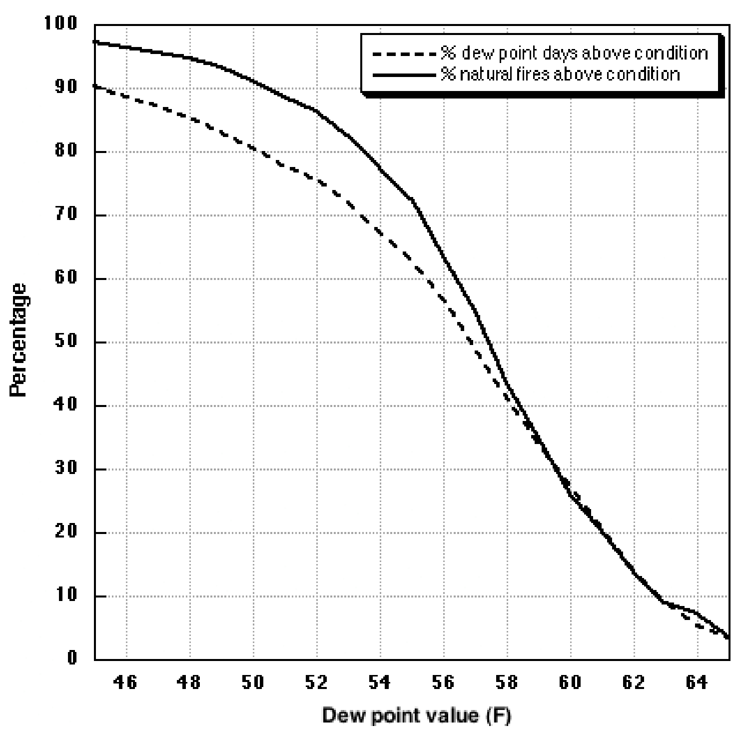

Figure 5.17 Percentages for dew point day frequency (dashed line) and natural fire count (solid line) for the 1-day condition.

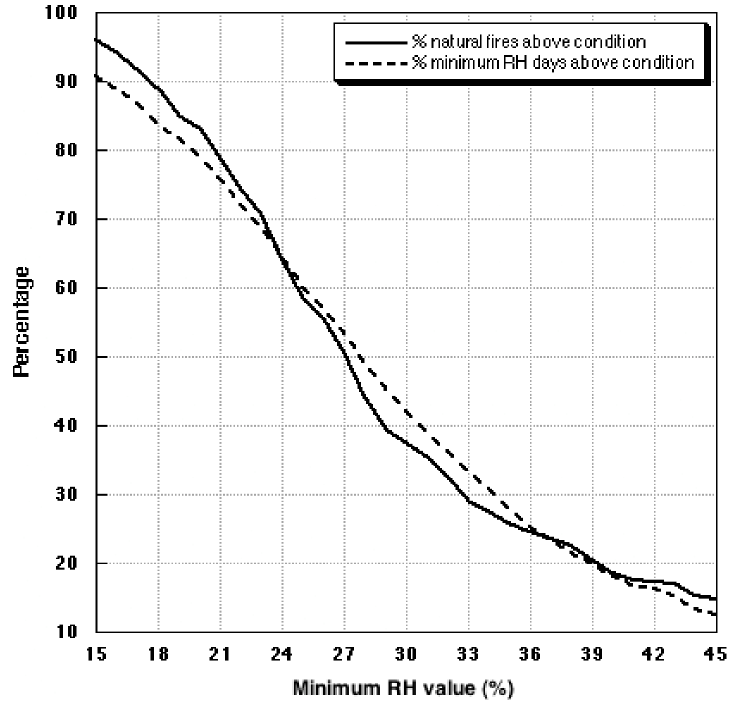

Figure 5.18 Percentages for minimum RH day frequency (dashed line) and natural fire count (solid line), for the 1-day condition.

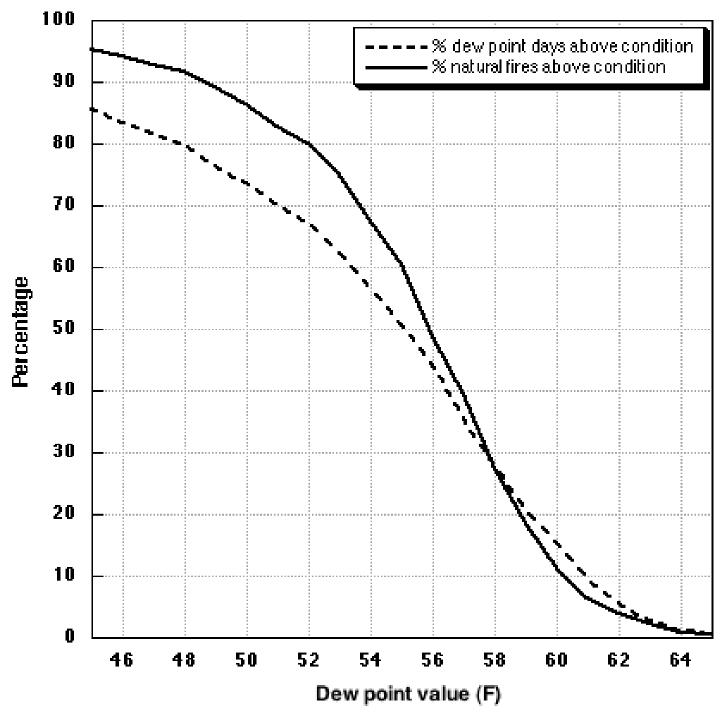

Figure 5.19 Percentages for dew point day frequency (dashed line) and natural fire count (solid line), for the 2-day condition.

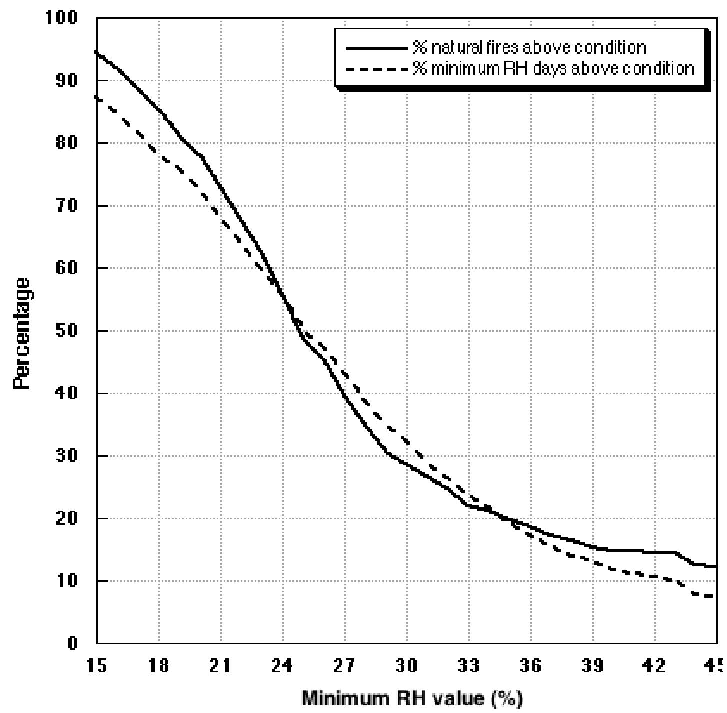

Figure 5.20 Percentages for minimum RH day frequency (dashed line) and natural fire count (solid line), for the 2-day condition.

The 3-day condition percentages for the dew point days and natural fires are shown in Figure 5.21. The fire and dew point day percentage curves intersect at 58 degrees for the 3-day condition, which was also observed for the 2-day condition (Figure 5.19). After 58 degrees, the percentage difference between the two curves is the same as for the 2-day condition (not more than 5% to 6%).

Figure 5.22 depicts the 3-day condition percentages for the natural fires and minimum RH days. The intersection of the two curves at 24% RH observed for the 1 and 2-day conditions is also observed for the 3-day condition. However, after this point the percentages of fires and minimum RH days appear to be about the same until 31% RH.

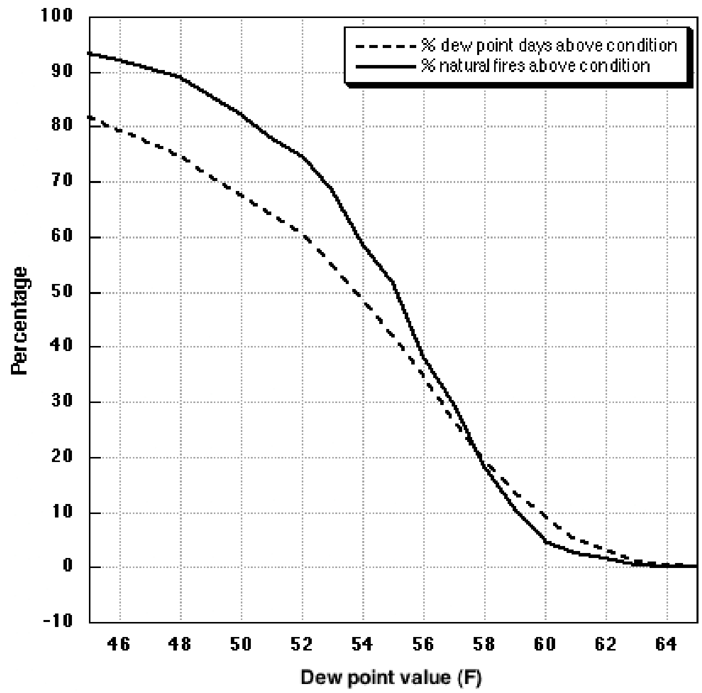

Figure 5.21 Percentages for dew point day frequency (dashed line) and fire count (solid line), for the 3-day condition.

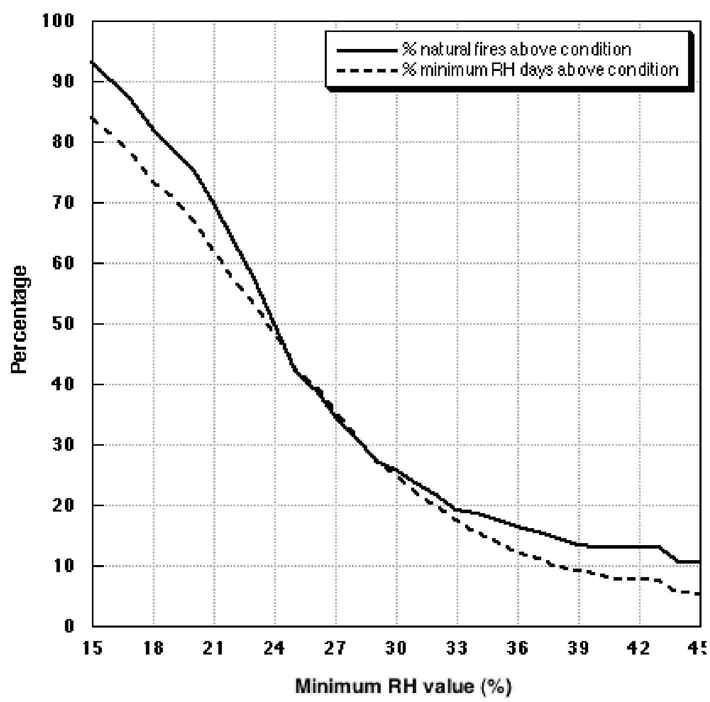

Figure 5.22 Percentages for minimum RH day frequency (dashed line) and fire count (solid line), for the 3-day condition.

Figure 5.21 illustrates that even with the Phoenix onset applied, and enforcing the same 3-day condition at 55 degrees *during* the monsoon season, there is still slightly over 50% of the natural fires occurring. However, it should be noted that the percentage of times this condition is observed is less than the number of single occurrences. This finding is different from the 'after onset' percentages earlier in this chapter. Those percentages were calculated with no conditions other than the onset definition itself. This result is not only using that same defined onset, but also implementing the 3-day condition each time it occurs within the season. Furthermore, the time period of analyses is different since the '45-days before and 45-days after' method that would include earlier dates is not used for this part of the analysis. Rather, it extends from the onset date to September 15th.

Although the percentage of fires and dew point days both decrease with higher dew point values, Figures 5.17, 5.19, and 5.21 (1, 2, and 3-day, respectively) show a greater rate of decrease (i.e., steeper slope) in the fire percentage curve after 55 degrees dew point that is not observed in the dew point day percentage curve. For simplicity, the slope values using only the 3-day condition for the percentages of fires and dew point days are plotted in Figure 5.23.

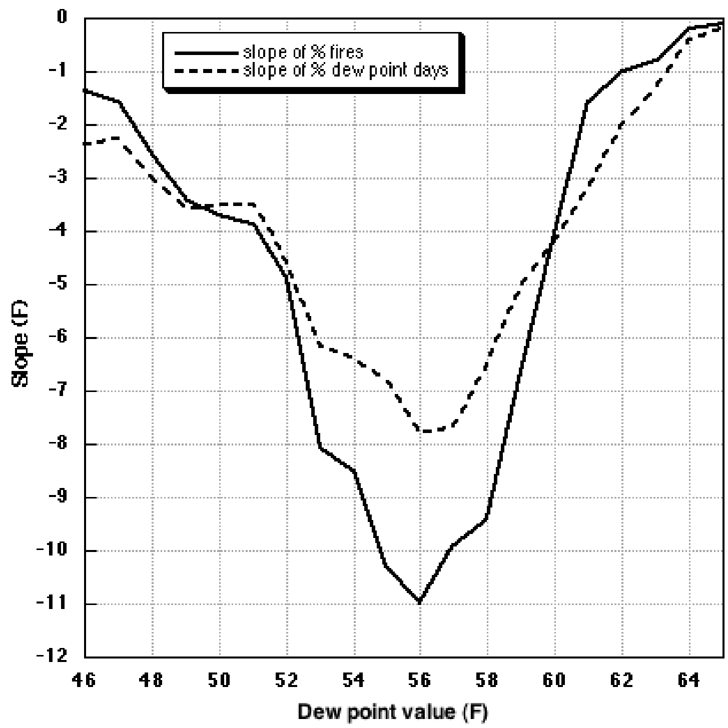

Figure 5.23 Slopes of % natural fires above condition (solid line), and % dew point days above condition (dotted line) for the 3-day condition.

From 49 to 60 degrees dew point, the slope is steeper (more largely negative) for the fire percentage than for the dew point days (Figure 5.23). From 54 to 56 degrees dew point, the difference between the two slope curves and the steepness of the slopes is greatest. At these values, the rate of decrease in fires is greatest compared to the rate of decrease in the dew point days. After 56 degrees, the rate of change becomes less for both fire and dew point day percentages. This finding implies that a dew point of 54 to 56 degrees for 3 consecutive days may have some atmospheric forcing on decreasing natural fires, but it is not significant enough to make a claim about these particular dew point values for 3 consecutive days as potential thresholds in fire occurrence. Clearly, further exploration into this observation is needed.

Figures 5.17 through 5.22 demonstrate some essential, if not unexpected, findings. As moisture increases (either dew point or minimum RH), natural fire percentages decrease concurrently as does the frequency at which these moisture values occur. Additionally, the percentage curves for dew point and minimum RH are characteristically distinct. For 1, 2 and 3-day conditions, the percentages for both the frequency of natural fires and dew point days gradually decreases until the mid 50's at which point the decrease becomes less gradual until the point of intersection is reached (59 degrees for 1-day, 58 degrees for 2 and 3-days). The natural fire frequency and the minimum RH day percentage curves from 15% RH to 24% RH appear to follow a linear pattern. After 24% RH (the RH value of intersection for 1, 2 and 3-day conditions), both of the percentage curves decline more gradually.

After the percentage curves intersect, at which point the ideal case of the moisture day percentage exceeding the natural fire percentage is represented, the differences are greatest for the 2 and 3-day conditions for dew point and the 1 and 2-day conditions for minimum RH. Although these differences were sufficient enough to be identified, they are relatively small and insignificant in the context of determining moisture thresholds.

For both dew point and minimum RH, the percentages become lower as another consecutive day is added to the condition. This suggests that natural fires might be decreasing because the moisture conditions at which they would be counted are occurring less in the atmosphere at multiple days rather than decreasing from atmospheric influences exclusively. When the slopes of both the fire and dew point day percentages are graphed, dew points of 54 to 56 degrees for 3 consecutive days appear to impact natural fire occurrence slightly. This observation, however, is subtle. From this analysis, it does not appear that any moisture value or range of values emerge as significant thresholds in decreasing natural fire occurrence.

CHAPTER SIX

DISCUSSION

The drop in the climatological number of fires occurring around July 7th in southeastern Arizona is rather abrupt. After this time, the fires continue to decline throughout the summer season. It was determined in Chapter 4 with natural and human caused fires separated that human fires were influencing the magnitude of the initial decline. The climatological fire occurrence for Northwestern Arizona, an area near the primary monsoon influence, exemplifies the disparities of human and natural fire occurrence further. Figure 6.2 shows the natural and human fire occurrence climatology for northwestern Arizona. While the sample size is smaller than for the other regions, the abrupt decline in human fires again suggests that atmospheric moisture may be inhibiting fire occurrence after the monsoon onset. However, the fairly consistent level of natural fires until mid-August does indeed suggest a monsoonal influence over the region, but not necessarily one of inhibiting fire occurrence since the numbers remain elevated throughout most of the summer. Note the peak in human fires corresponding to the 2 to 3-day period around the July 4th holiday. Also note that the peak in natural fires slightly lag the Phoenix climatological onset of July 7th by a few days.

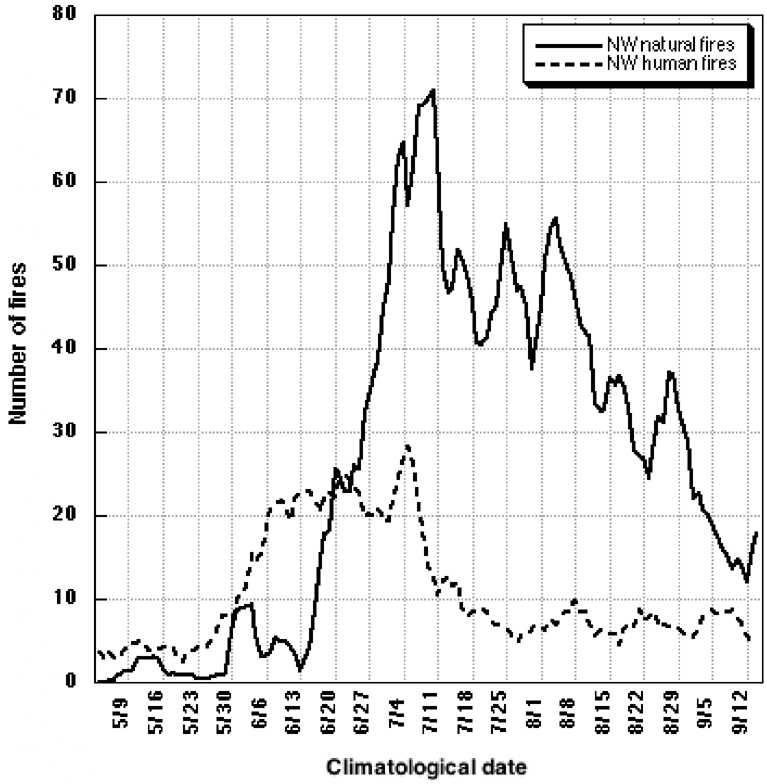

Figure 6.1 5-day running mean time series of natural (solid line) and human (dashed line) fire climatologies for northwestern Arizona for the years 1980-2002.

In southeastern Arizona, the strongest signal and most confounding result is the early and abrupt decrease in the number of human related fires. This decline is synonymous with the average monsoon onset date of July 7th for Phoenix. Natural fires do not follow this pattern, rather their numbers remain elevated throughout most of the summer. If atmospheric moisture alone were the influencing factor, then both fire causes would be equally affected. So a conceivable explanation for the drop in human fires is the lack of human ignitions from minimized human activity after July 7th. Perhaps the monsoon effects of increased rainfall, thunderstorms and rising humidity are limiting outdoor activities in relation to human comfort levels. This reasoning, currently speculative, would explain the differences in the natural and human fire occurrence rather than attributing it solely to atmospheric influence.

The natural fire climatology in Figure 4.3 shows that the number of fires peaks and remains elevated from July 5^{th} to July 17^{th}. The gradual decline thereafter occurs at the same time the lightning strikes continued to rise. From the potential moisture threshold analysis, the number of natural fires peak starting with the low to mid-50's dew points and above. In the dew point range of 60 to 63 degrees, fires sufficiently decrease from this peak. This could possibly be a result of increasingly wet thunderstorms associated with higher dew point values and consequently more precipitation reaching the ground (Maddox 1995).

The percentages from Table 5.1 for human fire occurrence and area burned after onset are much less than the percentages for natural fire occurrence and area burned. This occurs for both timber and shrub fuel types, and for large fires. There is more than a 20% difference between the percentages of the greater number of natural timber fires and the smaller area burned by natural timber fires after onset. This could be due in part to increased fuel moisture that inhibits fire growth, either directly or allowing more time for suppression response. Another plausible explanation is the increased rainfall in mountainous (timber) areas from orographically induced monsoon thunderstorms. This difference for human timber fires is not observed implying more of a non-atmospheric influence. This finding supports the concept that the natural fires may increase after the monsoon because of lightning, but there are fewer large ones likely due to increasing atmospheric moisture and precipitation. An example of this notion was demonstrated quite well for the years 1983 and 1984. Not only did a large number of fires from both human and natural causes occur, but these years were also considered two of the stronger monsoons in terms of precipitation, early onset, and the number of higher dew point/minimum RH days. However, the area burned for these years was not particularly large.

SUMMARY AND CONCLUSIONS

The climatologies of dew point, minimum relative humidity and fire occurrence in southeastern Arizona indicate a potential relationship between increasing atmospheric moisture from the Southwest Monsoon and decreasing fire occurrence. This potential relationship was investigated by using federal fire occurrence records and historical RAWS.

The climatology, and the interannual/intra-seasonal variability of fire occurrence, moisture elements and lightning were presented to illustrate the historical patterns. Undoubtedly, the variability of elements introduces complexity into this study. Based on the lightning climatology, human and natural caused fires were separated and shown to have different characteristic patterns. The large disparities in their climatologies warranted separate analyses for the two different causes.

Two atmospheric moisture definitions of the monsoon onset, Phoenix dew point and Southwestern GACC minimum relative humidity, were applied to assess their relevance in the context of fire occurrence. An elementary approach was undertaken by combining 23 years of fire and weather data and calculating the percentages of fires in terms of numbers and area burned based on fuel type that occurred after the defined onset. The counts from 45-days after the onset were then compared to the total counts of the 90-day period of 45-days before and 45-days after the onset. The results showed that both moisture definitions could apply to human fire occurrence, but neither applies to natural fire occurrence.

The human fire count percentages after the onset is 17.4% and 18.3% for shrub and 25.7%, and 24.1% for timber types (Phoenix and GACC definition, respectively). Based on their comparatively lower percentages, the area burned from human fires appears to be slightly more affected by the monsoon onset than the number of human fires. This was observed for both shrub and timber fuel types.

The percentages for the number of natural fires that occurred after the onset for shrub are 61.2% and 60.2%, and for timber, 59.3% and 57%, for the Phoenix and GACC definitions, respectively. These percentages of natural shrub and timber fires are much larger than what was observed for human fires.

A direct comparison of the natural fire percentages for the number of and the area burned by timber fires reveals a significant difference between the two. At least 57% of the timber fires occur after onset, which suggests the monsoon might be starting even more fires than before onset. The 37% for area burned from timber fires after onset suggests that the monsoon may be decreasing fire size.

In general, percentages of human fire occurrence, both in number and area burned are consistently lower than percentages for natural fire occurrence. If the human fires are actually decreasing from the lack in human activity, then certainly this is contributing to the lower percentages of human fires and area burned after onset. The percentages for both the GACC and Phoenix definitions were nearly identical so it does not appear that one is more useful over the other in association with decreasing fires.

Large fire occurrence for both human and natural fires was examined by calculating percentages of human and natural fire counts and area burned for the combined fuel types. Fuel types were not separated due to the smaller sample size of 193 large human fires and 105 large natural fires for the total 23 years. Any fire equal to or greater than 40 hectares was included as a large fire. The percentages for both human and natural large fires are slightly less than the percentages using all size human and natural fires. Over 55% of large natural fires occurred after either the Phoenix or GACC onset. Slightly less than 50% of the area burned by large natural fires occurred after either of the onsets.

The combination of fire counts and specific dew point or minimum RH values at which they occurred was examined to reveal a potential relationship between these two elements. Although not a particularly strong signal, there is a potential threshold of 60 degrees dew point for decreasing natural fire occurrence, but no threshold is identified for human fires. Neither natural nor human fire analyses elicited a signal in minimum RH as a potential factor in decreasing fire occurrence.

A range of dew point and minimum RH values was quantitatively evaluated in terms of percentages of natural fires and dew point and minimum RH days that occurred *above* specified conditions during the monsoon season. This was done to examine the relevance of multiple days as potentially more influential in decreasing natural fire occurrence as opposed to a single day as a condition. The results show that the percentages of the fire counts and dew point and minimum RH days decrease concurrently as the dew point and minimum RH value increases. At some dew point or minimum RH value, the percentages intersect indicating that natural fires are fewer in comparison to the dew point and minimum RH days. The percentages continue to decrease with higher values of dew point and minimum RH. This finding suggests that the decrease in fire counts may be a consequence of the atmospheric constraints that would limit the frequency of higher dew points and minimum RH values, rather than a physical association between moisture and fire occurrence. This observed upper moisture limit would restrict the number of fires to be counted at those higher values, assuming that moisture did not strictly inhibit fire occurrence. A greater rate of decrease in natural fires from 54 to 56 degrees dew point for 3 consecutive days compared to the number of dew point days suggests these dew point values perhaps have a slight influence on natural fire occurrence.

Several relevant findings for the southeastern Arizona monsoon region have been produced from this research. The significant conclusions are:

- Human and natural fire climatologies have characteristically different patterns
- The Phoenix and GACC definition of monsoon onset applies to human fire occurrence and human area burned, but not to natural fires
- A dew point value of 60 degrees or larger for a single day is a potential moisture threshold for decreasing natural fire occurrence. No dew point value emerged as a potential threshold for decreasing human fire occurrence
- A potential minimum RH threshold for decreasing natural or human fire occurrence was not identified
- No threshold value of dew point or minimum RH for 1, 2 or 3

consecutive days appeared as significant in decreasing natural fire occurrence

The results of this study have provided a better understanding of the atmospheric characteristics of the Southwest Monsoon in relation to fire occurrence. The findings have shown that the existing definitions of the monsoon onset do not apply to natural fire occurrence in southeastern Arizona. Rather, there appears to be a greater likelihood of natural fire occurrence with the commencement of the monsoon. This can become significant for fire weather specialists when assessing fire start potential. These findings are able to provide a foundation for continuing fire-monsoon research and will hopefully be of value for fire weather forecasters and fire management applications in southeastern Arizona.

FUTURE WORK

The possibility of precipitation rather than strictly increasing atmospheric moisture as the cause of decreasing fire occurrence necessitates further research. However, the limited availability of high temporal and spatial resolution precipitation datasets for this area, and for the time period of interest, are largely the reasons for not incorporating this element thus far. The relevance of precipitation as a potential mitigating factor is supported using SST (sea surface temperature) onset dates. Historical SST onsets of the monsoon, that are based on mean SST threshold values of 29º C or greater in the northern Gulf of California have been shown to be related to monsoonal rainfall in Arizona

(Mitchell et al. 2002). Figure 6.3 is a comparison of the SST onset dates and the historical onset dates from the Phoenix NWSFO (dew point) for the years 1983-2002.

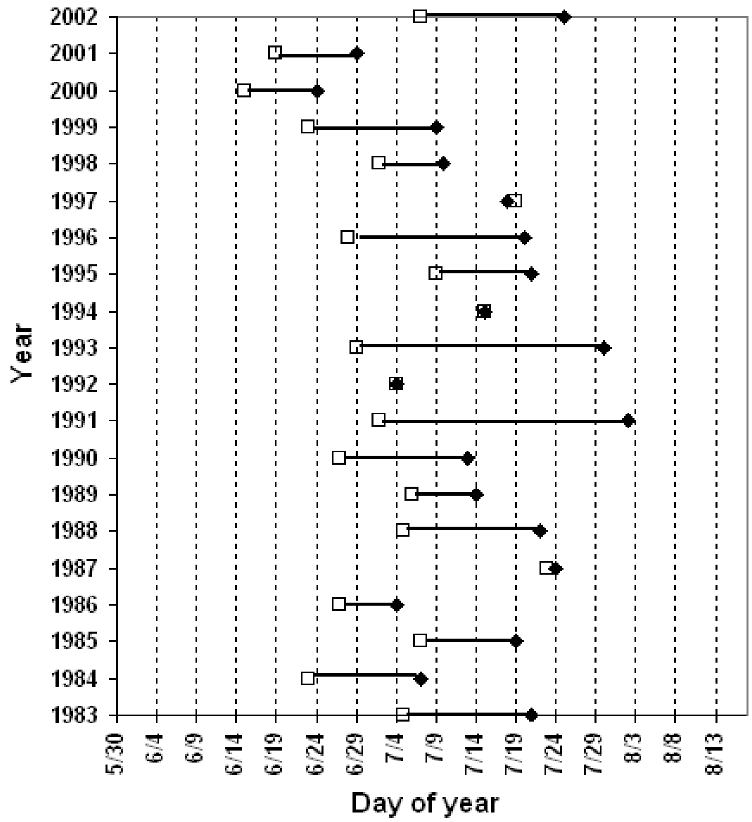

Figure 6.2 Historical SST (solid diamonds) and Phoenix (open squares) monsoon onset dates for the years 1983-2002, onset dates are given in Appendix B (SST) and Appendix C (Phoenix).

Out of twenty years, sixteen had later SST onset dates. Some of them are as much as 3 to 4 weeks later than the Phoenix onset. Because the SST thresholds are related to the timing of appreciable rainfall in Arizona, the later SST onset dates are reflective of a delay in precipitation. It was shown that the decline in climatological natural fire occurrence for southeastern Arizona around mid-July is not related to the Phoenix (dew point) definition of onset. The timing of the average SST onset date of July 16th is however, within the time period of decline in natural fires. This finding underscores further the possibility that precipitation rather than increasing atmospheric moisture is significant in terms of decreasing natural fire occurrence.

Other potentially mitigating fire-weather variables such as fuel moisture for different vegetation types should be explored as well in conjunction with fuel type and its sensitivity to atmospheric moisture. The fuel moisture content is controlled by atmospheric elements. Essentially as atmospheric moisture increases, the fuel moisture gradually increases becoming more wet. The time it takes for fuels to reach moisture equilibrium depends on the size of the fuel (10, 100, and 1000-hour time lags). At some fuel moisture threshold value, large fire growth is inhibited and at another value ignition is inhibited. The fuel moisture can increase more rapidly with precipitation but the rate at which this occurs depends on whether precipitation is falling all at once or more steady over time. Fuel moistures can be quantitatively examined in the same manner as dew point and minimum RH to assess the potential relationship between atmospheric and fuel moisture in the context of monsoon fire occurrence.

In this analysis, only point location, fuel type, and the cause of each fire were considered. An additional factor that could be influencing fire occurrence is the elevation of these fires. This information was not easily obtained from the federal databases but it could be derived or estimated using Arcview/GIS methods. Incorporating the elevation of individual fires may help in the investigation of the fire-monsoon relationship since meteorological elements, at which the analysis is attempting to relate to fire occurrence, are influenced by elevation as well. The highly varied topography of the southwestern U.S. would indeed make this task a challenge.

The dissimilar findings between human caused and natural caused fire occurrence needs to be examined from the sociological perspective. The goal would be directed toward learning whether the differences are largely due to anthropogenic or non-anthropogenic components. Ideally, researching visitation records of federal lands in southeastern Arizona could help explain the characteristic patterns in historical human fire trends based on outdoor activities. Unfortunately, at least for federal lands in the southwestern U.S., there is no widely implemented and maintained method that exists to regularly document and archive visitation statistics (Morehouse 2001). Regardless, these records would be more indicative of the recreational activities (i.e., camping, hiking) and would not include any of the non-recreational activities that also impact human fire occurrence.

Investigation of fire and monsoon relationships for the entire southwestern U.S. was beyond the scope of this study. The results have provided insight into the fire-monsoon association for southeastern Arizona, an area historically known to experience a greater impact of the Southwest Monsoon in relation to other adjacent areas of the southwestern U.S. Therefore, blanket statements regarding the fire-monsoon relationship cannot be made to represent the entire Southwest. However, this research could be expanded to include the broader region even though spatial and temporal variability of the monsoon impact can be larger for areas outside of the bounds of southeastern Arizona. The availability of federal fire occurrence and weather databases for the southwestern region would enable further quantitative analyses into the linkage between atmospheric elements influenced by the monsoon and wildland fire occurrence.

REFERENCES

Adams, D.K. and A.C. Comrie.1997: The North American Monsoon. *Bulletin of the American Meteorological Society*, **78**, 2197-2213.

Bradshaw, L.S., J.E. Deeming, R.E. Burgan, and J.D. Cohen, 1978: The 1978 National Fire-Danger Rating System: Technical Documentation. General Technical Report INT – 169, Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1984, 44 pp.

Brown, T.J., B.L. Hall, K.T. Redmond, and G.D. McCurdy, 2001: Great Basin RAWS Network Analysis. CEFA report 01-01, Climate, Ecosystem, and Fire Applications, Desert Research Institute, Reno, NV, 49 pp.

_______, B.L. Hall, C.R. Mohrle, and H.J. Reinbold, 2002: Coarse Assessment of Federal Wildland Fire Occurrence Data. CEFA report 02-04, Climate, Ecosystem, and Fire Applications, Desert Research Institute, Reno, NV, 31 pp.

Carleton, A.M., D.A. Carpenter and P.J. Weber. 1990: Mechanisms of interannual variability of the Southwest United States summer rainfall maximum. *Journal of Climate,* **3**, 99-1015.

Coarse-Scale Spatial Data for Wildland Fire and Fuel Management: USDA Forest Service, Department of Interior, http://www.fs.fed.us/fire/fuelman/index.htm.

Cummins, K.L., M.J. Murphy, E.A. Bardo, W.L. Hiscox, R.B. Pyle, and A.E. Pifer, 1998: A combined TOA/MDF technology upgrade of the U.S. National Lightning Detection Network. *J. Geophys Res*., **103**, 9035-9044.

Current Cover Type fuel model map: USDA Forest Service, Department of Interior, version 2000, 1 km, http://www.fs.fed.us/fire/fuelman/

Douglas, M.W., R.A. Maddox, K. Howard, and S. Reyes, 1993: The Mexican Monsoon. *Journal of Climate*, **6,** 1665-1677.

Fawcett, P.J., J.R. Stalker, and D.S. Gutzler, 2002: Multistage moisture transport into the interior of northern Mexico during the North American summer monsoon. *Geophysical Research Letters*, **29**, 9-1:9-4.

Hales, J., 1972: Surges of maritime tropical air northward over the Gulf of California. *Monthly Weather Review*, **100**, 298-306.

Higgins, R.W., Y. Yao, and X.L. Wang, 1997: Influence of the North American Monsoon System on the U.S. Summer Precipitation Regime. *Journal of Climate*, **10**, 2600-2621.

Mitchell, D.L., D. Ivanova, R. Rabin, T. Brown, and K. Redmond, 2002: Gulf of California Sea Surface Temperatures and the North American Monsoon: Mechanistic Implications from Observations. *Journal of Climate*, **15**, 2261-2281.

Maddox, R.A., D.M. McCollum, and K.W. Howard, 1995: Large-Scale Patterns Associated with Severe Summertime Thunderstorms over Central Arizona. *Weather and Forecasting*, **10**, 763-778.

National Interagency Fire Center (NIFC): Boise, ID, definition of large fire incidents, http://firemapper.sc.egov.usda.gov/modisrr/lg_fire2.php

National Weather Service, 2003: Phoenix Forecast Office Homepage, http://www.wrh.noaa.gov/Phoenix/general/55degree/index.html.

National Interagency Remote Automated Weather Stations Network: RAWS standards, http://www.fs.fed.us/raws/standards/

Rorig, M.L., and S.A. Ferguson, 2002: The 2000 Fire Season: Lightning-Caused Fires. *Journal of Applied Meteorology*, **41**, 786-791.

Southwest Geographic Area Coordination Center Homepage (Southwest GACC): Albuquerque, NM, Fire Behavior/Danger Outlooks http://www.fs.fed.us/r3/fire/swapredictive/swaoutlooks/swaoutlooks.htm.

Swetnam, T.W., and J.L. Betancourt, 1990: Fire-Southern Oscillation relations in the Southwestern United States. *Science*, **249**, 1017-1021.

CLIMAS (Climate Assessment Project for the Southwest), ISPE (Institute for the Study of Planet Earth), and LTRR(UA Laboratory of Tree-Ring Research), 2000: *The Implications of La Niña and El Niño for Fire Management*. Workshop Proceedings, Tucson, AZ.

APPENDIX A

Calculation of dew point (WRCC, *courtesy of Greg McCurdy*)

1) Constants:

   temp = temperature in Fahrenheit
   rh = relative humidity (%)

   for temp less than 0:
      constA = 6.1115
      constB = 22.452
      constC = 272.55
   for temp greater than 0:
      constA = 6.1121
      constB = 17.502
      constC = 240.97

2) Initializing variables:

   est = 10000000
   e = 10000000
   dew point = 10000000

3) Enter temp in F°:

   if rh greater than 0.0 and temp less than 1000:
      est = constA * exp((constB * temp) / (constC + temp))
      e = (rh / 100) * est
      dew point = (constC * log(e/constA)) / (constB - log(e/constA))

   if rh equal to or less than 0.0 and temp is greater than 1000:
      - dew point invalid

APPENDIX B

SST historical monsoon onset dates, (dates are midpoints of 7 day means, mean SST value must equal or exceed 29.5^{o}C), *courtesy of David L. Mitchell*

Year	Date of 29.5^{o}C N. GOC SST onset
1983	July 23
1984	July 9
1985	July 21
1986	July 6
1987	July 26
1988	July 24
1989	July 16
1990	July 15
1991	Aug. 4
1992	July 6
1993	Aug. 1
1994	July 17
1995	July 23
1996	July 22
1997	July 20
1998	July 12
1999	July 11
2000	June 26
2001	July 1
2002	July 27

APPENDIX C

Phoenix NWSFO historical onset dates (definition of 3 consecutive days at 55 degree dew point or higher), *courtesy of Doug Green*

Year	onset date
1980	July 19
1981	July 6
1982	July 6
1983	July 7
1984	June 25
1985	July 9
1986	June 29
1987	July 25
1988	July 7
1989	July 8
1990	June 29
1991	July 4
1992	July 6
1993	July 1
1994	July 17
1995	July 11
1996	June 30
1997	July 21
1998	July 4
1999	June 25
2000	June 17
2001	June 21
2002	July 9
2003	July 18