THE NORTH AMERICAN MONSOON SYSTEM IN SOUTHERN ARIZONA

by

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As members of the Dissertation Committee, we certify that we have read the dissertation prepared by Richard Raymond Brandt entitled The North American Monsoon System in Southern Arizona and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy

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DEDICATION

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ABSTRACT

The North American Monsoon System (NAMS) is a dominant factor in climate in the southwestern United States and northwestern Mexico. Despite the influence of the NAMS and the intense research efforts it receives, its predictability, its variability, and the details of its influence on the environment are not well understood. This dissertation is comprised of three papers, which collectively address these three aspects of this complex climate phenomenon through an examination of various data and analyses at multiple spatial and temporal scales, while focusing on impacts in southern Arizona. In the first paper, a modified definition of the NAMS is established to delineate dates for monsoon onset, bursts, breaks, and retreat. The results are applied to an atmospheric compositing study in the second paper and to an applied study of monsoon-wildland fire relationships in the third paper. In the second paper, geopotential height patterns that affect moisture advection are identified. Onset, retreat, and break timing and duration are impacted by shifts in the latitude of the mid-level anticyclone and by lower-level gradients and contour orientation. Analyses in the third paper reveal the some of the complex effects of monsoon onset, variations in break timing and duration, and monsoon retreat on fire occurrence. This research contributes to the current knowledge of the NAMS in general and to the specific regional impacts of the monsoon. The results can (1) improve meteorological forecasts through the recognition of synoptic and sub-synoptic patterns related to the NAMS and (2) help fire managers by expanding the current understanding of the regional controls of wildland fire.

CHAPTER 1 – INTRODUCTION

Explanation of the Problem

In the southwestern United States, the monsoon and the wildland fire season constitute two periods with strong environmental, societal, and economic impacts. Abundant research is available on both topics, but few publications consider their interaction. This deficiency is surprising, given the fairly recent growth of applied climatology (Changnon 1995, Hobbs 1997, Changnon 2004) and the increased concern on the observed and potential influences of climate and climate change on the environment and society.

The North American Monsoon System (NAMS) is the dominant factor in annual precipitation in northwestern Mexico and the southwestern United States, particularly Arizona and New Mexico. The official onset date, established by the National Weather Service, is determined using atmospheric moisture levels. In Tucson, for example, it is defined as the first of three consecutive days for which the daily mean dewpoint temperature is 54°F or greater. The mean onset is in early July (Glueck 1997). The gradual expansion of the Bermuda high and the development of a thermal low in the lower Colorado River Valley contribute to increased atmospheric moisture advection (Adams and Comrie 1997). Higher water content, indicated in measurements of dewpoint temperature, humidity, wet-bulb temperature, and precipitable water, signals the onset of the warm season precipitation regime.

During the monsoon, there are periods of higher and relatively lower atmospheric moisture content. These events, known respectively as bursts and breaks, are well documented in literature (e.g., Brenner 1974, Carleton 1986, Watson et al. 1994, Stensrud et al. 1997, Anderson et al. 2000, Douglas and Leal 2003, Zehnder 2004). Bursts are phases in which stronger moisture advection leads to increased atmospheric moisture. Breaks are the interludes between these surges of moisture or periods when atmospheric water vapor content is low relative to the more humid conditions associated with the monsoon. Thunderstorms can develop during both bursts and breaks, but whether the precipitation reaches the surface is dependent on the quantity of low-level moisture. The probability of precipitation increases during bursts due to higher levels of water vapor, although other dynamic factors must be present. Measurable precipitation is less likely during breaks due to the lower moisture content of the air. Dry thunderstorms occur when atmospheric uplift is sufficient to raise a parcel above the lifting condensation level, but dry lower levels of the atmosphere result in virga. These storms can, however, produce lightning and strong surface winds or outflow.

Rainfall during July, August, and September accounts for over 70% of the annual total precipitation in portions of northwestern Mexico; the percentages decrease to 40-50% in east-central and southern Arizona and much of New Mexico (Douglas et al. 1993). Precipitation maxima occur in July and August and then decrease substantially by October and November (Comrie and Glenn 1998). A secondary wet season occurs during the winter (December through March), when approximately 20% of the annual total precipitation falls (NCDC 2003). The remaining 30-40% of the region's precipitation results from synoptic-scale weather systems in the Westerlies during the spring and from decaying tropical systems after the monsoon and prior to winter.

The height of the fire season in the southwestern United States generally occurs from May to July (Westerling et al. 2003). Following an increase in precipitation during the winter, the wildland fire season typically begins in mid- to late spring as fuel moisture levels drop with lowering atmospheric moisture content. The season peaks in mid-June to early July, due at least in part to lightning strikes from dry thunderstorms (Watson et al. 1994). While conditions several years in advance can influence the incidence of large fires (Roger and Vint 1987, Swetnam and Betancourt 1998, Grissino-Mayer and Swetnam 2001, Crimmins and Comrie 2004), atmospheric and fuel moisture conditions immediately preceding the start of the fire season are also important. The wildland fire climax is followed by a fairly substantial decline in mid- to later summer. Typically, fewer fires occur during the remainder of the year.

Various authors have commented on two wildland fire-monsoon interactions: (1) an early summer peak in wildland fire frequency, followed by a decline after monsoon onset and (2) periodic post-monsoon escalations in fire activity (Swetnam and Betancourt 1990, Swetnam and Betancourt 1998, Grissino-Mayer and Swetnam 2000, Westerling et al. 2003, Crimmins and Comrie 2004). During the monsoon, breaks have the potential to affect wildland fire activity. The impact on fire incidence may depend on the duration and timing (early vs. later in the rainy season) of the break. Mohrle (2003) recently studied the apparent fire season-monsoon link in southeastern Arizona using dewpoint temperature and minimum (i.e., afternoon) relative humidity and suggested a dewpoint threshold for natural fire occurrence. Wildland fire count increases as dewpoint increases until approximately 60°F; 60-63°F appears to be the critical range for decreasing the occurrence of natural fires.

The most obvious impacts of wildland fire are the immediate effects on vegetation, although periodic surface fires do benefit the long-term ecosystem health. Animals may also be displaced by fire occurrence. Societal and economic impacts include concerns of public health and safety, human displacement, structural and property damage, lost income, and fire-fighting expenditures. The hazardous effects of the monsoon include the danger of lightning-ignited fires and potential for flash flooding, but it also supplies atmospheric moisture and precipitation to the region. Atmospheric moisture and precipitation increase fuel moisture, provide critical water for vegetation and animals, regulate groundwater resources (via recharge and decreasing reliance on irrigation), and can bring some relief from the extremely hot and dry summer conditions.

My studies focus on several aspects of the NAMS in southern Arizona from the late 1970s to the early years of the 21st century. I suggest a modified definition of the NAMS, which establishes dates for onset, bursts, breaks, and retreat. I then use the periods delineated by this definition to identify key variations in geopotential height patterns during the pre-, intra-, and post-monsoon periods. Finally, I apply the modified monsoon definition to distinguish the roles of these monsoon periods in controlling variability in wildland fires.

Approach

This dissertation falls under the geographical sub-field of climatology. Climatology involves the study of interactions in the climate system, with different branches specializing in different time and/or space dimensions or processes. These sub-disciplines include applied climatology, climate change and variability, dynamic climatology, physical climatology, regional climatology, and synoptic climatology (Yarnal 1993). The research in this dissertation lies at the blurred junction, or perhaps more appropriately, the overlap, of three sub-disciplines – applied, regional, and synoptic climatology.

Climate scientists have used a wide range of descriptions to define applied climatology and its foci (Hobbs 1997). In its most basic description, the field concentrates on the many interrelationships of climate with the environment and society. More specifically, it "describes, defines, interprets, and explains" how climate and human and natural phenomena interact (Changnon 2004). This dissertation fits into the last level of Changnon's (1995) description of the sub-discipline: employing recorded data to aid in research and decision-making.

Regional climatology divides the world into zones and examines the causes and effects of related climate characteristics and processes within these areas (Moses 1995). The entire dissertation falls under this sub-discipline. In the first section, I relate a meteorological variable (dewpoint temperature) to the process (the monsoon) that produces its variation. The second section examines variations in geopotential height patterns, and the delineation of periods is based on data representative of the region. In the third portion of this dissertation, I analyze the interrelationships between the wildland fire season and the monsoon.

Synoptic climatology, like applied climatology, has received increased attention in the past several decades. While the definitions of this sub-discipline vary on the size of the spatial scale and the length of the temporal scale, synoptic climatologists agree on the overall focus: to examine the relationship between surface environment and atmospheric circulation processes (Barry and Perry 1973, Yarnal 1993, Perry 2000, Barry and Carleton 2001). The second portion of this dissertation is a synoptic climatological analysis. I use the compositing technique described by Yarnal (1993) to determine the average low and mid-level geopotential height patterns associated with pre-monsoon, burst, break, and post-monsoon periods.

Organization of the Dissertation

This dissertation contains three separate but related papers, with each study formatted as a publication-quality paper and included as an appendix. Information from the first paper is the basis for the second and third papers. Each paper includes a summary and review of previous relevant literature.

Appendix A, entitled, "A Modified Definition of the North American Monsoon System for Southern Arizona," was prepared for submission to the *International Journal of Climatology*. Drs. Comrie and Yool provided assistance with the interpretation of the results and were instrumental in condensing the original document into a manuscript format. This paper presents a variation of the public or popular monsoon definition to establish onset and retreat dates, as well as burst and break periods, by using daily dewpoint temperature.

Appendix B, entitled “Climatology of Geopotential Height Variability During the Monsoon in Southern Arizona,” was prepared for submission to the *Journal of Climate*. In this paper, atmospheric composites developed with the North American Regional Reanalysis are used to study the variation of lower and mid-tropospheric constant-pressure surfaces before, during, and after the monsoon as determined with the modified definition. Patterns that promote and restrict moisture advection are described.

Appendix C, entitled, “The North American Monsoon System and Wildland Fire Frequency in Southern Arizona,” was prepared for submission to the *International Journal of Wildland Fire*. The research presented in this paper describes the regional relationship between the monsoon and the occurrence of wildland fire. I consider several aspects of the relationship: the pre-monsoon peak in fires, the decline after onset, the influence of bursts and breaks, and the periodic post-monsoon increase in wildland fire activity.

CHAPTER 2 – PRESENT STUDY

The methods, results, and conclusions of this study are presented in the papers appended to this dissertation. The following is a summary of the most important findings in this document. This research contributes to the current knowledge of the North American Monsoon System (NAMS) in general and to the specific regional impacts of the monsoon. Guided by a revised monsoon definition, the research focuses on the identification of geopotential height patterns conducive to moisture advection and the influence of atmospheric moisture variation on wildland fire frequency in southern Arizona. This analysis aids meteorologists in recognizing specific synoptic and sub-synoptic characteristics, which they can apply to forecasting activities. An improved understanding of the conditions that lead to monsoon onset, retreat, bursts, and breaks, and how these conditions affect wildland fire, can be useful to the planning and control activities of fire managers. Additionally, by disseminating this research in various outlets, stakeholders and the public can gain a greater appreciation of climate-environment interaction.

Appendix A – "A Modified Definition of the North American Monsoon System for Southern Arizona"

This paper presents a modification of the current public or popular definition of the NAMS used the by Tucson National Weather Service (NWS) and local media. We use the mean daily dewpoint temperature recorded at Tucson International Airport from

1961 to 2002 to establish monsoon onset and retreat dates, monsoon days, non-monsoon days, bursts, and breaks using dewpoint thresholds. The first day of the first occurrence of three consecutive days with mean daily dewpoint ≥ 54°F is the annual onset, provided there are no subsequent periods when the daily dewpoint is ≤ 32.6°F. (32.6°F is the mean non-monsoon dewpoint over the entire 32-year period.) The final day of the last occurrence of three consecutive days with mean daily dewpoint ≥ 54°F is the annual retreat, provided there are no preceding periods with a daily dewpoint ≤ 32.6°F. After defining the annual monsoon period, we analyze various seasonal relationships.

We find that the onset dates determined using the modified definition compare favorably with those of the Tucson NWS. A comparison of monsoon retreat dates, available from the NWS for a portion of the study period, shows only a slight variation. This implies that the proposed technique is a useful method of establishing the monsoon period without the need to analyze surface and upper-level pressure patterns. We also determine that, contrary to the conventional wisdom, monsoon duration is more strongly correlated with retreat date than onset date. In addition, there is little correlation between the timing or the duration of bursts or breaks and their mean dewpoint temperatures. The findings in this study are useful to weather forecasting and to understanding wildland fire patterns in the region. We use this modified monsoon definition to analyze geopotential height patterns in the second paper and to determine monsoon-wildland fire relationships in the third paper.

Appendix B – "Climatology of Geopotential Height Variability During the Monsoon in Southern Arizona"

In the second paper, we use the North American Regional Reanalysis (NARR) to investigate geopotential height patterns and their variation during the pre-, intra-, and post-monsoon periods. Most previous research focuses on one phase of the monsoon instead of the entire period and is usually restricted to one or two levels of analysis, e.g., the surface and 500 hPa. This study examines atmospheric composites at the standard pressure levels of 500, 700, 850, 925, and 1000 hPa from 1 June to 31 October over the period 1979-2002 to determine how variations in geopotential height impact moisture advection. During the monsoon, breaks are sub-divided by timing and duration due to their potential influence on wildland fire activity.

Mid-level synoptic-scale composites show a monsoon evolution that is similar to previous research. In particular, the 500-hPa anticyclone is near the Four Corners region around onset and during bursts and farther south with an elongated major (latitudinal) axis during breaks and at retreat. Variation also occurs in the latitude and in the extent of the major axis depending on break timing and duration. At lower geopotential height levels, the NARR shows that variations in isopleth gradient and orientation over the Gulf of California influence low-level moisture advection. In addition, the NARR may be capable of detecting convection along the western coast of Mexico and on the western slopes of the Sierra Madre Occidental in the form of higher geopotential heights in this region. These results will primarily aid forecasting efforts by meteorologists in the northern monsoon region. The potential recognition and prediction of onset, bursts, breaks, and retreat can also prove valuable for fire officials and stakeholders in resource management.

Appendix C – "The North American Monsoon System and Wildland fire Frequency in Southern Arizona"

The third paper is an applied research project that examines a climate-environment relationship in the southwestern U.S. More specifically, daily mean dewpoint data at Tucson International Airport and wildland fire data for Arizona Climate Division 7 (southern Arizona) during the period 1977-2001 are used to examine the effects of monsoon onset, bursts, timing and duration of breaks, and monsoon retreat on wildland fire. The monsoon period and bursts and breaks are defined using the modified definition described in the first paper. Links to fuel moisture are made, although quantitative measurements of this variable are not included.

Results from this study show that, for the study period, the peak in wildland fire occurrence is approximately one week prior to the mean monsoon onset date. On an annual basis, 80 percent of the years have a wildland fire count maximum within three weeks of their respective monsoon onset. Wildland fire occurrence then decreases from this pre-monsoon peak and remains steady from the mid-monsoon until retreat. Break timing and break duration both contribute to increases in fires, but their combination is the most important factor. Early long breaks lead to the greatest intraseasonal rise in wildland fire occurrence. In all break cases that result in a fire increase, there is an initial decline, followed by an upswing at the end of the break or early in the subsequent burst.

On average, there is only a very slight increase in wildland fires after monsoon retreat, and this is only evident on a weekly scale. When individual years show post-monsoon increases, it occurs most often in October and November. The conclusions drawn in this study are useful to regional wildland fire managers in understanding another factor that influences seasonal wildland fire behavior and to meteorologists who develop fire weather forecasts.

Summary

The three papers that constitute this dissertation address several questions on the intraseasonal variability of the NAMS, including its definition, its controls, and its contribution to climate-environment interaction. Although the focus is on southern Arizona, the influence of synoptic and sub-synoptic controls is evident. The results may be applicable to other portions of the northern monsoon region, i.e., those areas affected by the same mechanisms that influence pre-, intra-, and post-monsoon variations in southern Arizona, including the greater southwestern United States and far northwestern Mexico. This research is an example of how understanding the controls that influence a portion of the monsoon region and their interconnectedness with other regions is vital to understanding the entire NAMS phenomenon. The conclusions presented herein are valuable primarily to meteorologists and fire managers. Meteorologists can use this information to recognize atmospheric patterns that contribute to monsoon onset, bursts, breaks, and retreat, which can improve routine forecasts and seasonal products, such as fire weather forecasts. The potential increased quality and accuracy, in turn, can aid fire officials in their preparation and management of wildland fires. The results of this dissertation also contribute to the overall understanding of regional wildland fire controls.

Research Highlights

- The modified monsoon definition compares favorably with the Tucson NWS definition.
- Monsoon duration is more strongly correlated with retreat than with onset.
- The dewpoint temperature shows no consistent pattern and no correlation to the timing or duration of bursts and breaks.
- The latitude and west-east extent of the mid-level subtropical ridge axis varies with break timing and duration.
- The higher spatial and temporal resolution of the NARR reveals new details about the climatological life cycle of the NAMS.
- The Gulf of California long-gulf gradient and orientation of low-level contours are important considerations for determining NAMS onset, transitions between bursts and breaks, and NAMS retreat.
- On average, wildland fires peak approximately one week prior to mean monsoon onset. In 80 percent of individual years, the peak occurs within three weeks of monsoon onset.
- Early long breaks produce the greatest increase in wildland fire occurrence.
- The fire pattern associated with a break tend to have an initial decrease leading up to and early in a break, followed by a relatively low fire count, and then an upswing near the end of the break and at the beginning of the subsequent burst.

- On average, there is only a slight post-monsoon increase in wildland fires.
- Post-monsoon fire increases during individual years occur most frequently in October or November and are typically associated with a break followed by a brief burst at the end of the monsoon.

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APPENDIX A

A MODIFIED DEFINITION OF THE NORTH AMERICAN MONSOON SYSTEM FOR SOUTHERN ARIZONA

Richard R. Brandt

To be submitted to the *International Journal of Climatology*

Abstract

Summer rainfall associated with the North American Monsoon System provides nearly half the annual total precipitation in southeastern Arizona. While the monsoon involves a shift in the air flow patterns due to changes in the strength and location of semi-permanent pressure cells, the onset is generally defined using threshold of average daily dewpoint temperature (T_d). The Tucson National Weather Service (NWS) sets a season, which includes a cut-off of September 30, for calculating rainfall during this wet period. This technique is fairly user-friendly in terms of comparing monsoon rainfall amounts, but the significant moisture advection can persist into October past the NWS end date, thereby making monsoonal precipitation totals inaccurate. This study introduces a modified version of the "popular" or "public" definition of the monsoon, using T_d to determine onset and retreat dates, as well as intervening burst and break periods. Onset dates using the modified definition compare favorably with the Tucson NWS onset dates. The study also finds that (1) monsoon duration is more strongly correlated with retreat date than onset date; (2) monsoon days, or days when the T_d is 54°F, typically dominate the wet season; and (3) there is no correlation between the average T_d during bursts (or breaks) and their timing or duration. The modified definition will be used in future research to study monsoon period geopotential heights patterns and variations and wildland fire-monsoon relationships.

Introduction

The summer circulation pattern of the North American Monsoon System provides a major portion of the annual precipitation in northwestern Mexico and the southwestern United States, particularly Arizona and New Mexico, during July, August, and September. Summer rainfall accounts for over 70% of the annual total precipitation in portions of Mexico; the percentages decrease to 40-50% in southern Arizona and much of New Mexico (Douglas et al. 1993). Precipitation maxima occur in July and August and then decrease substantially during October and November, which is a climatologically dry period between the monsoon and the winter wet season (Comrie and Glenn 1998).

Although the monsoon involves a shift in the thermal wind (Maddox 2003), several conditions have been used to define its initiation. Various atmospheric moisture variables, e.g., dewpoint temperature, mixing ratio, equivalent potential temperature (θ_e), and precipitable water, from surface and upper-air instruments and satellites can be used to establish the onset. An increase in dewpoint temperature to or above a threshold is the most common practice, especially when informing the public. The Tucson and Phoenix National Weather Service (NWS) offices, and subsequently many television stations, define onset as the first of three or more consecutive days with a mean daily dewpoint ≥ 54°F and 55°F, respectively. Ellis et al. (2004) used two criteria to develop monsoon onset and retreat dates: (1) a regional mean $T_d \geq 50$°F for three consecutive days using measurements at Flagstaff, Phoenix, and Tucson in Arizona, Albuquerque, New Mexico, and El Paso, Texas, the five first-order observing sites in their monsoon region and (2) a regional precipitation threshold in which ≤ 20% of 193 stations in the Southwest record measurable rainfall.

Mitchell (1976) and Watson et al. (1994) demonstrated the utility of θ_e to separate air masses and describe the monsoon "boundary," respectively. Researchers have also employed lightning data, which has become available in the past 15-20 years from the Bureau of Land Management, for North American monsoon studies (Watson et al 1994, Maddox 2003). The type of variable will affect the estimated date of monsoon onset.

Periodic surges of maritime tropical (mT) air from the Gulf of California or bursts are well documented in meteorological and climatological literature (e.g., Brenner 1974, Carleton, 1986, Douglas 1995, Stensrud et al 1997, Kanamitsu and Mo 2003). Surges are associated with south-north pressure gradients across the Gulf of California region, favorable pressure distribution, e.g., upper-level high pressure in the Four Corners and a thermal low in southeastern lower Colorado River valley, high sea surface temperatures in the Gulf of California, and tropical storms or mesoscale convective systems in the east-central Pacific Ocean or southern Gulf of California (Adams and Comrie 1997).

Interludes between surges when moisture advection weakens and precipitation is non-existent or isolated are known as breaks. Few, if any, publications focus solely on the breaks, most likely because surges can result in precipitation and severe weather if other atmospheric variables are favorable. Understanding the conditions and their variation that support bursts and breaks is important for meteorological and hydrological forecasting, agriculture, and public safety. Since both conditions also influence fire activity (Brandt, Comrie, and Yool, in preparation), obtaining a climatology of intra-seasonal monsoon bursts and breaks is of interest to wildland fire researchers in the southwestern United States.

Bursts and breaks are composed of a series of monsoon days and non-monsoon days, respectively. “Monsoon day” refers to a day in which an established criterion, such as a mean dewpoint temperature value, is attained between onset and retreat. A “non-monsoon day” is a day when the criterion is not reached. Bursts, breaks, and monsoon and non-monsoon days can be determined by analyzing records of atmospheric moisture.

This study uses statistical analyses of dewpoint temperature to delineate monsoon onset, bursts, breaks, and retreat. The ultimate goals of this research are to determine the intraseasonal and interannual variations in, and associated characteristics of, monsoon onset, burst, break, and retreat and to establish a climatology for subsequent studies. Later investigations will include geopotential height analysis using the National Centers for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR; Mesinger et al. 2006) and wildland fire-monsoon interaction.

Data and Methods

Study Area

This study focuses on Arizona Climate Division 7 (AZCD 7), which includes much of southern Arizona (Fig. 1). Western AZCD 7 is mainly low desert interspersed with low mountain ranges, while the eastern portion consists of more numerous south-southeast-to-north-northwest oriented mountain ranges. Elevations vary from approximately 200 meters above mean sea level (msl) in the desert valleys of the west to around 3000 meters msl in the eastern mountains.

Climate Data

Dewpoint temperature (T_d) and relative humidity at Tucson International Airport were available from the National Climatic Data Center (NCDC). When the T_d was missing, it was calculated from the air temperature and relative humidity measurements using:

$$T_d = (T-(14.55+0.114*T)*(1-(0.01*RH))-((2.5+0.007*T)*(1-(0.01*RH)))^{3}-(15.9+0.117*T)*(1-(0.01*RH))^{14}) \qquad (1)$$

where T is air temperature in degrees Celsius and RH is relative humidity (Parry 1969). When tested in cases where T_d values were known, the results of the formula were consistently within 0.3°F of the measured value.

Air temperature and dewpoint temperature, when available, were supplied in degrees Celsius. Dewpoint temperature was converted to degrees Fahrenheit using the standard formula:

$$T_F = 1.8*T_C+32 \qquad (2)$$

Mean daily T_d was calculated by averaging the hourly values over 24 hours. Suspicious values, such as large T_d increases or decreases over a short period and anomalously high or low values, were not included in the calculation. Days with mean T_d less than 0°F were retained, as such low values, though unusual, can occur. Periods of ten days or more with negative values are considered erroneous (Tucson NWS 2005). The longest period with negative readings from 1961-2002 was 5 days. Only seven days had missing T_d values.

The mean daily T_d determines monsoon onset and retreat dates, monsoon and non-monsoon days, and break and burst periods. We propose and use a new method to determine the annual monsoon onset and retreat dates, which also aims to eliminate confusion about the cause of high T_d's (mid-latitude or tropical cyclones or the monsoon circulation) near the retreat. The mean T_d is calculated for each day of the year from 1961-2002. These values are used to establish the average monsoon onset and retreat dates using the Tucson NWS definition, i.e., the first of three or more consecutive days with daily T_d that are at least 54°F. (Values of 53.5°F or higher are rounded to 54°F.) The mean T_d for the remaining non-monsoon period days is then calculated (32.6°F). To determine the onset date for each year from 1961-2002, we find the first occurrence during June or July with a mean daily $T_d \geq 54°F$ for at least three consecutive days. If two or more subsequent days have average daily $T_d \leq 32.6°F$, then the next sequence of three or more days with daily $T_d \geq 54°F$ establishes the onset date. If there are no subsequent days when the mean daily T_d is $\leq 32.6°F$, then the first day of that period is the monsoon onset date.

For the retreat date, we determine the final day of the last occurrence during August, September, or October when the mean daily $T_d \geq 54°F$ for at least three consecutive days. If there are at least two prior days when the mean $T_d \leq 32.6°F$, then we locate the previous occurrence of mean daily $T_d \geq 54°F$ for three or more days. It is set as the retreat date of the monsoon if there are no days when the mean daily $T_d \leq 32.6°F$ prior to this period. Later periods when the T_d reached or exceeded 54°F are assumed to result from a mid-latitude or tropical cyclone or other non-monsoonal circulation. The large-scale circulation should otherwise be conducive to the advection of sufficient moisture to keep T_d above 32.6°F. We recognize the possibility of non-monsoonal circulations prolonging the established retreat date.

Non-monsoon days (NMD) occur when the mean $T_d < 54°F$ between monsoon onset and retreat. Breaks are two or more consecutive NMDs. A monsoon day (MD) is a day when the mean $T_d \geq 54°F$ from monsoon onset to retreat. Bursts refer two or more consecutive MDs. Both onset and retreat are therefore considered bursts. Bursts occur after a break and continue until the next break. A single day when the T_d is $\geq$ 54°F is classified as part of a break if it is embedded in a period of NMDs. Likewise, a single day when the T_d is < 54°F is classified as part of a burst if it is embedded in a period of MDs. The definition varies slightly from other studies that may label a burst as a period in which the T_d exceeds a pre-determined value or when the T_d increases substantially over a short period.

To eliminate the slight skewing during leap years with standard Julian days, we label days from 1 June (day 1) through 31 October (day 153). The onset and retreat of the monsoon falls within this period for each year of the study.

Results and Discussion

The moisture variables from Tucson, the only first-order recording station in AZCD 7, are considered representative of region-wide conditions, although this assumption can lead to potential problems. Even with a standard T_d lapse rate of 1.0°F per 1000 feet, values could vary by up to 7-8°F over the region. In addition, the T_d and RH values can vary throughout a region during the monsoon due to other factors, such as varying wind direction and pooling of moisture in favored areas.

The mean monthly T_d is calculated by determining the 42-year mean for each day, and then averaging those values for each month. The pattern for the average T_d for the period indicates fairly low values for much of the year, except for mid- to late summer

(Figure 2). From January through May, the T_d remains steady near 30°F before significant increases occur, including a rise of 18.9°F from June to July. The maximum monthly T_d occurs in August (58.7°F) before values decrease into the 30's by October. The lowest average monthly T_d occurs in April (27.2°F).

Figure 3 shows mean daily T_d for July through September. The line for 54°F is supplied, because it is the value used to establish the monsoon onset, retreat, bursts, and breaks. There is a general downward trend through March with slight increases in last April, indicating that the lowest T_d occurs in April, and continuing through May (not shown). There is a steep upward trend through June and early July as the shifting atmospheric circulation advects more moisture into to the area. The first period of three consecutive days with mean daily $T_d \geq 54$°F is 8-10 July; therefore, the mean monsoon onset using this method is 8 July. The T_d remains above 54°F for the remainder of July and during the entire month of August. The maximum average daily T_d occurs on 10 August (61.3°F), before T_d decreases. This downward trend continues through December (not shown). 13 September is the mean retreat of the monsoon in AZCD 7 using this method.

The annual onset date varies by as much as 38 days. The earliest onset occurs on 17 June 2000, while the latest is 25 July 1987. The mean, median, and mode of the onset date are 3 July. The standard deviation is 7.55 days. The retreat dates show more variation, with a range of 65 days. The earliest retreat date is 17 August 1979, and the latest is 21 October 2000. The mean retreat date is 22 September, with a median of 23 September and mode of 28 September. The standard deviation is 14.14 days. The greater standard deviation of the retreat dates compared to the standard deviation of the onset dates agrees with Ellis et al (2004), although the absolute values vary. Monsoon duration varies by up to 94 days with a minimum of 33 days in 1979 and a maximum of 127 days in 2000. The mean duration is 82 days, with a median and mode of 80 days. The standard deviation is 18.04 days.

Onset dates since 1949 in Tucson are available from the Tucson NWS (2006), and retreat dates and duration from 1965-1995 are supplied in Glueck (1997). In the late 1990s, after the publication of Glueck (1997), the Tucson NWS established a monsoon period (15 June-30 September), in part to aid year-to-year comparison of seasonal precipitation (Glueck 2005). Onset dates using the new technique compare the favorably with those using the Tucson NWS definition. The only significant discrepancies are in 1972 and 1978 when the T_d dropped below 32.6°F after the NWS-established onset. Retreat date and duration show more variation, but 20 of 32 years in the modified definition are within ±5 days of the Tucson NWS values. Since the NWS based its designation of the retreat on daily weather patterns (Ellis et al 2004), the technique of averaging dewpoints to determine onset and retreat and the assumption related to atmospheric circulation described above appears valid.

With approximately 40-50% of the total annual precipitation falling from July through September in AZCD 7, the monsoon rains are an important source of water for communities and farming. A longer monsoon duration suggests a prolonged period of higher precipitation probabilities. In fact, Ellis et al. (2004) showed that, on average, wet seasons are nearly twice as long as dry seasons. Understanding how onset and retreat relate to monsoon duration can therefore be useful to water and fire managers and agriculture.

The general consensus is that an early onset translates into a longer duration. The data is study show that a strong negative correlation (-0.670) exists between monsoon onset and duration, so an early onset date is typically indicative of long monsoon duration, while a late onset usually signifies a short duration (Figure 4a). The coefficient of determination (R^2) is 0.449 (statistically significant at the 1% level). The correlation between retreat and duration is even stronger (0.918), with an R^2 of 0.843. This result means that years with an early retreat correlate with a short monsoon duration, and late retreat correspond to a longer duration (Figure 4b). Given the percent variance explained, retreat is more important to monsoon duration than onset, contrary to the prevailing notion. A negative correlation exists between onset and retreat, but it is not statistically significant.

It is important to analyze the MDs, NMDs, bursts, and breaks during each season, as they directly relate, by definition, to the amount of moisture in the atmosphere and thus to the formation of storms and precipitation. MDs account for the majority of days over the duration of the monsoon both for the entire period and for all individual years. The mean number of MDs per season is 62 over a mean season duration of 82 days (75.6%), which is comparable the value reported by Ellis et al. (2004). The number of MDs varies from 28 days in 1979 to 84 days in 1983 and 1999, while the season duration ranges from 33 days in 1979 to 127 days in 2000. The minima and maxima of MDs and season duration therefore do not necessarily coincide. The percentage of MDs ranges from a minimum of 55.3% (52 of 94 days) in 1962 to a maximum of 95.8% (68 of 71 days) in 1969.

The number and duration of breaks and bursts, as well as T_d during these episodes, are also important from precipitation, lightning, and fire perspectives. More and/or longer bursts imply more days when atmospheric moisture content is higher and precipitation chances are greater. More precipitation suggests higher fuel moisture and lower likelihood of (large) lightning- or human-caused wildland fires. The total number of breaks per season ranges from 1 to 8 with a mean and mode of 3 with a standard deviation of 1.67 (Table 1). For the period of study, break duration ranges from 2 to 9 days with a mean of 5 days and a standard deviation of 1.79. Breaks in individual years persist from 2 to 17 days. There is only a weak positive correlation between the total number of breaks and mean duration (0.175).

An average monsoon consists of approximately 4 bursts (standard deviation = 1.67). The mean burst length is 16.8 days with a standard deviation of 7.05 days and a range of 27. In individual years, burst lengths range from 2 to 71 days (Table 1). From 1961-2002, the correlation and explained variance between number of bursts and duration are -0.761 and 0.578, respectively. Burst duration is therefore important to burst count, which makes good intuitive sense, since longer bursts allow for fewer total bursts.

Mean MD and NMD T_d's for the period are 60.5°F and 47.6°F, respectively. The NMD mean indicates the relative dryness that can occur during the monsoon, although this value is significantly higher than the average T_d outside the monsoon period (32.6°F). Mean seasonal difference between MD and NMD T_d ranges from 10.1°F in 1981 to 16.4°F in 1987. This difference hints at the mean strength of moisture advection during the monsoon. A low mean MD-NMD difference corresponds to weaker mean moisture advection on MD, while a high mean difference signifies stronger mean moisture advection on MD.

Mean seasonal burst and break T_d's are comparable with the MD and NMD values. Bursts average 60.4°F, while breaks average 47.4°F (Table 1). The proximity indicates that the technique used to assign burst and break periods does not adversely affect the T_d analysis despite some MDs being included in breaks and some NMDs included within bursts.

There is no apparent pattern in the mean T_d during bursts or breaks. For the study period, a weak negative correlation exists between burst timing and mean T_d, while a weak positive correlation exists between break timing and mean T_d. Bursts or breaks occurring early in the monsoon therefore have neither a higher nor lower mean T_d than later bursts or breaks. There also is no consistent pattern between the burst or break duration and mean T_d. A weak negative correlation exists between duration and mean burst T_d. Breaks show a weak positive correlation between duration and mean T_d. In both instances (timing of bursts or breaks vs. mean T_d and duration of bursts or breaks vs. mean T_d), individual seasons have high correlations. The reason for this relationship is uncertain, but it may be related to teleconnection patterns and variations.

Conclusions and Recommendations

This study presents a new technique to define the monsoon utilizing T_d that considers atmospheric circulation but eliminates the need to analyze pressure patterns. The monsoon onset from 1961-2002 and retreat and duration from 1965-1995 determined with this method compare favorably with those established by the Tucson NWS.

Monsoon onset and retreat dates and duration show much variation over the study period. The earliest and latest onset dates vary by 38 days, while the extremes of the retreat dates vary by 65 days. The mean onset date is 3 July, and the mean retreat is 22 September. The Tucson NWS mean onset and retreat dates are 3 July and 30 September, respectively, the latter of which is fixed. The mean retreat date during the 1965-1995 period when the Tucson NWS determined retreat dates (Glueck 1997) was September 16. Monsoon duration varies by up to 94 days with a mean length of 82 days. Additionally, while onset and retreat dates are have strong correlations with the monsoon duration, the retreat date has a greater influence on monsoon duration than does the starting date.

NMDs, MDs, breaks, and bursts are also show significant variation. MDs dominate the monsoon period both on average and for all individual years, which agrees with previous research. Mean burst duration is over three times greater than mean break duration.

No apparent pattern of mean T_d exists during either breaks or bursts. Breaks that occur early in the monsoon have neither higher nor lower mean T_d's than later breaks; the same is true for bursts. There also is no consistent pattern or significant correlation between the duration of bursts or breaks and respective mean T_d's.

Determining and forecasting the onset, retreat, and duration of the monsoon, as well as burst and break occurrence and duration, has important implications for understanding weather and regional wildland fire patterns. Future research will use the climatology developed in this paper and the NCEP NARR (Mesinger et al. 2006) to determine mean atmospheric patterns associated with these phenomena. The climatology will also be useful to study monsoon-wildland fire relationships.

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	Burst	Break
Mean count	4	3
Mean duration (days)	17	5
Maximum length (days)	72	17
Mean dewpoint (°F)	60.4	47.4

Table 1. Climatological statistics for bursts and breaks from 1961-2002. The mean count is the mathematical average over the period. Mean duration and maximum length are given in days. Mean dewpoint is in degrees Fahrenheit.

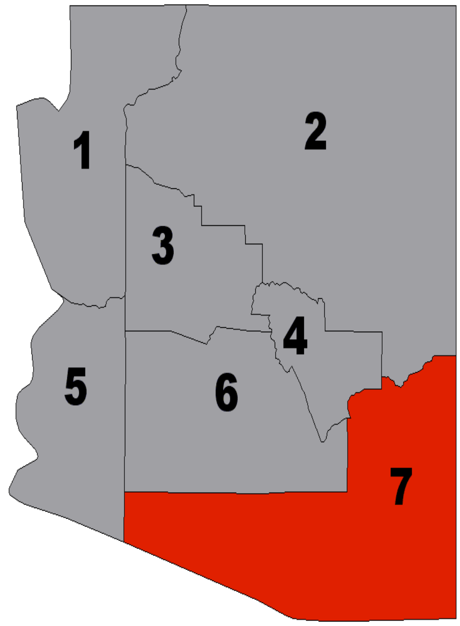


Figure 1. Climate divisions in Arizona. Climate division 7, highlighted in red, is the study area.

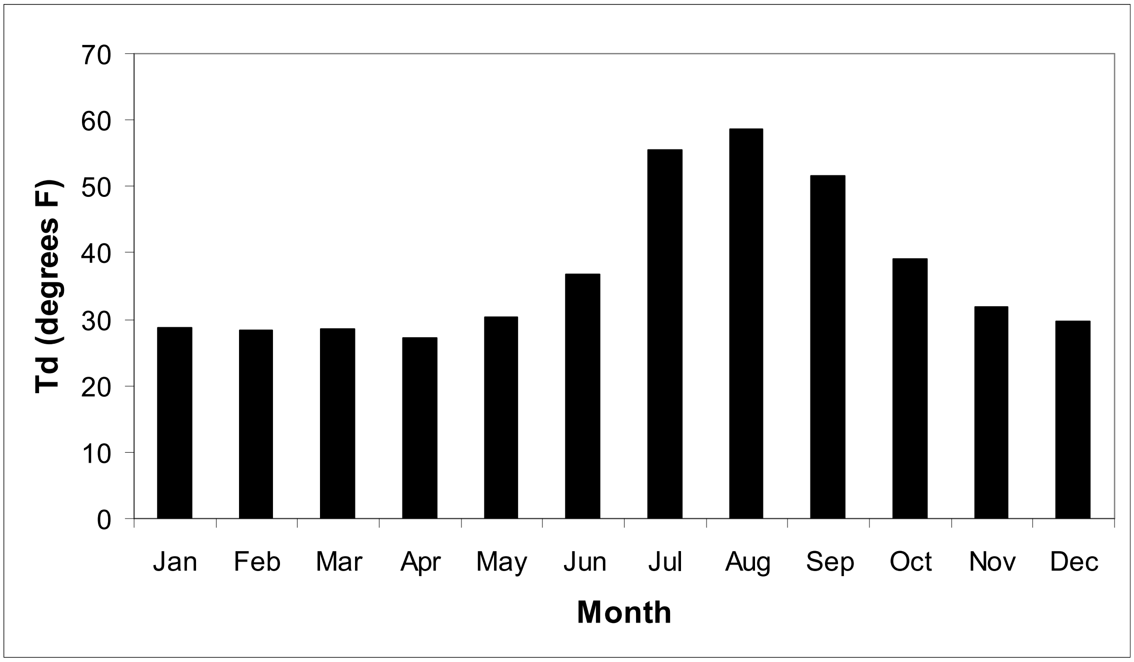


Figure 2. Mean monthly dewpoint temperature in degrees Fahrenheit at Tucson for January-December from 1961-2002. The higher dewpoints during July, August, and September indicate the mean monsoon period.

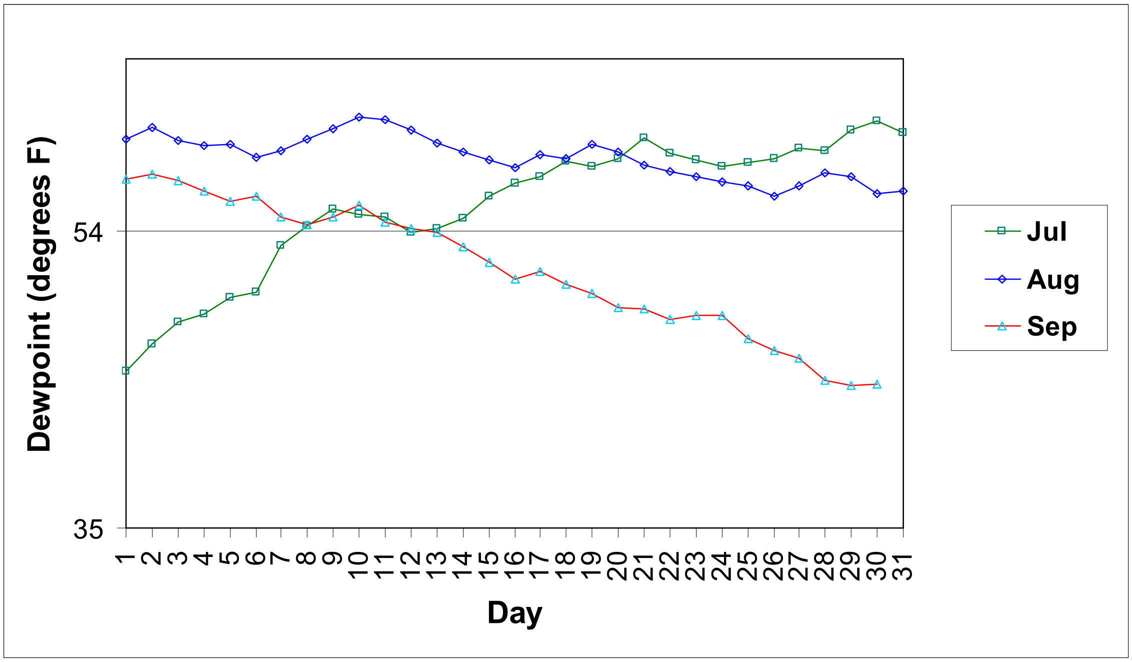
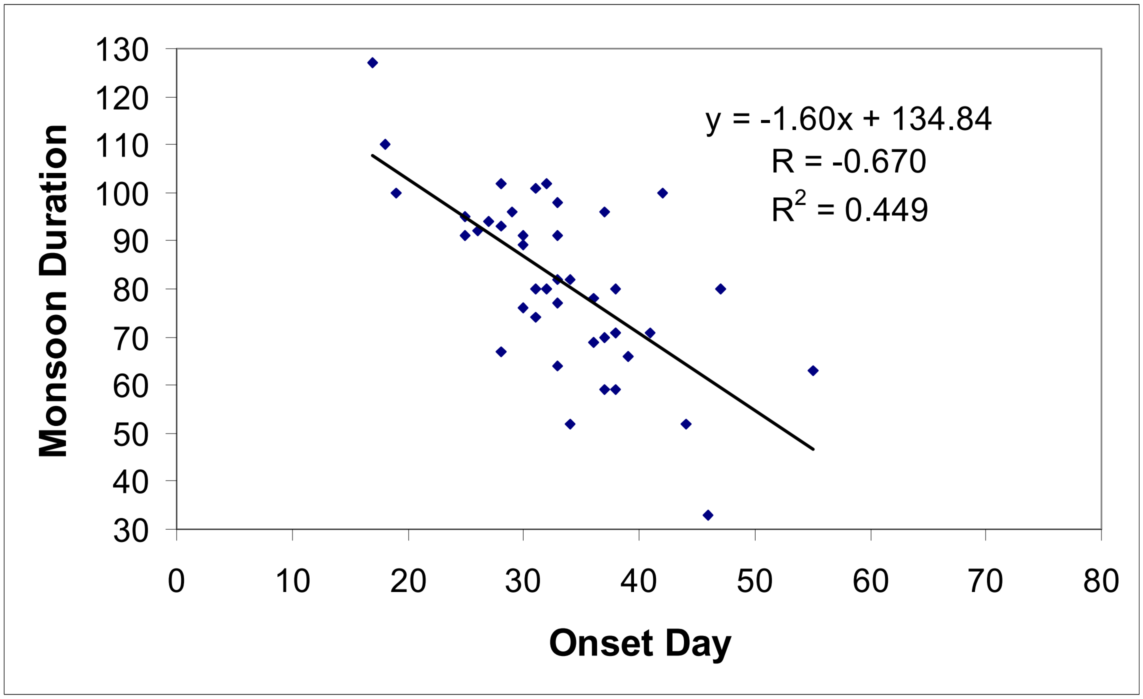


Figure 3. Mean daily dewpoint temperature at Tucson in degrees Fahrenheit for July-September from 1961-2002. The line for 54°F indicates the threshold for monsoon onset and retreat. The mean monsoon onset and retreat for the period are 8 July and 13 September, respectively.

(a)



(b)

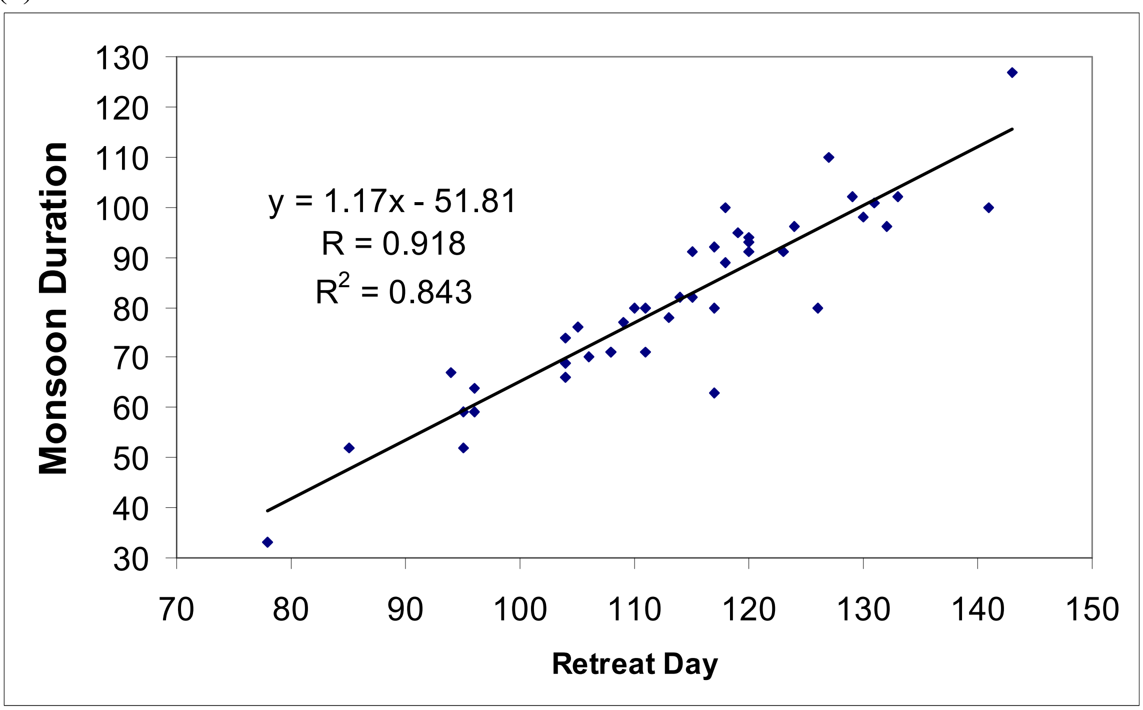


Figure 4. Monsoon duration as a function of (a) onset day and (b) retreat day. Correlation and explained variance are also given.

APPENDIX B

CLIMATOLOGY OF GEOPOTENTIAL HEIGHT VARIABILITY DURING THE MONSOON IN SOUTHERN ARIZONA

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Abstract

The North American Monsoon System (NAMS) is a major component of the climate and ecosystems of the southwestern United States. Atmospheric pressure patterns affect the timing and strength of moisture advection into the region. During the wet phase of the monsoon period, bursts and breaks occur as circulation patterns vary. Understanding the atmospheric flow during these phenomena is important to explaining their impacts. We follow the modified definition reported by Brandt (submitted) to determine annual monsoon onset and retreat, as well as burst and break periods. Composite analyses of the low and mid-level atmospheric patterns from 1979-2002 are developed using the North American Regional Reanalysis (NARR) to examine the nature and variation of geopotential height patterns and atmospheric flow during the monsoon.

Synoptic-scale NARR composites show the mid-level ridge following a morphology during the pre-, intra-, and post-monsoon periods that is similar to previous research. During onset and bursts, the ridge is in a more northerly position with a southeast to northwest oriented axis. The ridge shifts farther south with an elongated latitudinal axis during breaks. The same orientation occurs at the end of and after the monsoon. This study shows that the latitude and the extent of the major axis vary with break timing and duration. The high resolution of the NARR reveals the variation in the gradient and orientation of the 850-, 925-, and 1000-hPa geopotential height contours over the Gulf of California (GoC) that influence low-level moisture advection. The magnitude of the moisture advection depends upon both the strength of the long-gulf gradient and the orientation of the geopotential height contours relative to the GoC axis.

Introduction

The North American Monsoon System (NAMS) supplies much of the annual precipitation in northwestern Mexico and the southwestern United States, particularly Arizona and New Mexico. The monsoon involves a seasonal shift in atmospheric pressure patterns. Although researchers recognize the monsoon as a shift in atmospheric circulation, they have defined its initiation using numerous variables, including equivalent potential temperature (Mitchell 1976, Watson et al. 1994), lightning data (Watson et al. 1994, Maddox 2003), precipitation (Tenharkel 1980, Okabe 1995), and a combination of elements (Ellis et al. 2003, Douglas et al. 1993). Dewpoint temperature thresholds are the most common practice, especially when informing the public.

The wet phase of the monsoon contains periodic advection of moisture interspersed with relatively drier episodes known respectively as bursts and breaks. During a burst, a southerly or southeasterly airflow pushes a surge of maritime tropical (mT) air northward from the Gulf of California (GoC). These are well documented in meteorological and climatological literature (Brenner 1974, Carleton, 1986, Watson et al 1994, Douglas 1995, Stensrud et al 1997, Kanamitsu and Mo 2003). These surges are associated with numerous features and patterns, including a south-north pressure gradient across the GoC region, favorable pressure distribution (e.g., high pressure in the Four Corners), tropical storms in the east-central Pacific Ocean (Adams and Comrie 1997).

Breaks are the interludes between surges, in which there is a reduction in moisture, and precipitation is non-existent or isolated. Understanding the conditions, as well as the variation in conditions, that support bursts and breaks is important for meteorological and hydrological forecasting and agriculture. Forecasts can be improved if meteorologists are able to recognize the development of factors leading to a burst or break. Agricultural interests lie in the use or conservation of irrigation water sources. Since bursts and breaks also can affect fire activity, depending on their timing (early vs. later in the rainy season), duration, and frequency (Brandt et al. submitted), obtaining a climatology of monsoon bursts and breaks is of interest to wildfire researchers in the southwestern United States.

The factors that influence atmospheric moisture must be studied to explain the causes of the bursts and breaks. Surface and upper-air data, especially pressure and geopotential height analyses and composites, are therefore valuable tools. Previous NAMS studies incorporate some consideration of these data in their consideration of bursts and breaks. Some of this research uses upper-level data in conjunction with satellite imagery. Satellites have been shown to be useful in tracking surges initiated by an easterly wave (Brenner 1974). In addition, total cloud cover change over a few days is related to bursts and breaks (Carleton 1985). A modeling study supported by satellite imagery successfully predicted the timing and general location of convection over the GoC that was instrumental in initiating a surge (Stensrud et al. 1997).

In the past ten years, reanalysis data have become available to the scientific community (Kalnay et al. 1996, Kistler et al. 2001, Kanamitsu et al. 2002). Monsoon research using these databases covers a wide range of foci. Some of these studies mainly consider the monsoon *en bloc*. Sea surface temperatures (SSTs) in the tropical Pacific Ocean affect the latitudinal position of the monsoon ridge, while North Pacific SSTs regulate the longitudinal location (Castro et al. 2001). Specific humidity composites for periods near monsoon onset and retreat indicate the advance and retreat of regional moisture (Ellis et al. 2004). In additions, the 500-hPa monsoon ridge is typically farther north in May and October with an early onset and a late retreat (Ellis et al. 2004).

Other research addresses, at least in part, the use of reanalysis data to study bursts and possible causes. A strong correlation exists between the passages of tropical easterly wave troughs over western Mexico and bursts (Fuller and Stensrud 2000). These authors also suggest a relationship between westerly waves and the strength of bursts. Self-organizing maps have led to the development of principle climate patterns that represent pre-monsoon, onset, burst, break, retreat, and post-monsoon conditions (Cavazos et al. 2002). Recent research has also demonstrated the influence of the Madden-Julian Oscillation on bursts through its impact on easterly waves and tropical cyclones (Lorenz and Hartmann 2006).

More recently, the North American Regional Reanalysis (NARR) has become available. The database covers a smaller region with higher spatial and temporal resolution and provides a much-improved representation of atmospheric pressure patterns and flow in the troposphere (Mesinger et al. 2006). The NARR is therefore a sound choice to study circulation patterns associated with the NAMS. Only two published studies to our knowledge have used the NARR to investigate monsoonal moisture advection. While the NARR does show the evolution of the monsoon well, it overestimates the magnitude of the GoC low-level jet and the associated moisture advection (Mo et al. 2005). Additionally, bursts induced by tropical storms and hurricanes are typically stronger with deeper low-level southerly flow and tropical moisture (Higgins and Shi 2005).

Previous studies are restricted mainly to the mid-level monsoon patterns and typically focused on only one phase of the period, such as onset, bursts, breaks, or retreat. The former may be due in part to Carleton's (1986) argument that synoptic-scale changes in the mid- to upper troposphere, rather than near the surface, are more crucial to characterizing bursts and breaks. Early research attributed low-level temperature and pressure gradients to bursts, describing upper-air circulation patterns as "causative factors" that initiate bursts (Brenner 1974). Many others have looked in detail at the structure of the GoC low-level jet (e.g., Douglas 1995, Anderson et al. 2001). Only a few researchers have reported on the synoptic patterns at multiple levels (Higgins and Shi 2005). Of these studies, Douglas and Leal (2003) focus only on bursts, relating them to eastern Pacific tropical storms, while Xu et al. (2004) describe monsoon onset with respect to geopotential heights, zonal winds, rainfall, and skin temperature.

This study examines NAMS variability by considering the entire duration of the monsoon, from one week before onset to one week after retreat, using composite maps generated with NARR to analyze geopotential height patterns. During the monsoon period, we analyze both bursts and breaks, with special attention given toward timing and duration of breaks due to their role in fire (Brandt et al. submitted). We anticipate that the higher spatial and temporal resolutions of the NARR will provide a more detailed view of the variation in geopotential height patterns before, during, and after the monsoon. In addition to demonstrating further advantages of the NARR, this information will be valuable for operational purposes, such as forecasting monsoon onset and retreat and bursts and breaks and understanding temporal wildland fire patterns in southern Arizona.

Data and Methods

Study Area

This study focuses on two regions. The first region is synoptic in scale and includes much of North America and adjacent portions of the Atlantic and Pacific oceans (Figure 1). It is bounded by 20°-60°N, 50°-150°W. The second region is sub-synoptic; it includes the southwestern United States, northwestern Mexico, and the adjacent area of the Pacific Ocean (Figure 2). It is bounded by 18°-38°N, 100°-120°W.

Climate Data

Hourly and daily dewpoint temperature data recorded at Tucson International Airport (TUS) from 1961 through 2002 and obtained from the National Climatic Data Center are the basis for determining the monsoon period. We follow a modified definition of the NAMS for southern Arizona (Brandt, submitted), which provides dates for annual onset and retreat, as well as burst and break periods. We consider the dewpoint recorded at TUS, the only first-order reporting station in southern Arizona, as representative of moisture conditions in the region.

Breaks are sub-divided by timing – early or late – and by duration – short or long. "Early" and "late" refer to the first half of the monsoon and second half of the monsoon, respectively. “Short” refers to breaks with durations of 6 days or less, roughly the synoptic meteorological period, while “long” refers to breaks greater than one week in length. Using these qualitative descriptions, four combinations of breaks exist in this study – early short, early long, late short, and late long.

We identify 70 breaks during the period analyzed (Table 1). In terms of timing, the majority (40) of the breaks are late, likely related to the gradual weakening of the circulation patterns and gradients (e.g., air temperature, GoC SSTs) in the region (Higgins et al. 1997, Cavazos et al. 2002). Short breaks account for the most breaks by duration (50). The reason for this is unclear. It follows then that late short breaks (27) have the highest count of the four sub-divisions.

Geopotential Heights

Atmospheric composites for the standard levels of 500, 700, 850, 925, and 1000 hPa are developed using the North American Regional Reanalysis (NARR; Mesinger et 2006), which is available from the NOAA-CIRES Climate Diagnostics Center (CDC) at http://www.cdc.noaa.gov/cdc/data.narr.html. The NARR covers North America and adjacent portions of the Atlantic, Pacific, and Arctic oceans with 32-kilometer resolution at the lowest latitudes. The analyses are available every 3 hours from 1 January 1979 through 31 December 2004 and are continuously updated. Daily plots are averages of the 3-hourly data. We focus only on the period from 1979 through 2002, as this is the common period between the data sets.

We use the daily NARR composites to analyze mean geopotential heights before, during, and after the monsoon. For the period before the monsoon, or the pre-monsoon, we examine composites for the week and the day prior to onset. The monsoon period itself consists of composites for onset day, the first day of all bursts, the last day of all bursts, the first day of all breaks, the sub-divisions of breaks including all early breaks, the last day of all breaks, and the last day of the monsoon. The period after the monsoon, or the post-monsoon, includes composites of the day after monsoon retreat and the week after the retreat date. We focus only on the standard levels from 500 hPa to 1000 hPa, as these levels are most important in low- and mid-level moisture advection during the monsoon. We do not analyze the wind fields over the GoC, because the NARR overestimates the meridional wind at multiple levels, including the GoC low-level jet (Mo et al. 2005).

Results and Discussion

Mid-Atmospheric Levels

During the week prior to monsoon onset, a 5900-m anticyclone is located over much of the southwestern U.S. and northwestern Mexico (Figure 3a). Circulation around the high is from the southwest, which is a dry pattern for southern Arizona. The remainder of the U.S. is dominated by nearly zonal flow, with a shallow trough along the West Coast. On the day prior to onset, the 500-hPa subtropical high strengthens and is centered slightly farther north in New Mexico (Figure 3b). The 5900-m contour expands mainly in the longitudinal direction, with some northward expansion into the central U.S.

The 500-hPa composite for monsoon onset day indicates a farther northward shift of the center of subtropical high into north-central New Mexico, near the Four Corner region, which is very similar in location and strength to the pattern shown by Cavazos et al. (2002). The ridge also expands farther to the east (Figure 3c). Furthermore, the major axis is oriented in a more southeast to northwest direction, allowing for mid-level moisture advection from the Gulf of Mexico.

One week prior to onset, a similar pattern occurs at 700 hPa, except the highest heights associated with the anticyclone are near Florida (Fig. 4a). The trough along the West Coast appears deeper, extending to southern California and continuing the dry southwest flow pattern typical of pre-monsoon conditions. By the day prior to onset, the 700 hPa heights increase further, especially from the Texas Gulf Coast into southern and eastern New Mexico (Figure 4b). The flow at the level, therefore, is more easterly, allowing for more Gulf of Mexico moisture advection into the northern NAMS region. The 700-hPa ridge continues to expand westward into eastern Arizona through monsoon onset, which results in increasing heights in the region (Figure 4c).

The 500-hPa height pattern for the first day of bursts shows a weaker and smaller ridge axis compared to the pattern for the onset (not shown). Additionally, this ridge is centered farther east – over eastern New Mexico – with a more southeast to northwest orientation. When the onset date excluded from the composite, the ridge axis is even smaller, is centered slightly farther south, and has a sharper southeast to northwest orientation (not shown). On the last day of bursts, the axis of the 500-hPa ridge is considerably farther south (centered over southern Texas) and has a significantly longer latitudinal (major) axis than longitudinal (minor) axis (not shown). The trough along the West Coast is less noticeable, and zonal flow dominates much of the area outside the monsoon region. On the first day of breaks, the subtropical ridge axis remains in a west-to-east orientation with zonal flow across the entire U.S. (not shown). The ridge is considerably weaker, as the 5900-m height contour is broken into two lobes over north-central Mexico and the north-central Gulf of Mexico.

The ridge at 700 hPa is more defined during on the first day of bursts as well, with a closed height contour of 3195 m centered over Texas (not shown). While the axis of the West Coast trough is in a similar location to the onset dates, it is slightly broader, so any disturbances rotating around the base of the trough may have a greater chance of impacting the northern periphery of the monsoon region. Zonal flow dominates the country at 700 hPa on the last day of bursts, as the subtropical ridge has expanded westward, and the axis is at a more southerly position (not shown). In the Southwest, the circulation shows a drier southwesterly pattern. On the first day of breaks, the 700-hPa composite pattern shows little change compared to the last days of bursts.

During early short breaks, the highest heights at 500 hPa are over south-central New Mexico (Figure 5a). Otherwise, the height and flow pattern is similar. Early long breaks show a slightly different pattern to early short breaks. The highest heights (5925+ m) are centered near the southern Arizona-New Mexico border (Figure 5b). The major axis is oriented in a more east-to-west direction, and 5900-m isopleth extends farther west into the far eastern Pacific Ocean. As a result, the trough along the West Coast is shallower and weaker. Composites of late short breaks indicate a 5825-m ridge extending from central Baja California into the Gulf of Mexico (Figure 5c). The ridge is weaker and farther south than both types of early breaks. Nearly zonal flow dominates the entire country. Late long breaks show a combination of early long breaks and late short breaks in that flow is less zonal than during shorter breaks, but heights are significantly lower than earlier breaks. The ridge axis is slightly farther south, and southwest flow is over the northern monsoon region (Figure 5d).

At 700 hPa, the major axis of the ridge extends from far southern New Mexico into the northern Atlantic Ocean during early short breaks (Figure 6a). The broad West Coast trough prevents the subtropical ridge from expanding farther westward. This pattern would allow moist flow into the far northwestern portion of the NAMS region. As the ridge then shifts eastward, the moisture could filter into southern Arizona. During early long breaks, the subtropical ridge axis extends farther west and is positioned farther southward than during early short breaks (Figure 6b). The West Coast trough is deeper and about 1.5 times broader. The location of the ridge translates into much higher heights over the northern GoC. These factors result in a more west-southwesterly flow at this level. With late short breaks, the 700 hPa ridge is significantly weaker than early breaks (Figure 6c). Heights are only 3180 m, compared to 3195 m in the earlier breaks. Maximum heights extend from southern New Mexico into east-central Texas. The West Coast trough again limits the westward extend of the subtropical ridge. Late long breaks have a slightly deeper West Coast trough than do their short counterparts (Figure 6d). The highest heights, enclosed by the 3180-m contour, are smaller and are positioned farther to the south and west over the Rio Grande Valley.

By the last day of the monsoon, the 500-hPa subtropical ridge is farther south than at any other point during the monsoon, with the highest heights extending from far southern Baja California eastward through the Caribbean Sea (not shown). A trough extends from the central Canada into the Southwest (not shown). Atmospheric circulation patterns in the northern monsoon region signals a return to the dry westerly flow. Composites of the day after monsoon retreat indicate a farther eastward shift of the western U.S. trough (not shown). Northwesterly flow begins to dominate in the mid-levels of the atmosphere, as a ridge of high pressure shifts into the far eastern North Pacific. The subtropical anticyclone flattens further. In the week after monsoon retreat, a weak trough is present at 500 hPa in the western U.S. (not shown). Flow is mainly westerly in the northern NAMS region.

On the last day of monsoon, the 700-hPa trough axis is slightly farther east – from the northern Great Plains into eastern New Mexico – than at 500 hPa (not shown). A secondary trough is also located in California and northern Baja California. The subtropical ridge extends from the southern GoC east-northeastward into the Atlantic. Composites of the day after monsoon retreat show a farther eastward shift of the western U.S. trough (not shown). Northwesterly flow begins to dominate in the mid-levels of the atmosphere, as a ridge of high pressure shifts into the far eastern North Pacific in association with the a more shallow California trough. The subtropical ridge is at approximately the same latitude and extends slightly farther westward. In the week after monsoon retreat, a mean trough is present from the California coast to just west of Baja California (not shown). Flow in the northern NAMS region is more southwesterly.

Lower Atmospheric Levels

During the week prior to onset, the 850-hPa heights indicate a 24+-meter height gradient from the southern GoC to the northern end, or the long-Gulf gradient (LGG; Figure 7a). The isopleths cross the Gulf perpendicular to its axis (southwest to northeast). The highest heights near the Gulf are along the western coast of mainland Mexico. This area may be associated with the convection that occurs along the coast and on the western slopes of the Sierra Madre Occidental as the monsoonal moisture moves northward prior to the onset of the monsoon in southeastern Arizona. On the day prior to onset, there is an increase in heights along the length of the Gulf, and the LGG weakens to approximately 14 m (Figure 7b). Isopleths have a more north-south orientation, especially in the southern Gulf, as the ridge expands along the western Mexican coast. At onset day, the height patterns changes slightly (Figure 7c). First, isopleths along nearly the entire GoC are aligned north-south, with those in the southern Gulf just west of north. In addition, heights are higher along much of the Gulf and the western Mexican coast, up to 4 m higher in many areas. Lastly, the LGG is stronger, now approximately 18 m, especially in the northern Gulf near the islands of Ángel de la Guarda and Tiburón. The shift in the contour orientation is important in the moisture advection. With a fairly smooth surface, i.e., less friction, such as the Gulf waters, the angle between the contour line and the direction of airflow decreases. Winds would therefore be from the southeast, a favorable direction for moisture advection.

At 925-hPa, a 30-m LGG exists during the week prior to onset (Figure 8a). Isopleths are oriented south-southwest to north-northeast in the northern and southern

Gulf and southwest to northeast in the central Gulf. The ridge along the western Mexican coast is centered slightly farther south than at 850 hPa. By the day prior to onset, the 925 hPa LGG tightens slightly and isopleths over the southern Gulf are oriented nearly north to south (Figures 8b). Heights in the trough along the eastern Baja California coast shift southeastward. On onset set, the ridge along the western Mexico coast strengthens and expands along the coast (Figure 8c). As a result, the gradient tightens, especially just north of the islands. Heights range from 765 m at the extreme northern end to around 800 m at the mouth of the Gulf. In addition, the pattern of the isopleths transitions from a south-southwest-to-north-northeast orientation in the northern Gulf to slightly south-southeast-to north-northwest orientation in the southern portion.

The 1000-hPa LGG is approximately 45 m in the week prior to onset (Figure 9a). Isopleths in the northern Gulf are oriented west-southwest to east-northeast, while those in the southern portion are south-southwest to north-northeast. On the day prior to onset, the LGG tightens slightly (50 m; Figure 9b). Isopleths shift in a similar fashion to the 925 hPa pattern, as the trough along the eastern Baja coast deepens. These changes result from the strengthening and expansion of the thermal low in the Southwest. On onset day, heights increase along the entire Gulf, but the LGG remains at approximately 50 m (Figure 9c). Isopleths in the southern Gulf are oriented north to south.

On the first day of bursts, the 850-hPa pattern is similar to onset day, with a south-southeast to north-northwest alignment along the southern portion of the Gulf (Figure 10a). Heights are about 4 meters higher than onset day throughout the NAMS region. The highest heights in the NAMS region remain along the western Mexican coast. The LGG is approximately 20 m. The tightest portion of the LGG continues to be in the northern portion of the Gulf. As bursts ends, the western Mexican coast ridge begins to merge with a ridge in the eastern Pacific Ocean, resulting in height increases over much of the region (Figure 10b). This causes a slight weakening of the LGG (18 m). Isopleths over the Gulf become oriented southwest to northeast, or perpendicular to the axis of the Gulf, which is less conducive to low-level moisture advection. On the first day of breaks, heights decrease, and the LGG relaxes further (16m; Figure 10c). The height pattern resembles that during the week prior to monsoon onset. More specifically, the ridge along the western Mexican coast merges with the ridge in the Pacific.

On the first day of bursts at 925 hPa, we see the highest geopotential heights along the Mexican coast just south of the mouth of the Gulf (Figure 11a). The LGG is at 33 m in response to the strength of this ridge. The orientation of the isopleths in the southern Gulf is south-southeast-to-north-northwest, which transitions to south-southwest to north-northeast in the central and northern Gulf. By the last day of bursts, the eastern Pacific ridge strengthens and merges with the western Mexican ridge (Figure 11b). As a result, heights increase along the Gulf, most notably in the northern portion (up to 9+ m). The LGG also weakens to approximately 24 m. In addition, the isopleths gain a more southwest to northeast orientation. Heights decrease on the first day of breaks, but the LGG remains at approximately 24 m (Figure 11c). Isopleths are nearly perpendicular to the axis of the Gulf.

The LGG is approximately 45 m at 1000 hPa on the first day of bursts (Figure 12a). Isopleths are oriented south to north in the southern portion of the Gulf and transition to southwest to northeast in the northern portion. Height contours are approximately 5 m higher than during the onset date composites. On the last day of bursts, the LGG weakens considerably to 35 m, as the thermal low in Nevada weakens (Figure 12b). Heights increase approximately 10 m in the northern Gulf. A strengthening ridge is also evident in the eastern Pacific. Isopleths are aligned perpendicular to the axis of the Gulf. Some contours in the northern Gulf are oriented nearly west to east. Further weakening LGG (30 m) is evident at on the first day of breaks (Figure 12c). Heights rise approximately 5 m in nearly the entire NAMS region. Isopleths in the northern Gulf are generally aligned west to east, while those in the southern Gulf are oriented southwest to northeast. The combination of the weak LGG and the contour alignment support weak moisture advection.

During early short breaks, the LGG at 850-hPa (14 m) is weaker than during the first and last days of bursts, and heights are slightly higher (not shown). Isopleth orientation is south-southwest to north-northeast. The eastern Pacific ridge has merged with the western Mexico ridge. Heights are slightly higher over the entire Gulf during early long breaks compared to early short breaks (not shown). Isopleths are nearly perpendicular to the axis of the Gulf. The eastern portion of the eastern Pacific ridge is also up to 4 m higher. With late short breaks, heights are also much lower, but the ridge is still evident along the western Mexican coast (not shown). The LGG is fairly weak (14 m). Isopleths are oriented generally south-southwest to north-northeast. The 850-hPa ridge along the western Mexico coast is slightly stronger and extends across the southern portion of the Gulf during late long breaks (not shown). The LGG is tighter than during the late short breaks. In addition, a trough is present south of Baja California.

At 925 hPa, the LGG is approximately 24 m during early short breaks (not shown). The isopleth pattern is similar to the last day of bursts. During early long breaks, the 925-hPa ridge in the eastern Pacific strengthens and expands to the western Mexican coast (not shown). The gradient is fairly strong in the northern Gulf, but it remains weak in the southern Gulf. Even with a 30-m LGG, the expansion of the Pacific ridge apparently precludes strong moisture advection. The LGG is at 24 m during late short breaks (24 m; not shown). Heights near the mouth of the Gulf are similar to the pre-monsoon period, but the northern Gulf heights are significantly higher. The contour pattern and strength of the LGG during late long breaks are quite similar to the late short breaks (not shown). The eastern Pacific ridge is slightly weaker, while the thermal low has strengthened.

The 1000-hPa pattern for early short breaks shows isopleths oriented nearly west to east in the northern Gulf and south-southwest to north-northeast in the southern Gulf (not shown). The LGG is fairly weak (35 m). At 1000 hPa, the LGG is stronger (45 m) during early long breaks than during the early short breaks (not shown). It is the same as the LGG on the first day of bursts at this level. The main difference is a stronger and more organized thermal low on the first day of bursts. The low during early long breaks, is weaker, has several lobes, and covers a much of the Southwest. Additionally, higher heights associated with the Pacific ridge extend farther eastward at this level. The LGG is weak (30-35 m) during both types of late breaks (not shown). Isopleths are oriented nearly north to south in the southern Gulf and west to east in the northern Gulf.

The composites for the 850 hPa pattern on the day of monsoon retreat indicate a 20-m LGG and significantly lower heights along the length of the Gulf (Figure 11a). Isopleths are in a south-southwest to north-northeast orientation. The highest heights are along the western Mexican coast. The center of the thermal ridge has shifted just west of the California-Nevada border. On the day after the monsoon retreats, 850-hPa heights are slightly higher, with a somewhat stronger LGG (22 m; Figure 11b). The western Mexican ridge is stronger and remains along the coast. In addition, isopleths are aligned nearly perpendicular to the axis of the Gulf. During the week after retreat, the LGG weakens to 14 m, with a very weak gradient in the southern Gulf (Figure 11c). Isopleths are oriented southwest to northeast. A weak trough is located south of Baja California.

On the day of monsoon retreat, the LGG at 925 hPa is approximately 27 m, with the weakest portion of the gradient in the southern Gulf (Figure 14a). Isopleths are oriented nearly perpendicular to the axis of the Gulf. The LGG weakens on the day after monsoon retreat, now at only 24 m (Figure 14b). The eastern Pacific ridge remains merged with the western Mexican coast ridge. The thermal low in southern Nevada is considerably weaker. During the week after monsoon retreat, the LGG is remains at 24 m, with the weakest portion of the gradient in the southern portion of the Gulf (Figure 14c). Isopleths remain perpendicular to the axis of the Gulf.

The 1000 hPa composite for the day of monsoon retreat indicates a very weak LGG (30 m), which is equal to the LGG on the first days of breaks and during late breaks

(Figure 15a). The isopleth pattern is unique; the trough that was over Baja California or along the Baja-GoC coast up to this point is now along the axis of the Gulf. In the northern Gulf, the isopleths are oriented generally west to east. The low along the Colorado River is also much weaker than earlier in the monsoon. On the day after monsoon retreat, the LGG remains at 30 m, with the trough holding over the Gulf (Figure 15b). The thermal low over the lower Colorado River continues to weaken as well. During the week after monsoon retreat, the LGG weakens further, now less than 30 m (Figure 15c). In addition, the synoptic-scale pattern (not shown) indicates ridging in the eastern U.S. at 850, 925, and 1000 hPa. This would result in moisture advection into the Great Plains related to the out-of-phase precipitation relationship between the Southwest and the Great Plains (Okabe 1995, Higgins et al. 1999, Mo et al. 2005).

Conclusions and Recommendations

This study identifies composite geopotential heights and associated circulation before, during, and after the monsoon to understand the nature and variation of patterns that lead to monsoon onset, bursts, breaks, and retreat. We follow the method of determining onset, bursts, breaks, and retreat using dewpoint thresholds developed by Brandt (submitted). We generate composite maps at the standard pressure levels of 500, 700, 850, 925, and 1000 hPa using the NARR database (NOAA-CIRES CDC 2006). This analysis adds to previous research in the use of the higher resolution NARR data and the focus on all aspects of the monsoon, including specific types of breaks differentiated by timing (first half of the monsoon [early] vs. second half of the monsoon [late]) and duration (less than one week [short] vs. one week or more [long]).

At the synoptic scale, the patterns generally agree with previous research using geopotential height to study the NAMS. The 500-hPa anticyclone shifts from a location over the southwestern U.S. and northwestern Mexico to a more northerly position. In conjunction with this shift, the axis of the ridge gains a southeast to northwest orientation. These events allow for mid-level moisture advection into the northern NAMS region. The ridge weakens slightly and is centered slightly farther east during the first day of bursts. At the end of bursts, the ridge shifts southward, and the axis stretches longitudinally. The ridge is also farther south during breaks. We also find that the latitude of the major axis of the ridge varies break timing and duration. Near the end of breaks, the 500-hPa pattern resembles the first day of bursts. On the last day of the monsoon, the subtropical ridge is even farther south. In addition, a trough extends from south-central Canada into the southwestern U.S. This trough eventually leads to westerly flow, which marks the retreat of the monsoon.

At 700-hPa the subtropical ridge is more conducive to moist mid-level flow by the day prior to onset. The ridge expands farther westward by the onset date, causing a tightening of the trough off the U.S. West Coast. This ridge is centered over Texas during the first day of bursts. At the end of bursts, beginning of all breaks, and during early breaks, the 700-hPa ridge expands and shifts southward. Again, the division of the breaks by timing and duration reveals previously unreported results. The difference between early short breaks and early long breaks is the westward extent of the subtropical ridge and the strength and width of the West Coast trough. During late breaks, heights decrease considerably. Long late breaks show a slightly deeper West Coast trough than short late breaks. On the last day of breaks, the geopotential height pattern is similar to the first day of bursts. The West Coast trough shifts farther east and a secondary trough develops at the end of the monsoon. The 700 hPa flow becomes more northwesterly, then southwesterly after the monsoon retreat.

The composites of the lower levels at the synoptic scale, especially at 925 and 1000 hPa, do not show the desired detail, so we zoom in the on GoC region, which covers latitudes from 18° to 38°N and longitudes from 100° to 120°W. This more meticulous inspection of the geopotential heights yields information about the LGG and isopleth orientation throughout the NAMS period that has not been described in prior research.

At 850 and 925 hPa monsoon onset and bursts are marked by a tightening of the LGG, with the strongest portion of the gradient near the islands of Ángel de la Guarda and Tiburón in the northern Gulf. Geopotential heights are also generally higher across nearly the entire region during these periods than during the pre-monsoon. The orientation of isopleths over the waters of the GoC is also unique. They are generally south to north in the northern Gulf and south-southeast to north-northwest in the southern Gulf. The intensification of the ridge along the western Mexican coast appears to cause the above impacts. This ridge may be the manifestation by the NARR of the thunderstorms that develop along the coast and on western slopes of the Sierra Madre Occidental. The 1000 hPa pattern is similar to those at 850 and 925 hPa, except the isopleths have a south to north orientation along much of the southern Gulf. As the bursts end, heights continue to increase, but the LGG weaken. At the same time, the orientation of the 850 and 925 hPa isopleths take on a more south-southwest to north-northeast over the Gulf. At 1000 hPa, the isopleths are oriented nearly perpendicular to the axis of the Gulf.

These results have potential implications in forecasting the onset and retreat of the monsoon, as well as burst and break periods. We caution that the maps shown throughout the report are composites and are therefore not representative of the character of each onset, burst, break, or retreat. Previous research shows that a variety of factors, including tropical-based weather phenomena (e.g., hurricanes, tropical storms, easterly waves) and upper lows and troughs in the Westerlies, can initiate monsoon onset or bursts. Depending on their frequency, they may not appear in climatologically averaged maps. Surface patterns and low-level geopotential heights may still take on an appearance similar to what is described above.

This study raises several questions for future research, adding to those posed and implied by other investigations. Is the ridge along the western Mexican coast in the NARR a manifestation of the convection along the western slopes of the Sierra Madre Occidental? In addition, is the apparent expansion of the eastern Pacific ridge related to increased convection south of the GoC? Another area of future research will involve the appearance of surface patterns and geopotential height patterns in the NAMS region associated with the meteorological phenomena that lead to onset and bursts. Continual improvement in available analysis products, such as the NARR, and additional funded field projects, like the North American Monsoon Experiment, can add to the current understanding of the NAMS.

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Break timing and duration	**Number of events**
Early short	23
Early long	7
Late short	27
Late long	13

Table 1. Number (fraction in percent) of total breaks Tucson during the period 1979-2002. Breaks are sub-divided by timing and duration (see text for descriptions of the categories).

Figure 1. Synoptic-scale region, including most of North American and surrounding portions of the Atlantic and Pacific oceans. The map is centered at 40°N, 100°W.

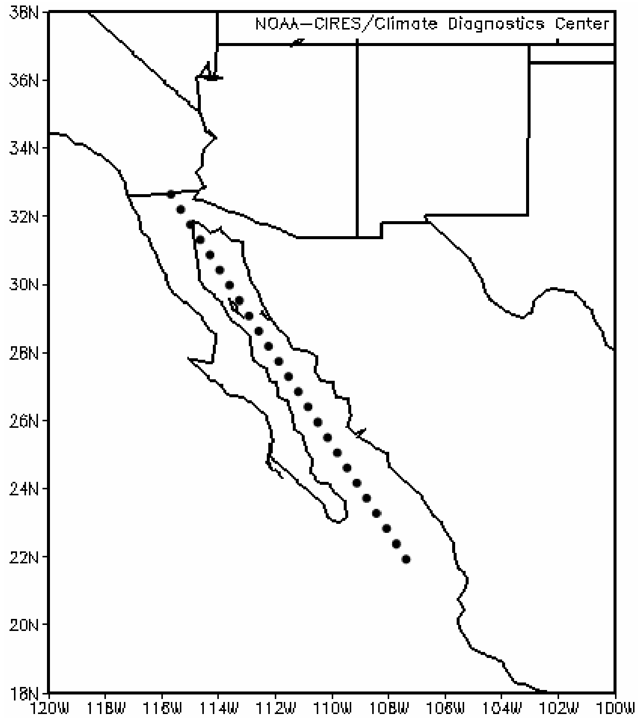
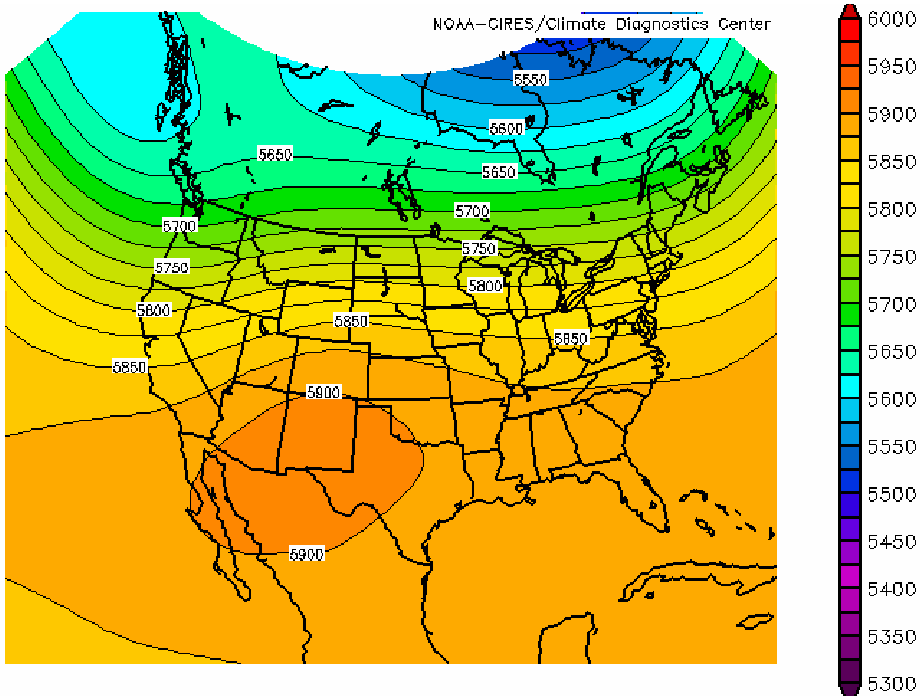


Figure 2. Sub-synoptic-scale region, including the southwestern United States, northwestern Mexico, and adjacent portions of the Pacific Ocean. The dotted line represents the axis of the Gulf of California.

(a)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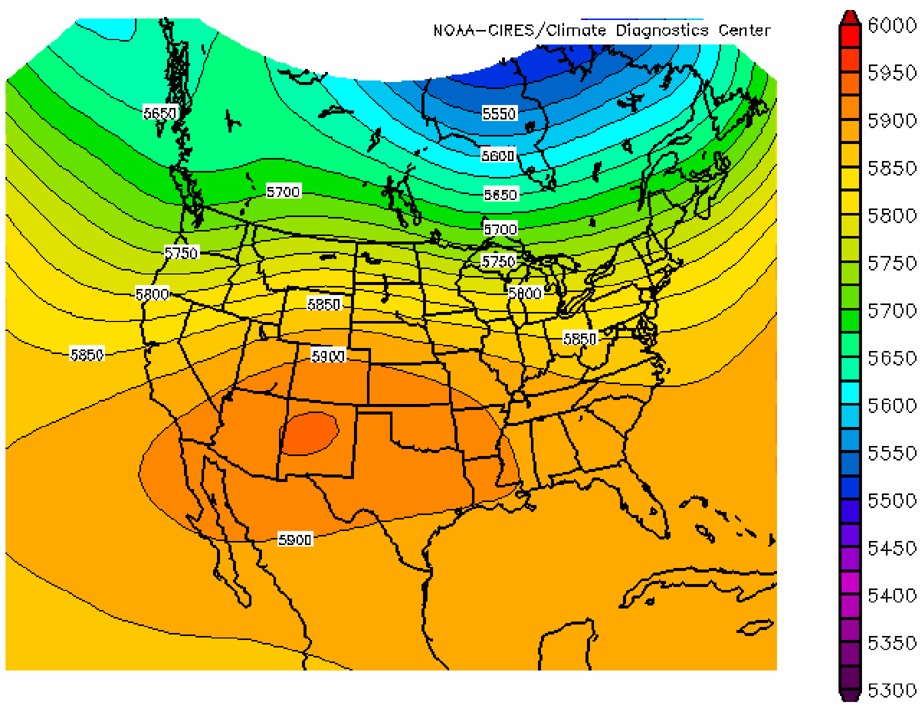
(b)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(c)

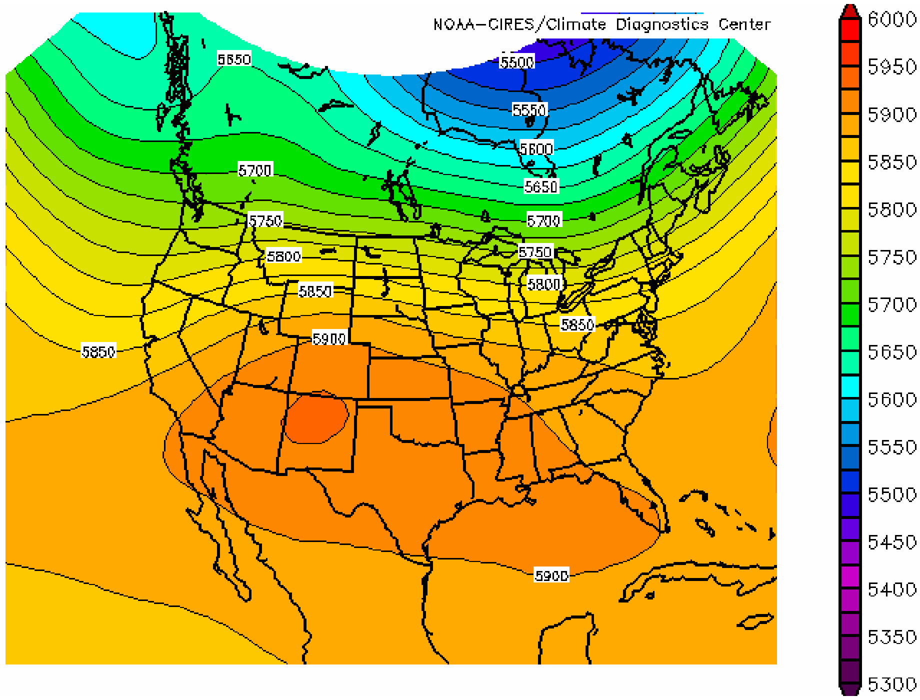
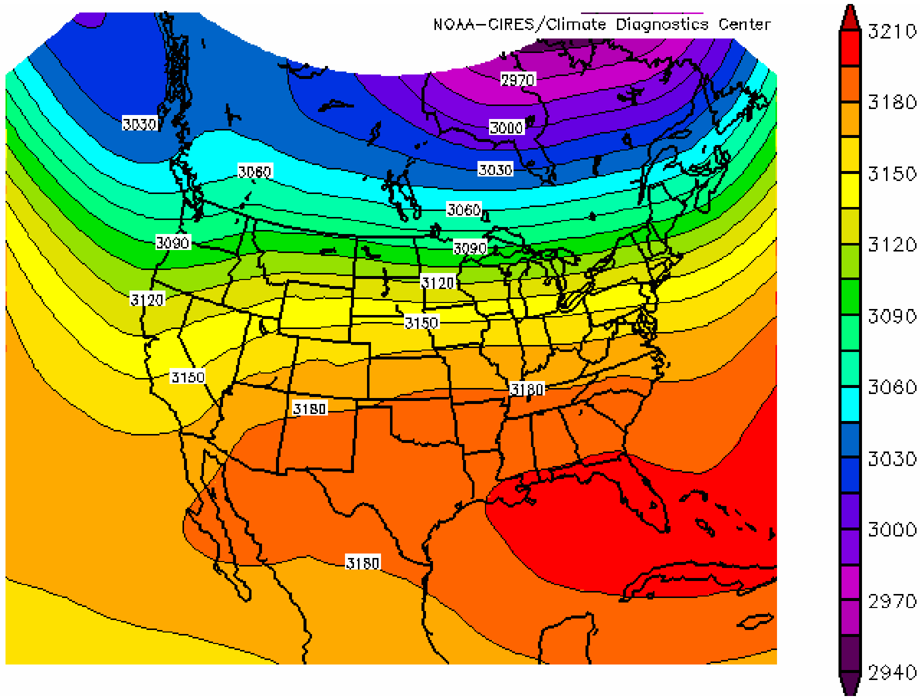


Figure 3. 500 hPa synoptic composite for *(a)* one week prior to monsoon onset, *(b)* one day prior to monsoon onset, and *(c)* day of monsoon onset.

(a)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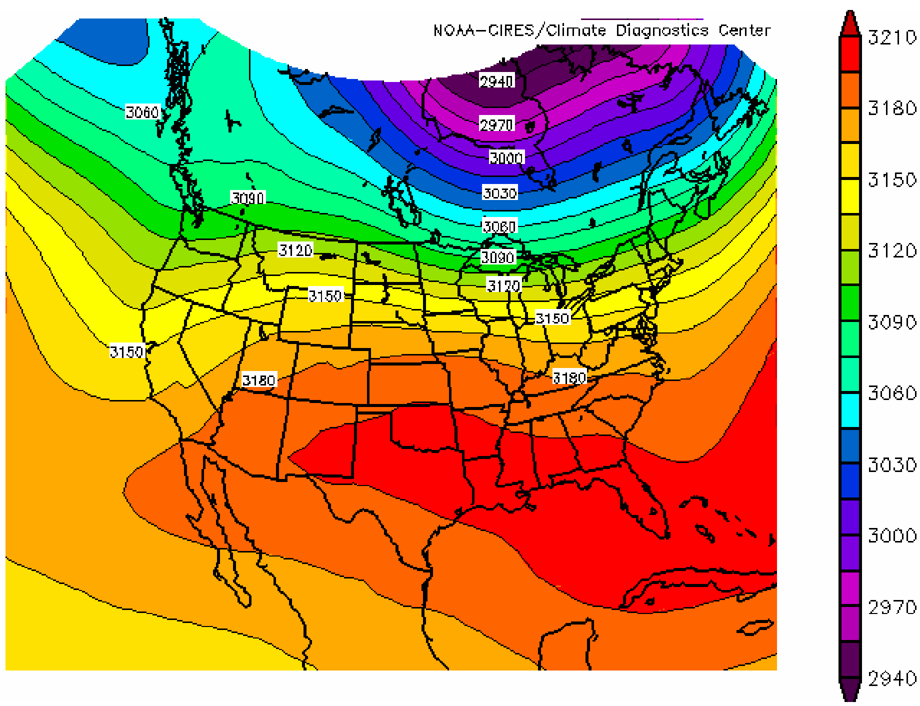
3030
3000
2970
2940

(b)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2940

(c)

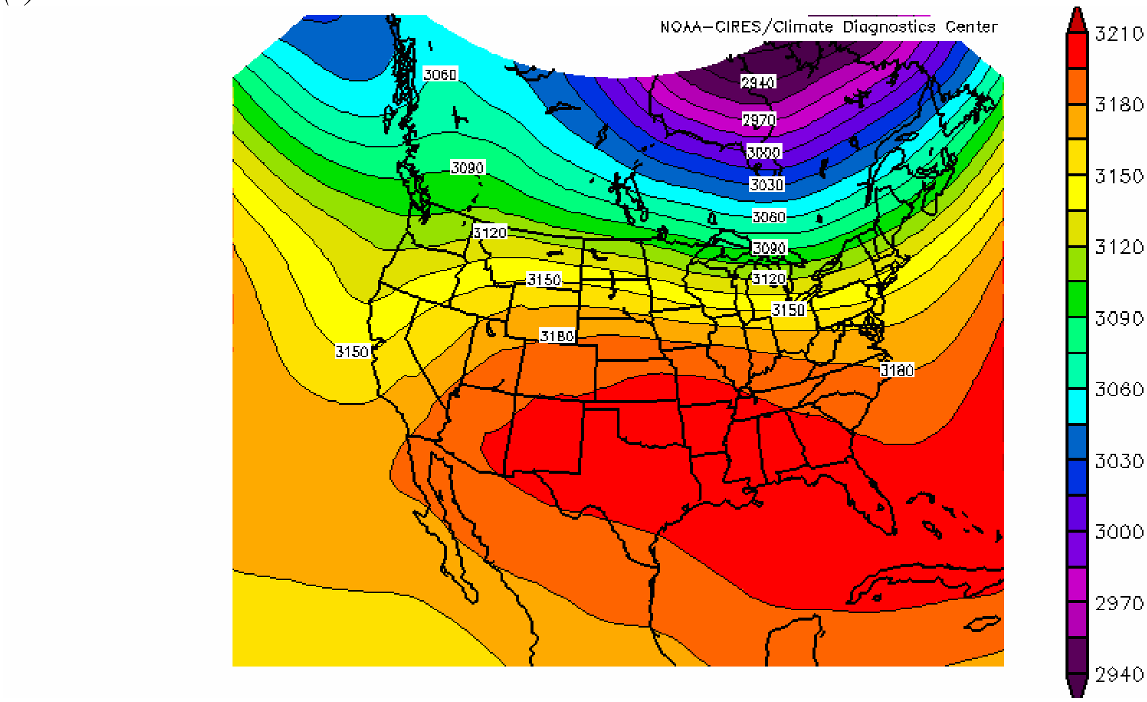
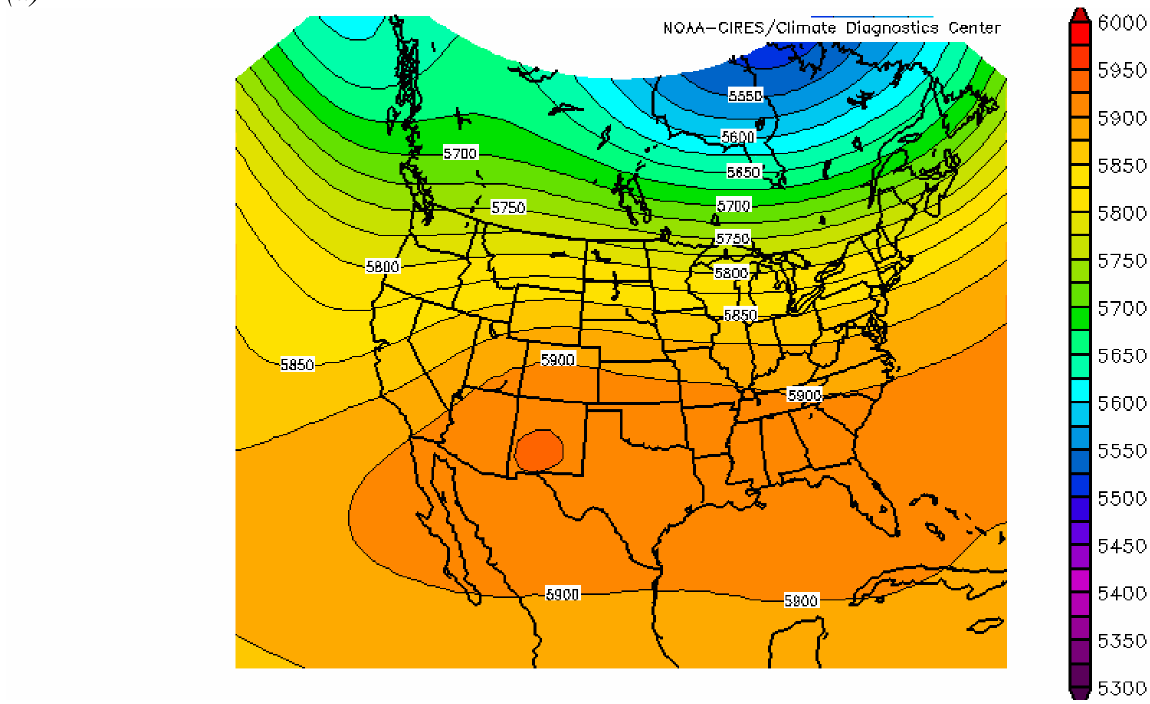


Figure 4. Same as Figure 3*(a-c)*, except for 700 hPa.

(a)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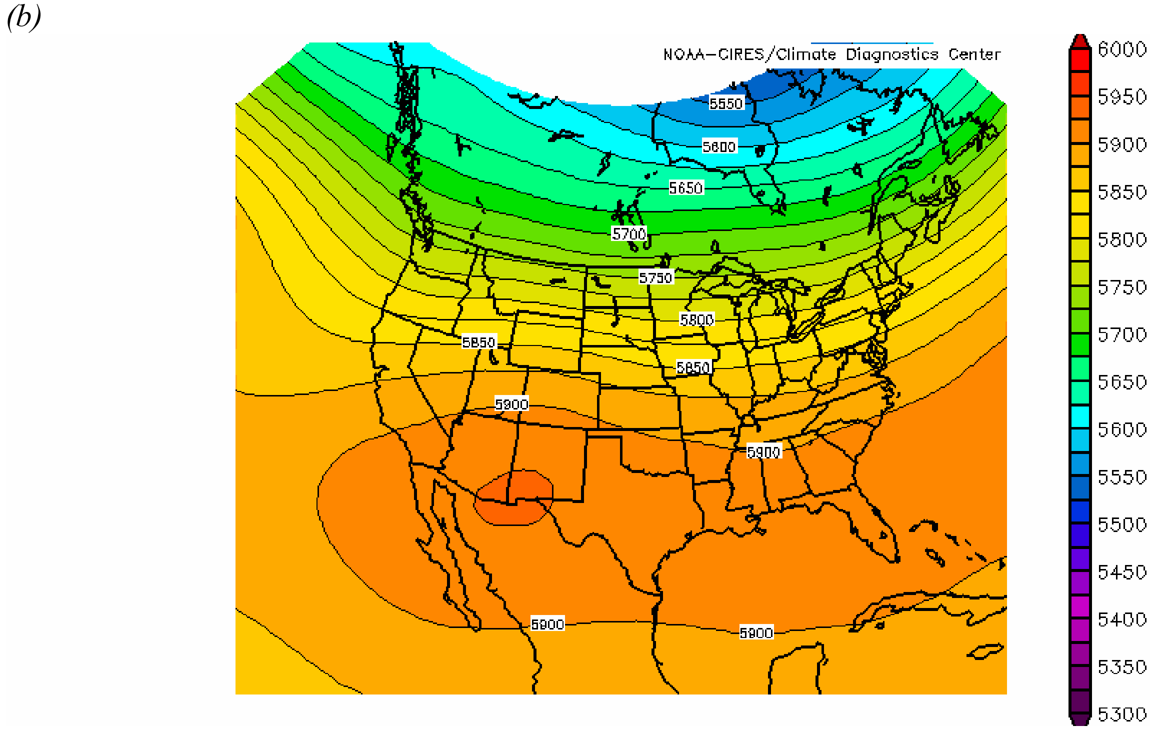
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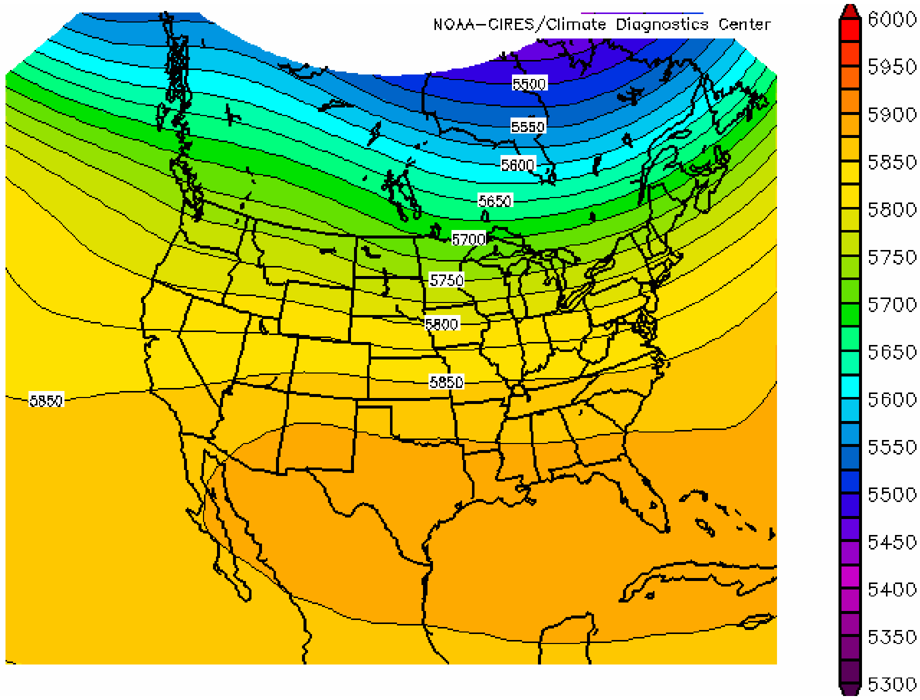
(c)



(d)

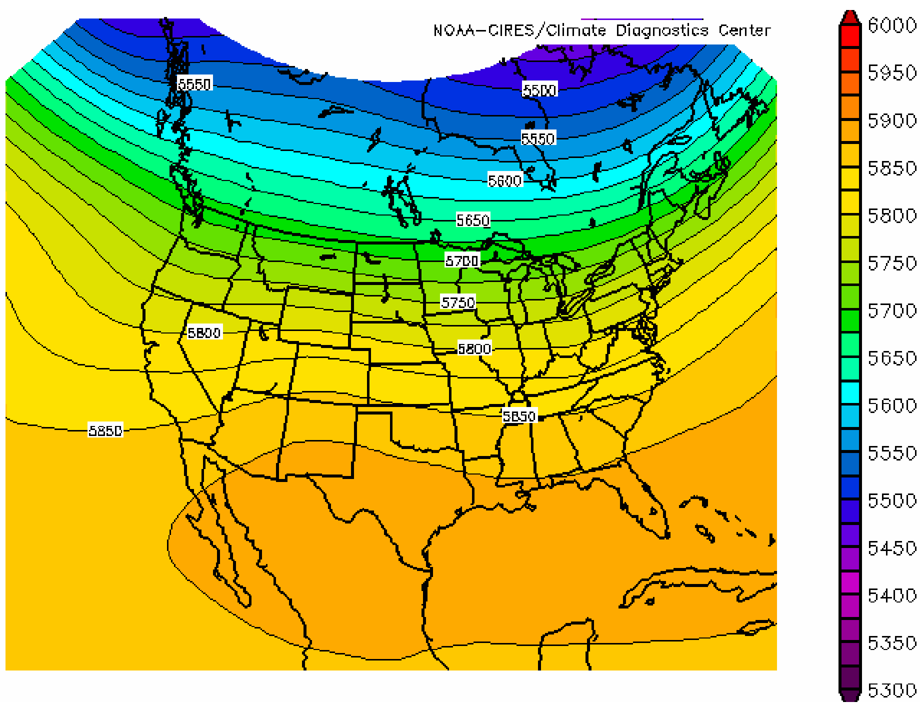
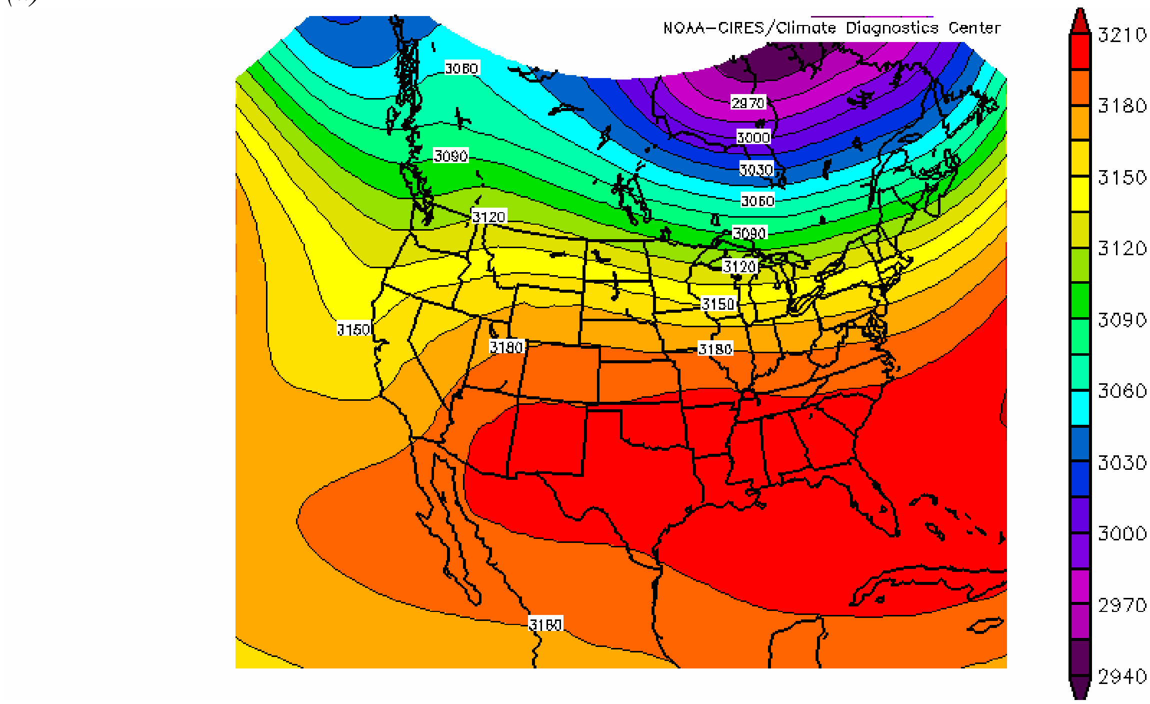


Figure 5. 500 hPa synoptic composite for *(a)* early short breaks, *(b)* early long breaks, *(c)* late short breaks, and *(d)* late long breaks.

(a)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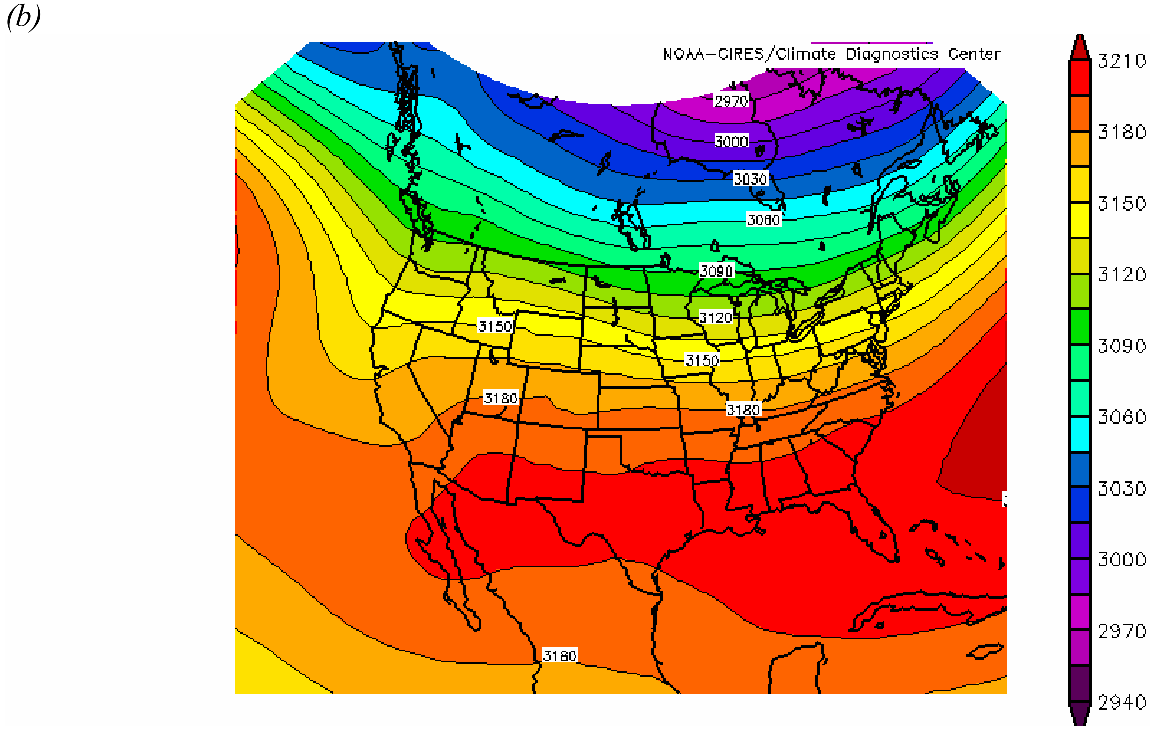
(b)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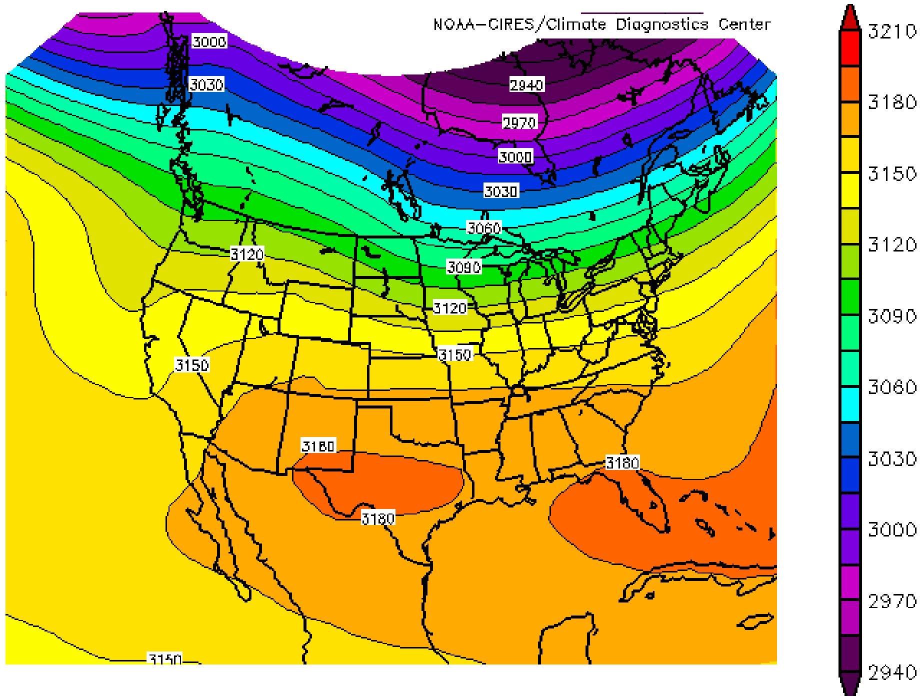
(c)



(d)

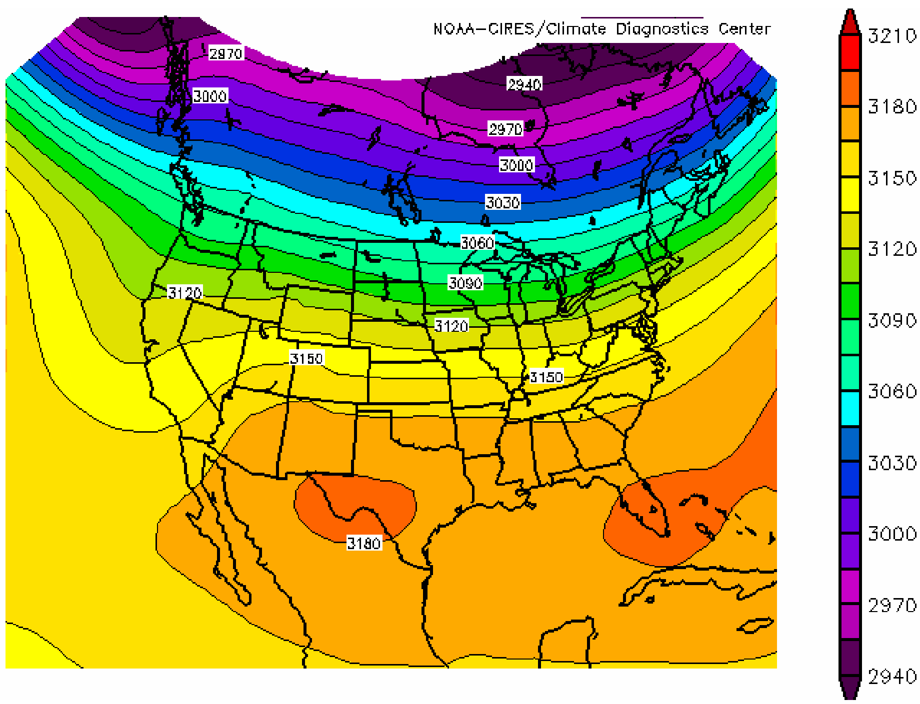
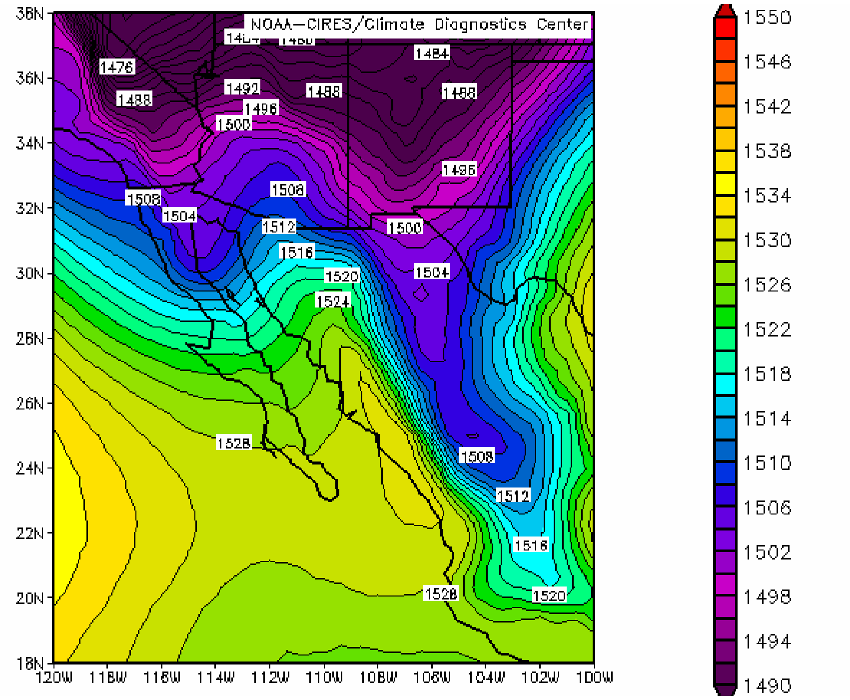


Figure 6. Same as Fig. 5*(a-d)*, except for 700 hPa.

(a)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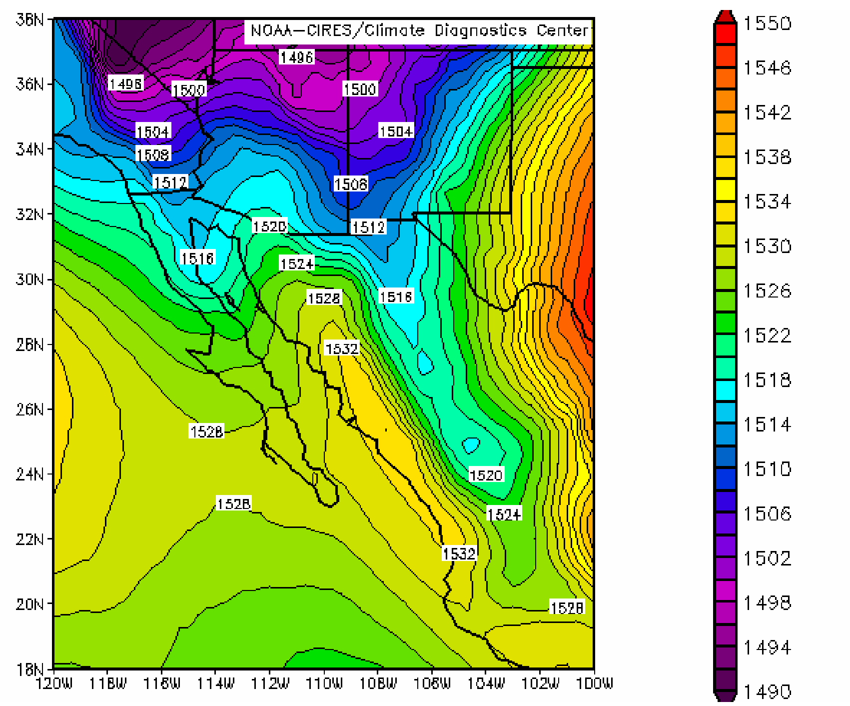
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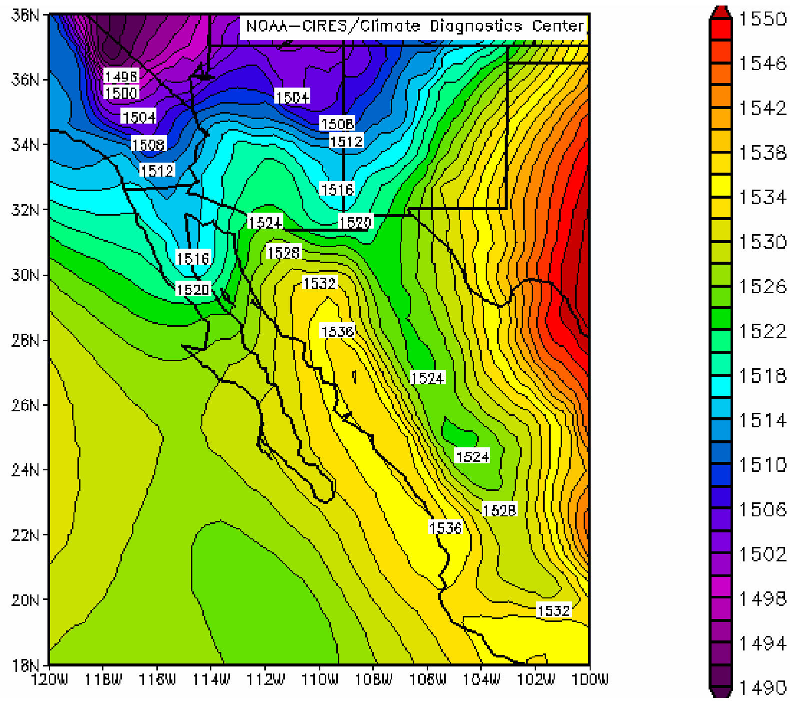
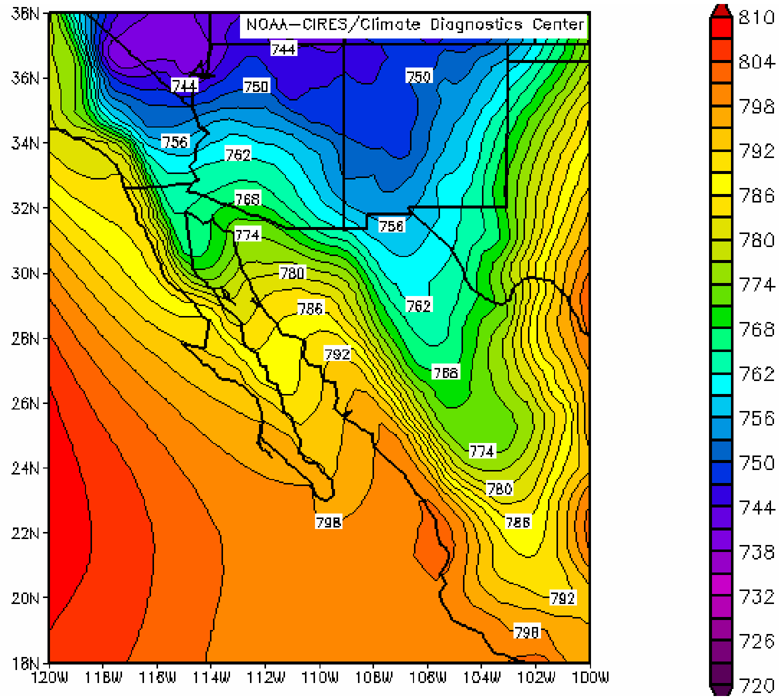


Figure 7. 850 hPa sub-synoptic composite for *(a)* one week prior to monsoon onset, *(b)* one day prior to monsoon onset, and *(c)* day of monsoon onset.

(a)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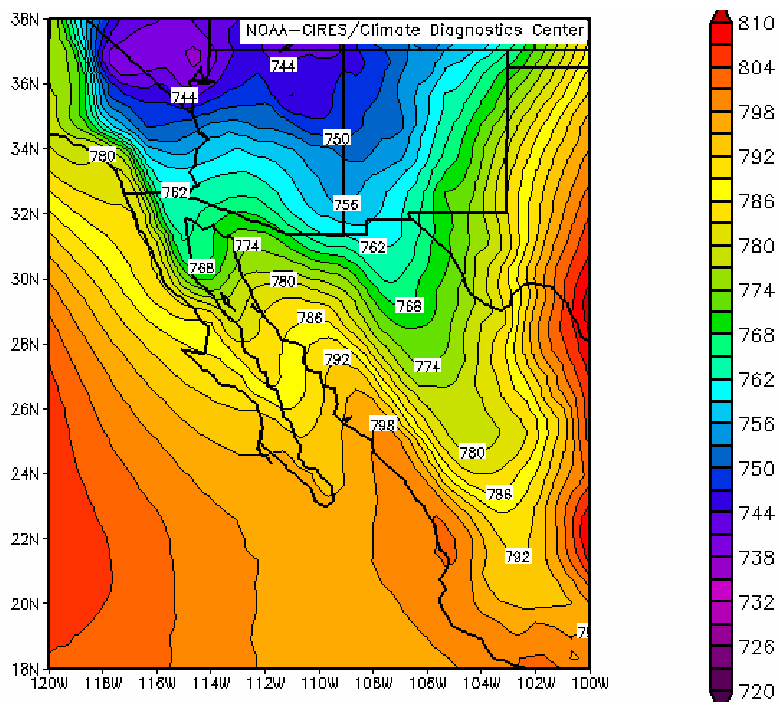
(b)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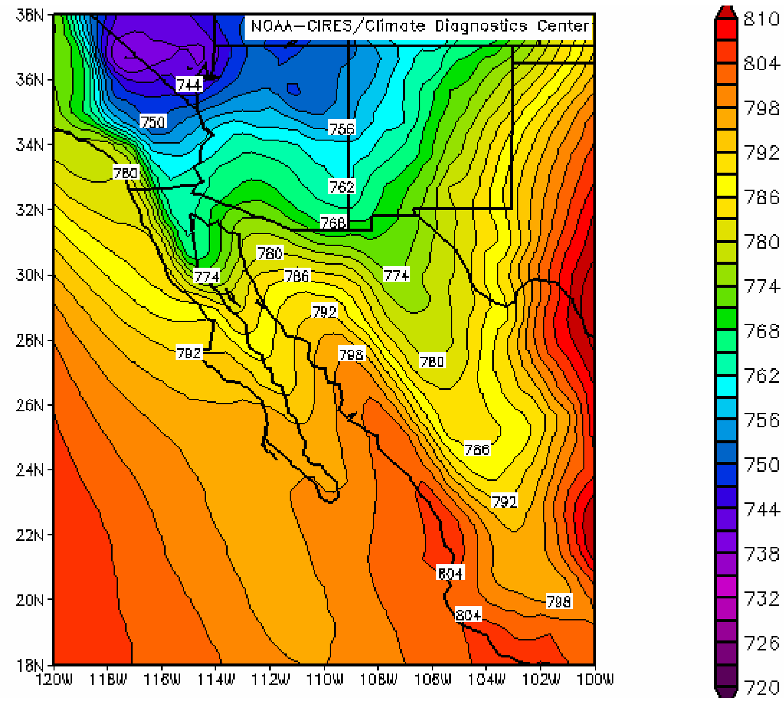
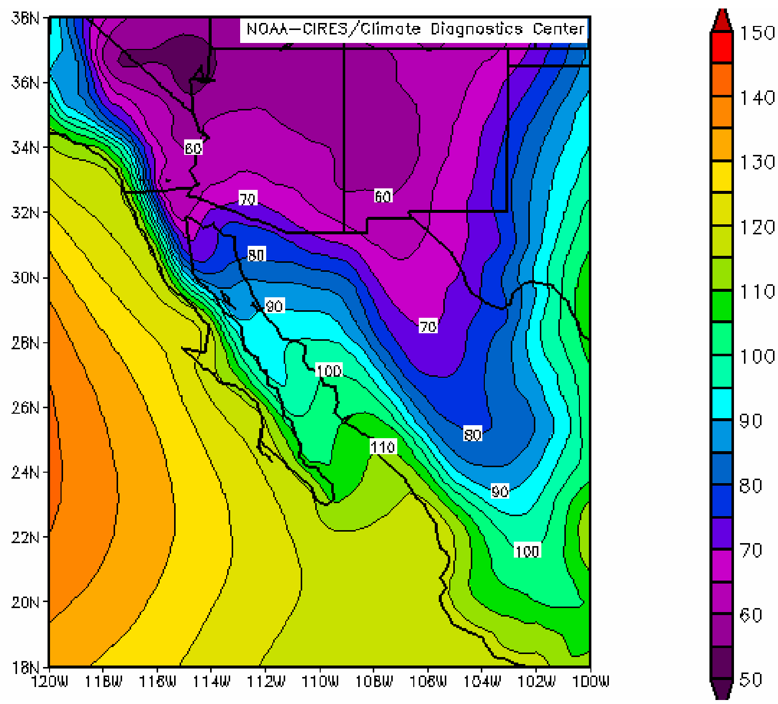


Figure 8. Same as Fig. 7*(a-c)*, except for 925 hPa.

(a)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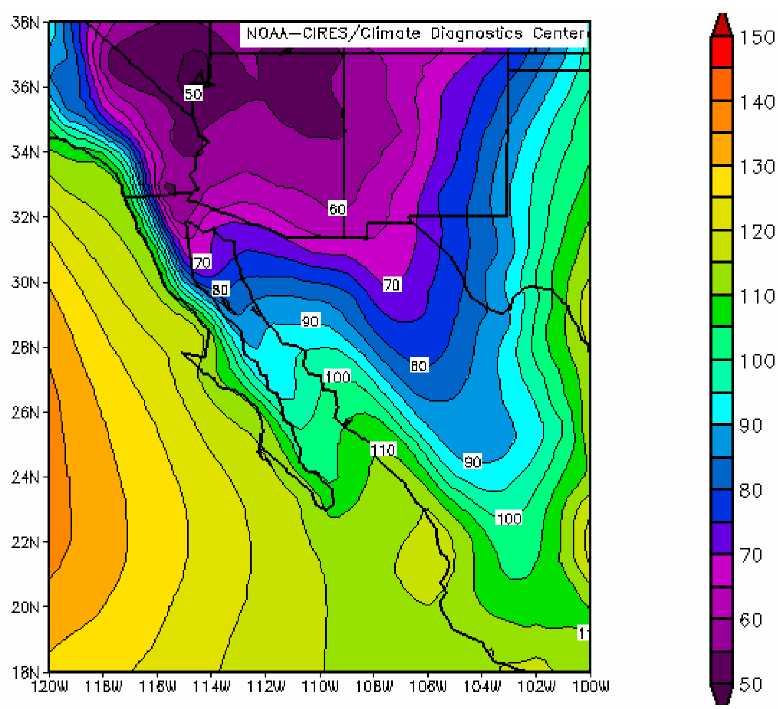
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(c)

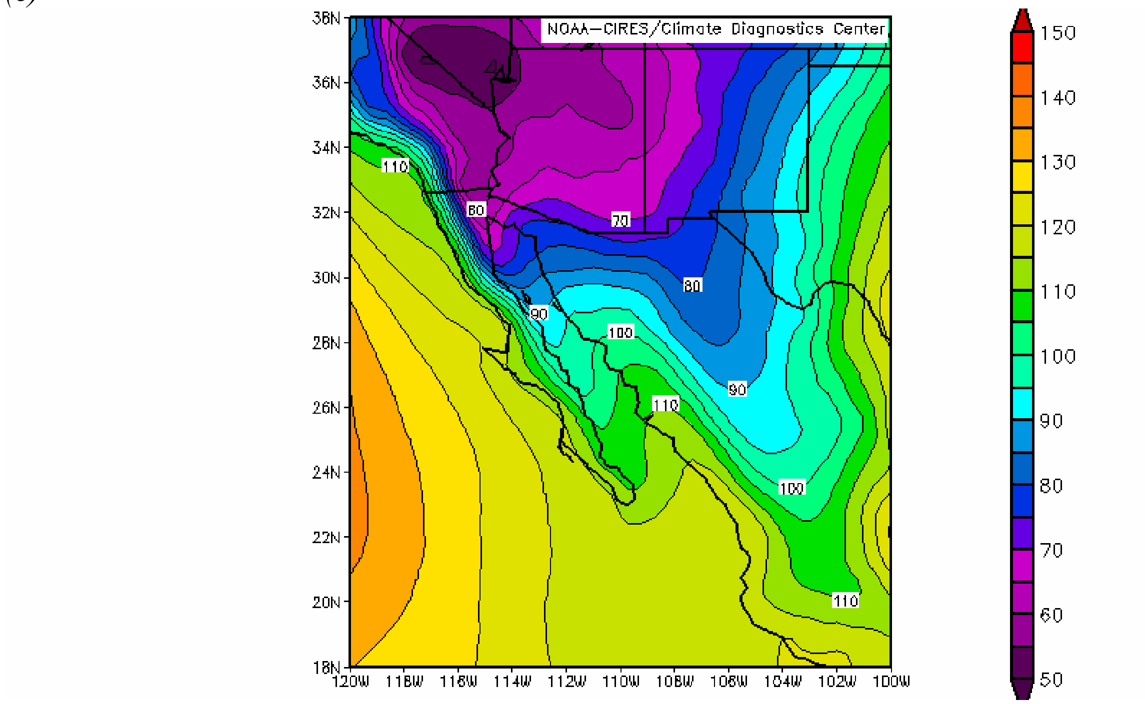
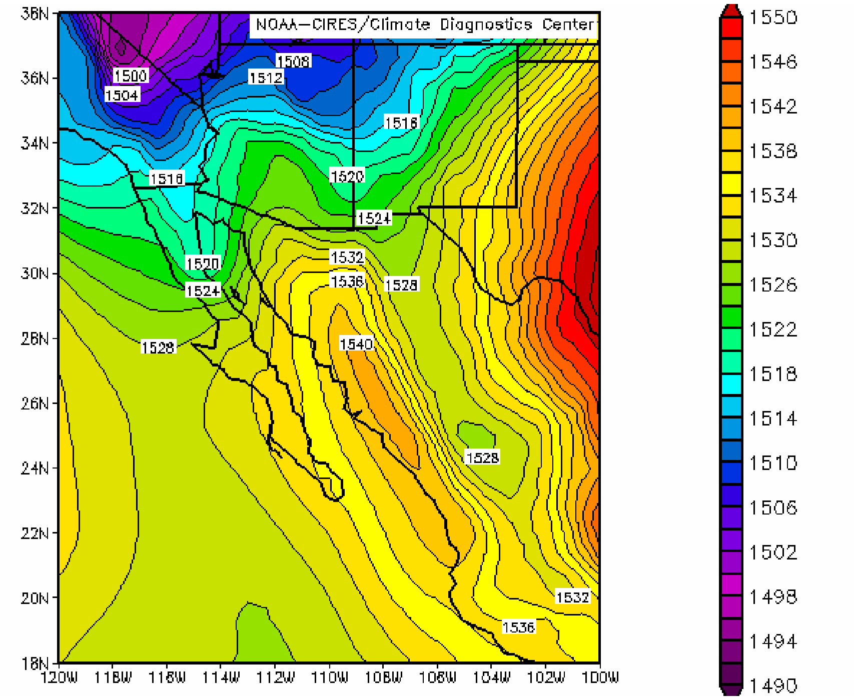


Figure 9. Same as Fig. 7*(a-c)*, except for 1000 hPa.

(a)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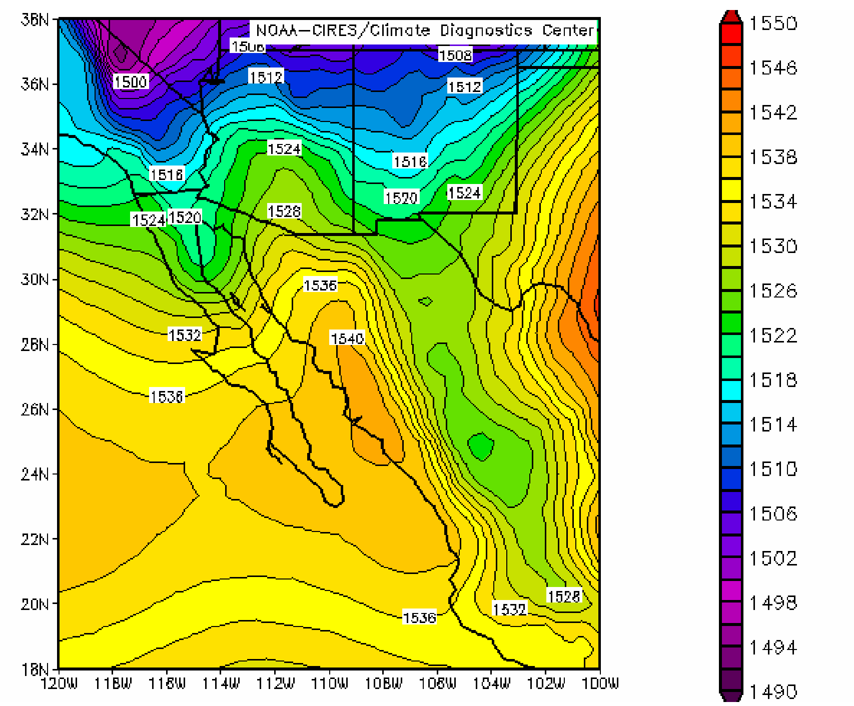
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(c)

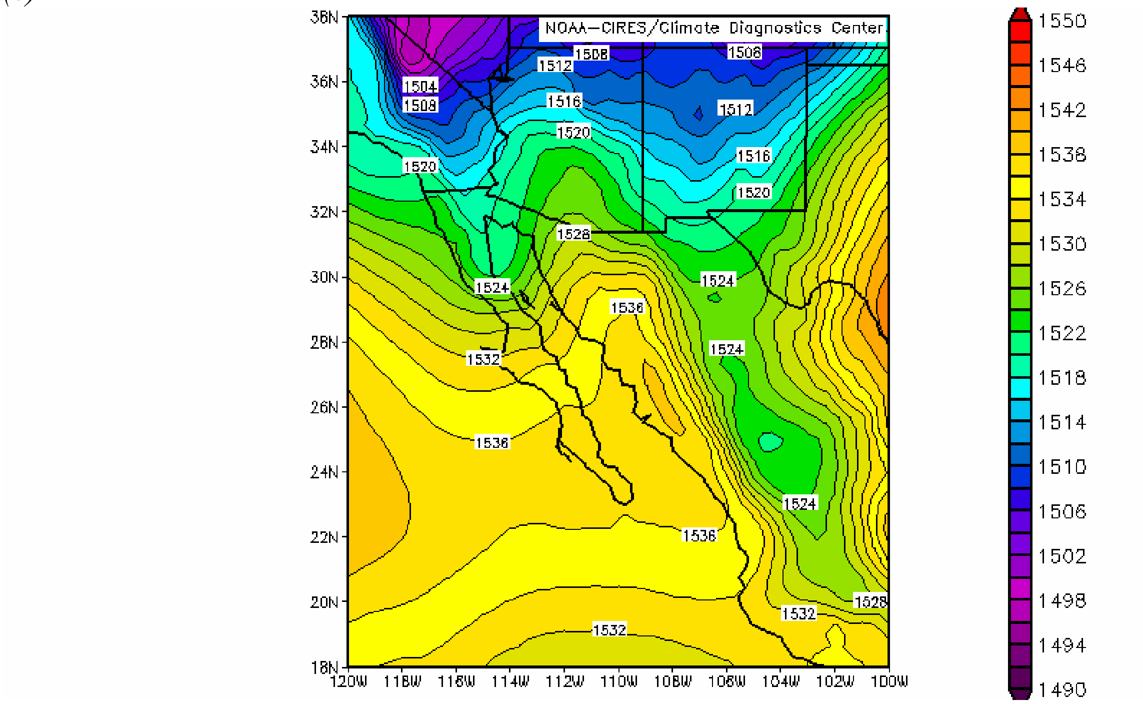
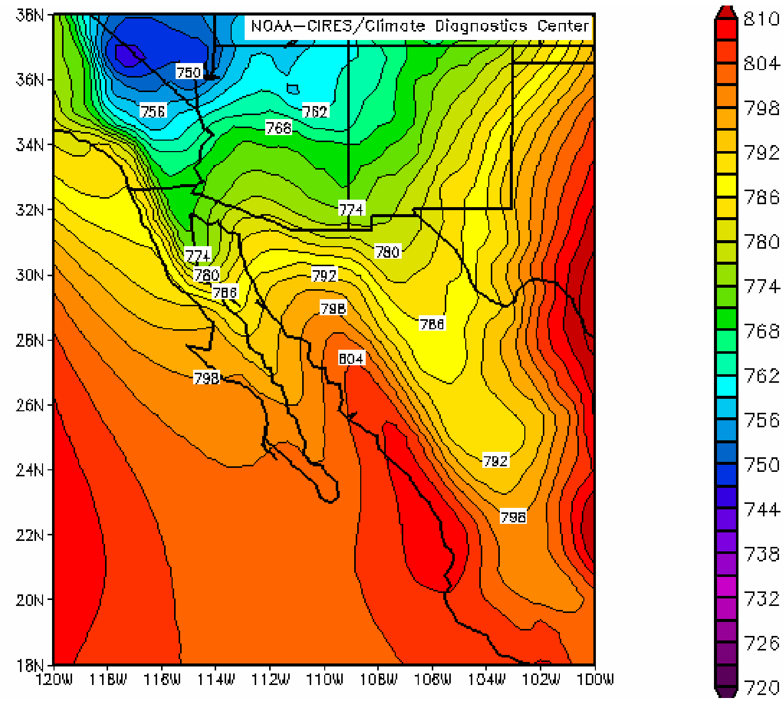


Figure 10. 850 hPa sub-synoptic composite for *(a)* first day of burst, *(b)* last day of burst, and *(c)* first day of break.

(a)



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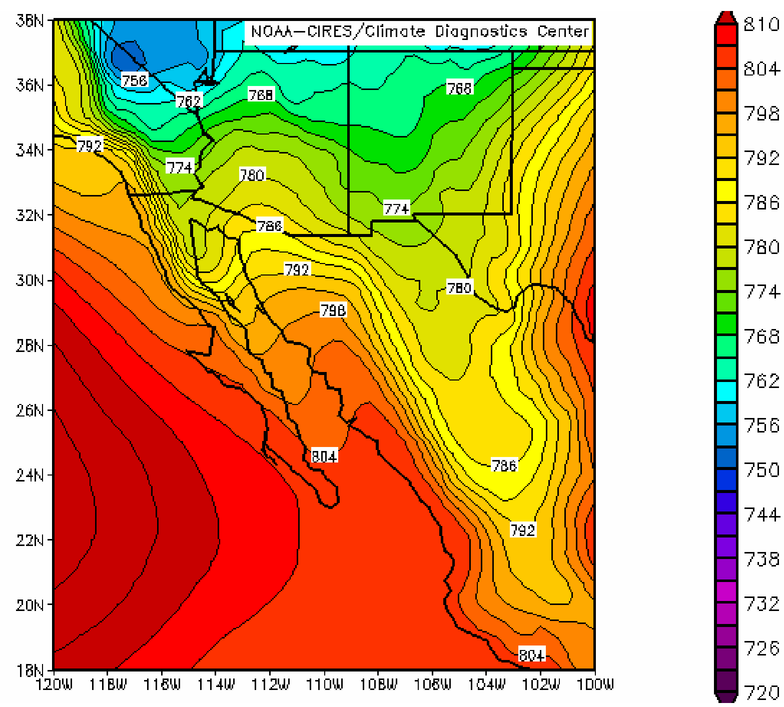
(b)



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(c)

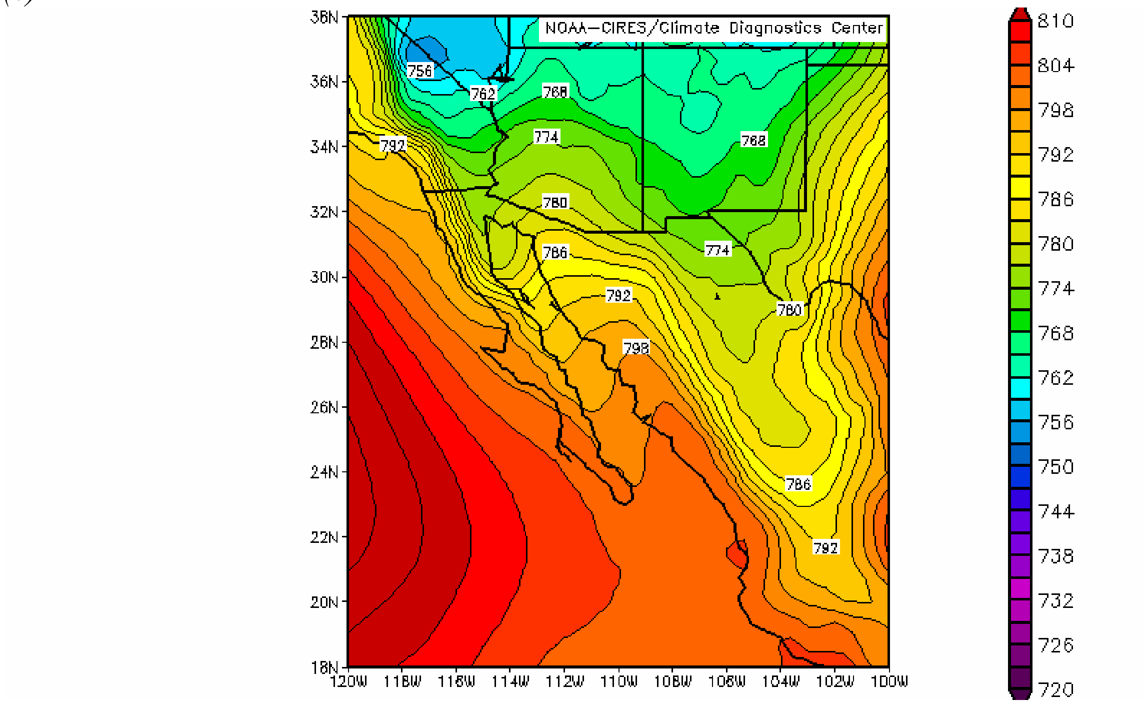
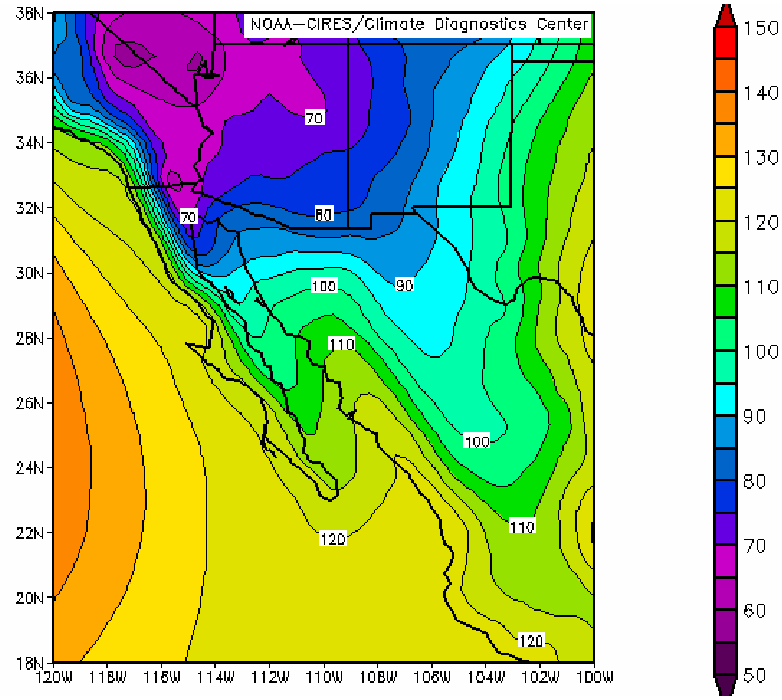


Figure 11. Same as Fig. 10*(a-c)*, except for 925 hPa.

(a)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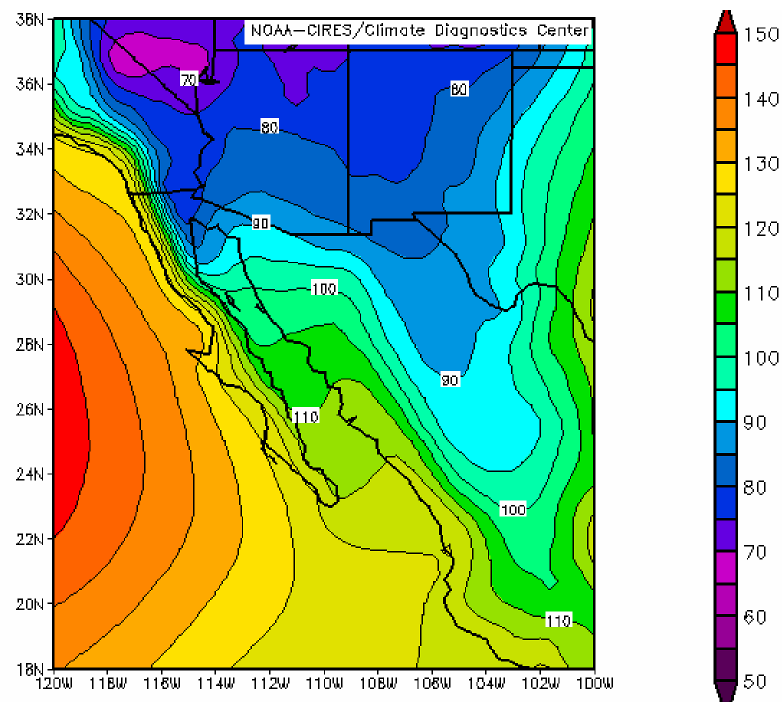
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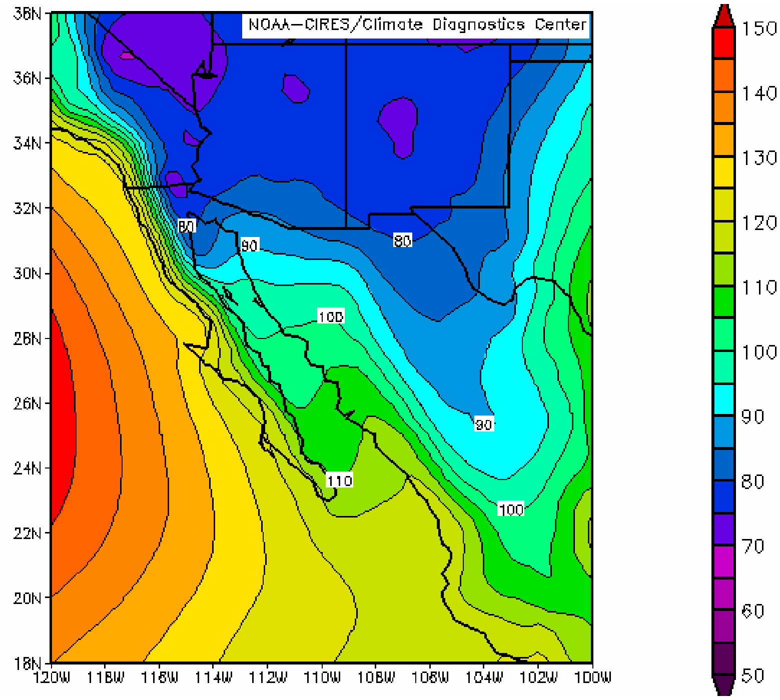
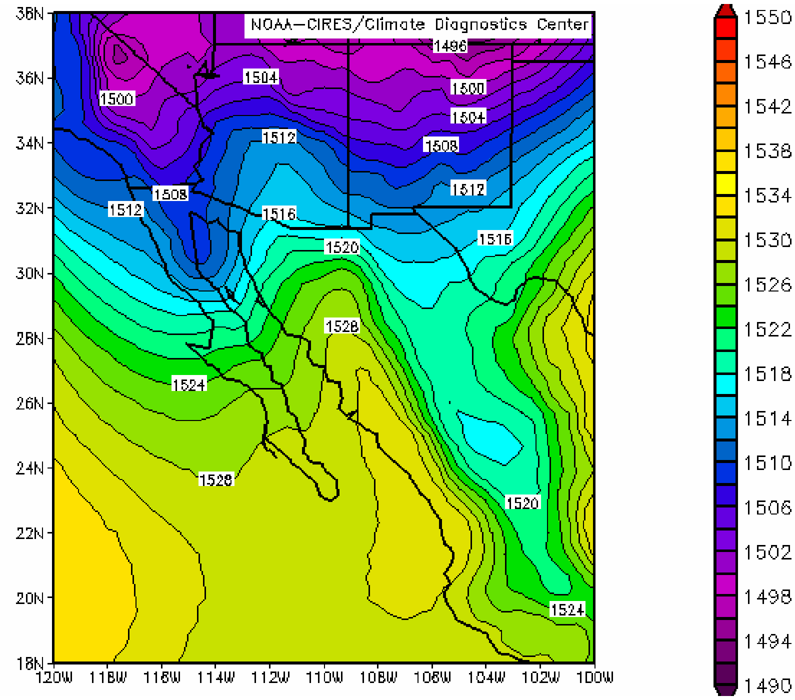


Figure 12. Same as Fig. 10*(a-c)*, except for 1000 hPa.

(a)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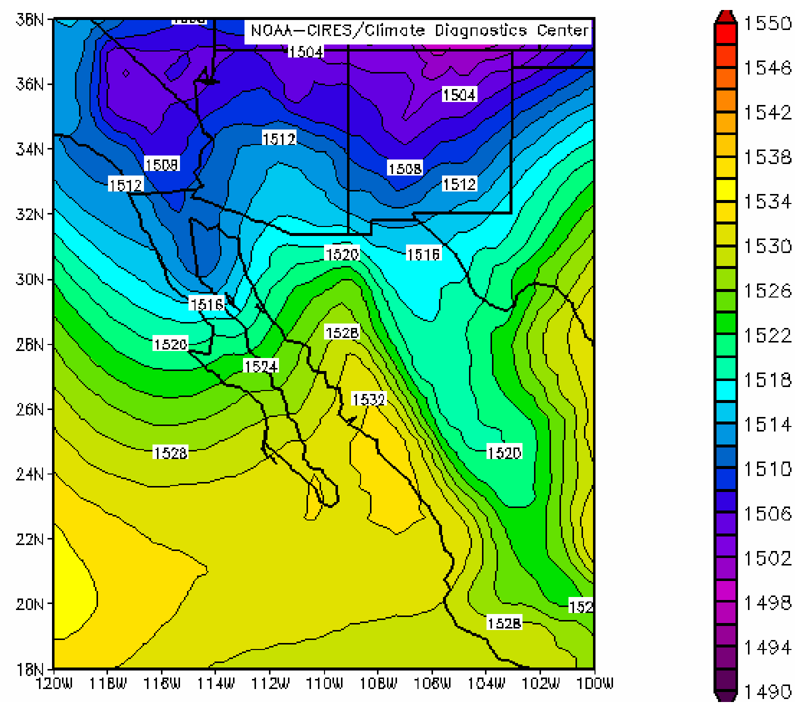
(b)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(c)

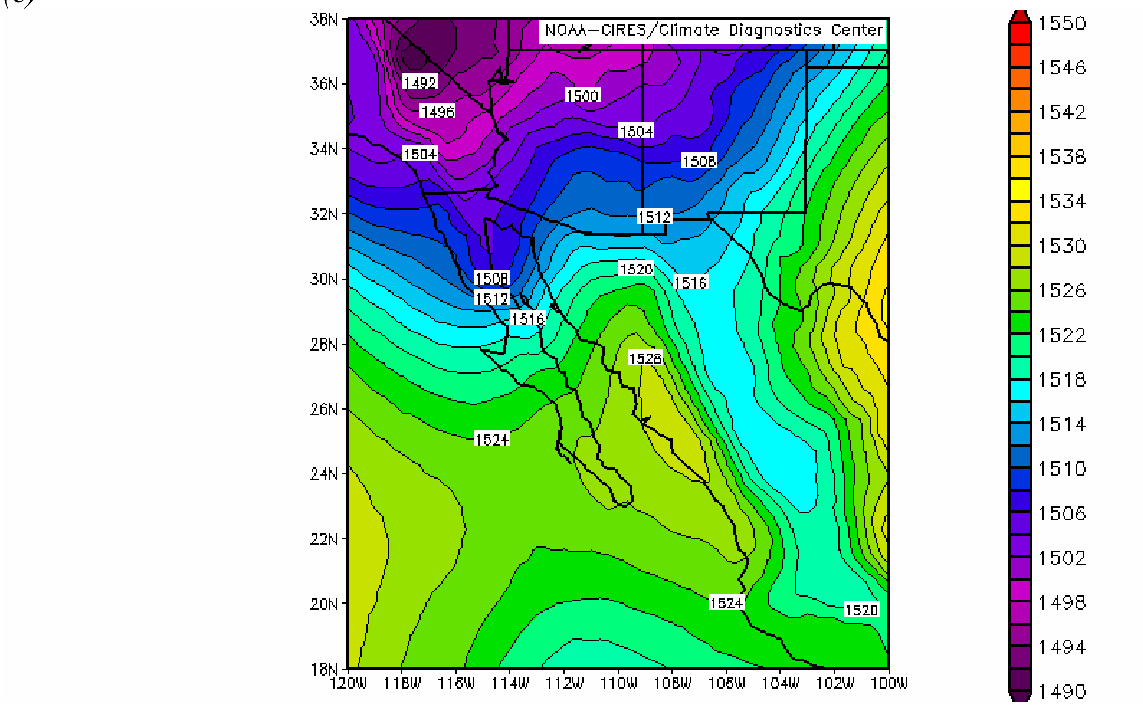
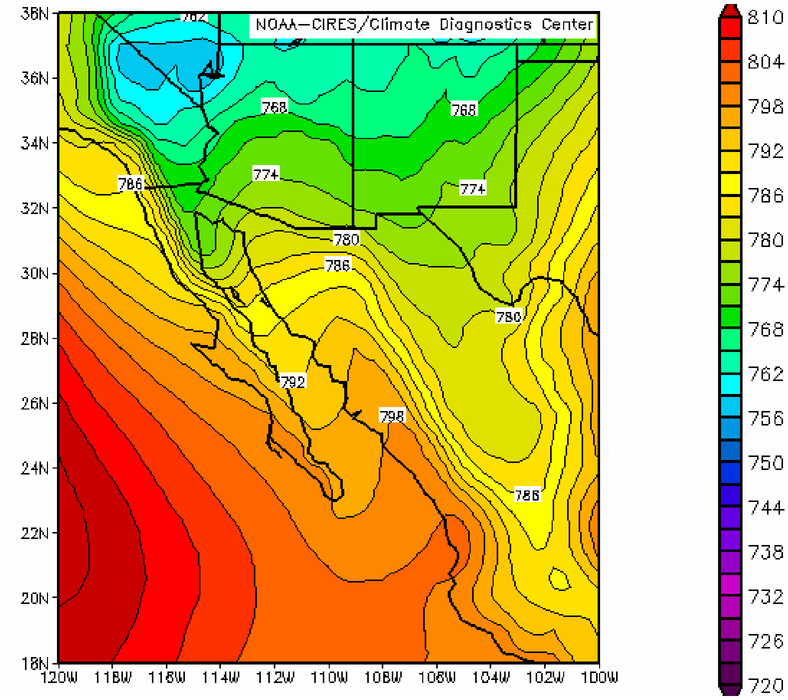


Figure 13. 850 hPa sub-synoptic composite for *(a)* day of monsoon retreat, *(b)* one day after monsoon retreat, and *(c)* one week after monsoon retreat.

(a)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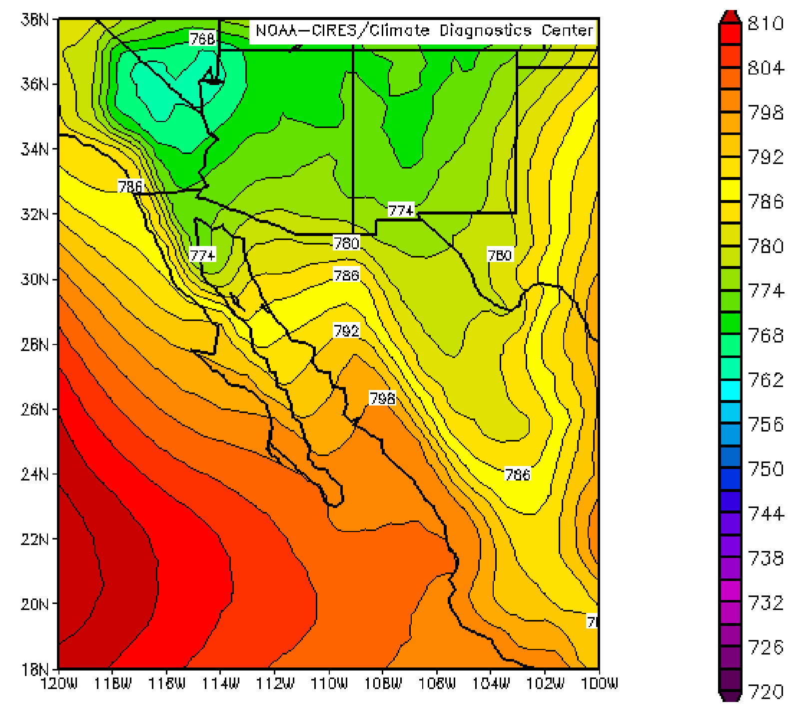
(b)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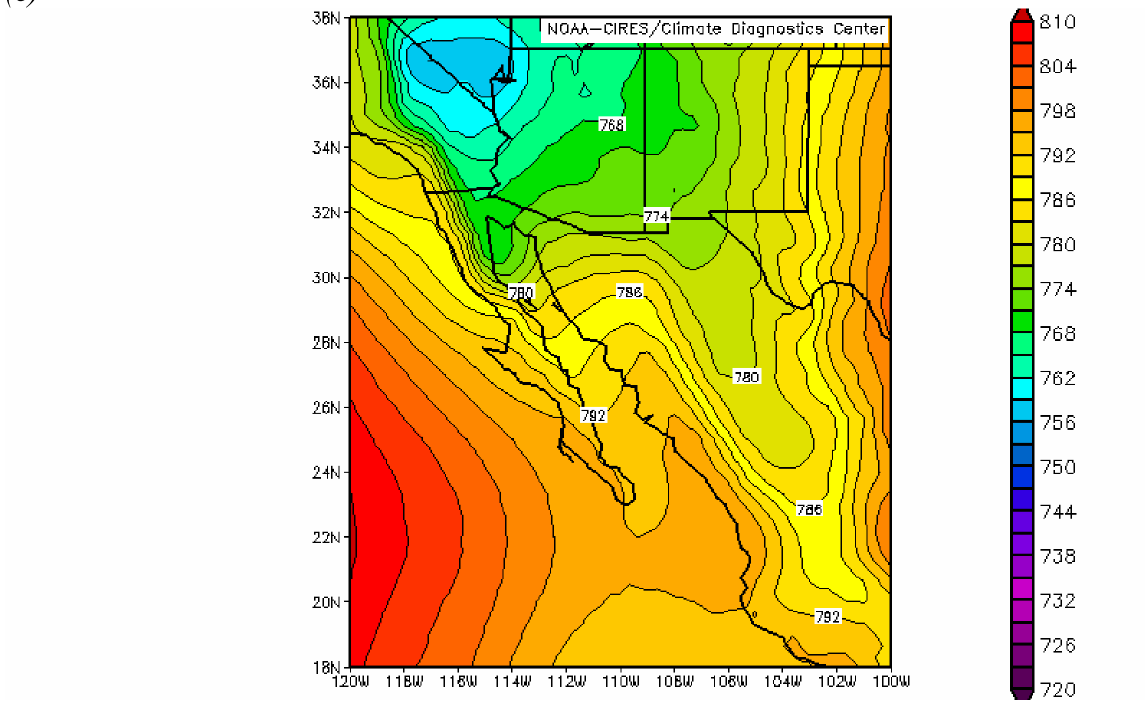
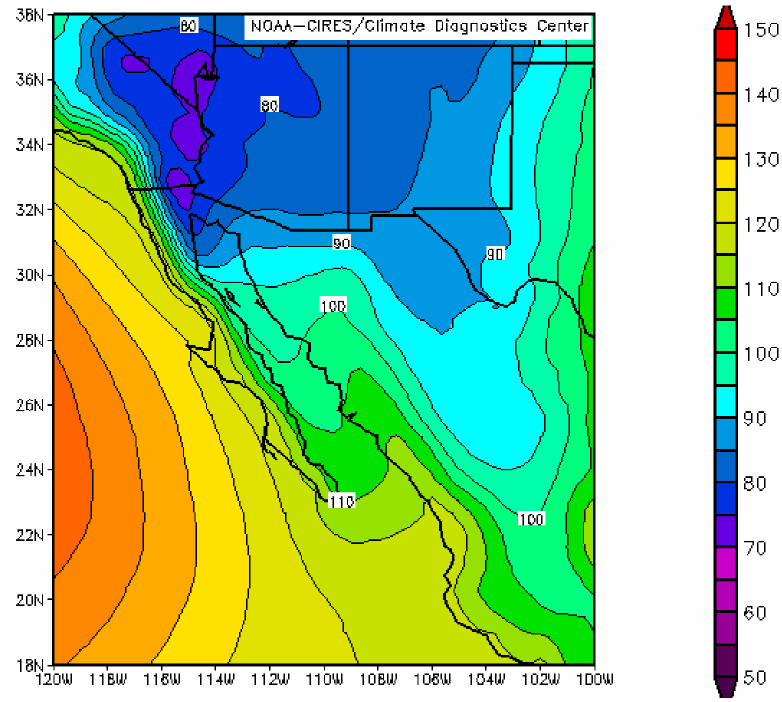


Figure 14. Same as Fig. 13*(a-c)*, except for 925 hPa.

(a)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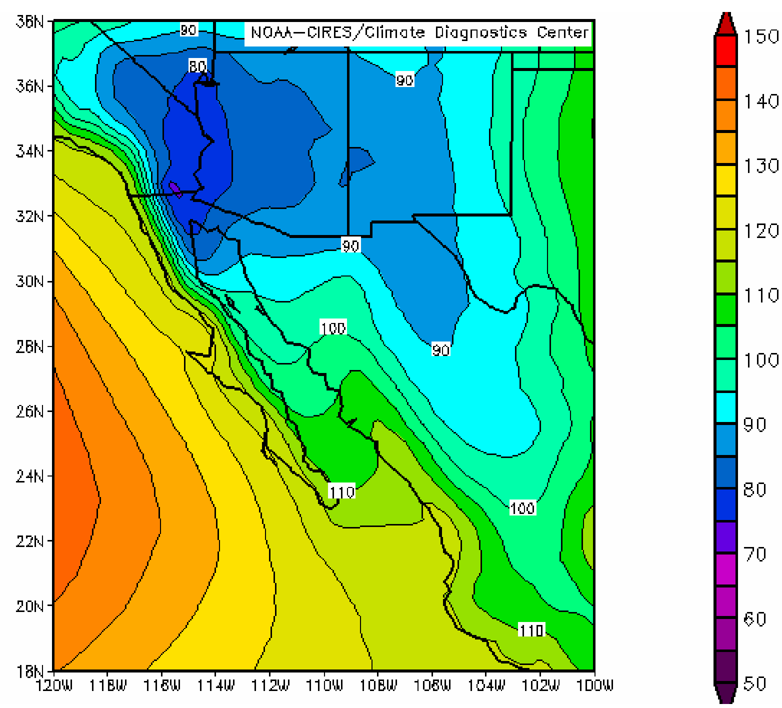
(b)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(c)

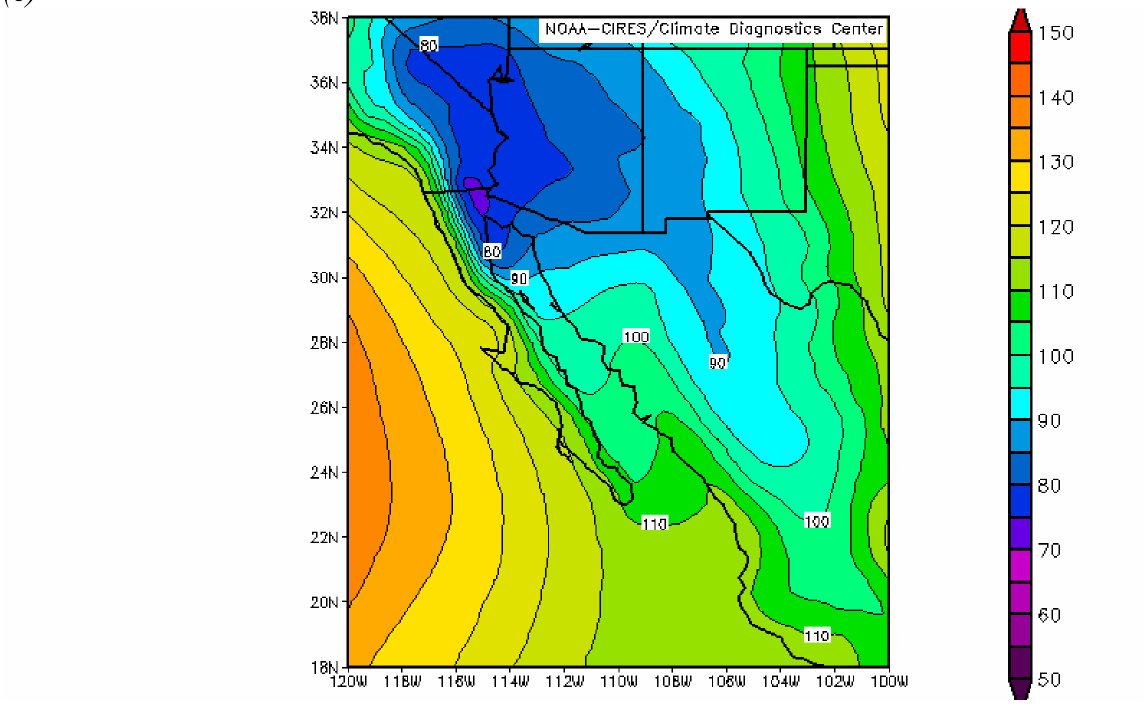

Figure 15. Same as Fig. 13*(a-c)*, except for 1000 hPa.

APPENDIX C

THE NORTH AMERICAN MONSOON SYSTEM AND WILDLAND FIRE FREQUENCY IN SOUTHERN ARIZONA

Richard R. Brandt, Andrew C. Comrie, and Stephen R. Yool

To be submitted to the *International Journal of Wildland Fire*

Abstract

While wildland fire in the western United States can be beneficial to ecosystem health as part of a natural cycle, the annual cost of firefighting reaches into the tens to hundreds of millions of dollars. Climate mediates the length and severity of the wildland fire season, but we currently do not understand fully the details of regional climate controls. Although researchers and fire managers agree that wildland fire occurrence in the Southwest generally declines during the monsoon period, but there is little published information on the details. This research uses wildland fire data for Arizona Climate Division 7 and dewpoint temperature at Tucson International Airport over the period 1977-2001 to analyze the fire-climate relationship, as well as the impact of monsoon burst and break timing and duration on wildland fire occurrence and a postulated post-monsoon increase in wildland fires. Some results are (1) wildland fire occurrence peaks approximately one week prior to the mean monsoon onset date; (2) early, long breaks (8-10+ days) produce the greatest intra-monsoon wildland fire increase; and (3) on average, there is only a very slight increase in post-monsoon wildland fire, although a larger upswing occurs in some years.

Introduction

Wildland fire in the western United States is part of a natural cycle of maintaining ecosystem health, but the cost of firefighting reaches into the tens to hundreds of millions of dollars annually. Climate mediates the duration and severity of the wildland fire season, but we lack a detailed understanding of regional climate controls. There is a consensus that wildland fire occurrence decreases with increased monsoonal moisture, but the details of their interaction are largely unknown. Data for some years also indicate a post-monsoon escalation in fires, or a second fire season during October or November. The analyses were mainly casual until recently (Mohrle 2003). Various authors have commented on the early monsoon wildland fire decrease or the post-monsoon increase (Swetnam and Betancourt 1990, Swetnam and Betancourt 1998, Grissino-Mayer and Swetnam 2000, Westerling et al. 2003, Crimmins and Comrie 2004), but they do not emphasize mechanisms. Understanding the intricacies of the wildland fire-monsoon relationship is important due to the strong environmental, societal, and economic impacts of fire and the monsoon in the southwestern United States.

The height of the wildland fire season in the southwestern United States generally occurs from mid-June to early July (Westerling et al. 2003) due to declining fuel moisture throughout the spring and lightning from high-based, or dry, thunderstorms in late spring and early summer (Watson et al. 1994). The decrease in fire activity from late June/early July to September can be attributed in part to the North American Monsoon System (NAMS). Atmospheric moisture and precipitation combine to increase fuel moisture after the monsoon onset.

The fuel moisture taxonomy relates plant diameter to the time (lag) necessary for the plant to reach two-thirds of its equilibrium with the surrounding environment and is based on a logarithmic scale (USFS 2006). Small-diameter plants, such as grasses and shrubs, are 1- or 10-hour fuels, while large-diameter plants, such as mature trees, are 100- to 1000-hour fuels. Small fuels react more rapidly to moisture advection associated with the monsoon. As atmospheric moisture and precipitation increase, these small fuels maintain or gain high moisture levels, making them less susceptible to fire ignition (Pyne et al. 1996). Monsoon breaks, or periods of low atmospheric moisture and precipitation, therefore, affect wildland fire activity. Depending on the fuel diameter and the duration of a break, sufficient moisture loss may occur, resulting in a more easily ignited fuel.

The impact on fire incidence likely depends on the duration and timing (early vs. later in the rainy season) of the break. This topic is a void in the current literature. A recent study did consider the fire season-monsoon link in southern Arizona using dewpoint temperature and minimum, i.e., afternoon, relative humidity and suggested a dewpoint threshold or “critical range” for natural fire occurrence (Mohrle 2003). This research, however, does not explicitly discuss the relationships between breaks and wildland fire.

We investigate hypothesized associations between wildland fire frequency and the NAMS in southern Arizona. Determining these associations is necessary to understand the temporal variations in wildland fire patterns. This research has three aims: (1) to determine the relationship between the end of the wildland fire season and the onset of the monsoon; (2) to decipher intra-seasonal and interannual variations in wildland fire occurrence during monsoon breaks; and (3) to examine the nature and causes of the post-monsoon increase in fire occurrence and its variability.

Study Area

Arizona Climate Division 7 (AZCD 7), which covers southern Arizona (Figure 1), experiences many wildland fires annually, with some blazes exceeding several tens of thousands of acres. Much of the region is characteristic of the Basin and Range topography of the western U.S. Elevations vary from approximately 200 meters above mean sea level (msl) in the desert valleys of the west to nearly 3000 meters msl in the southeast-to-northwest oriented mountain ranges of the east.

Data and Methods

Wildland Fire Data

The Laboratory for Tree-Ring Research at the University of Arizona supplied fire data from 1977-2001 for AZCD 7. The records contain the start date, location by latitude and longitude, elevation, and acres burned for each reported fire. We do not distinguish between ignition sources (human- versus lightning-caused) nor do we include prescribed burns.

Climate Data

Mean daily dewpoint temperatures (T_d) at Tucson International Airport (TUS) from 1984-2001 was acquired from the National Climatic Data Center (NCDC) database.

Hourly T_d data for 1977-1983 were obtained from the NCDC surface and upper-air observations. The mean daily T_d was calculated by averaging the hourly values over 24 hours for this period. We then determine monsoon onset and ending dates and burst and break periods using a modification of the Tucson NWS technique (Brandt submitted).

Breaks are designated as periods of two or more days when the mean daily T_d drops below 54°F at TUS. Bursts refer to periods of two or more days when the mean daily T_d is 54°F or greater. We divide breaks into four categories based on timing and duration (Table 1). "Early" refers to a break that occurs in the first half of the monsoon, while a "late" break occurs in the second half of the monsoon. A short duration break is six days or less, while a long break last for seven days or more. Of the 78 breaks during the monsoon periods from 1979-2001, the majority were long short breaks, followed by early short breaks.

Results and Discussion

Wildland Fire Analysis

Analysis of the seasonal fire incidence in AZCD 7 over the 25-year period follows the expected temporal pattern. There is a fairly steady increase in occurrence from January to April, followed by a sharper increase through June (19.33% of the annual fire count from April to June), a steep decline through August (21.8% of the annual fire count from June to August), and then low fire frequency through the end of the year (Figure 2). Other researchers have found a similar wildland fire pattern (Westerling et al. 2003).

The May through October period accounts for at least 58% of the fire count during individual years and 75.4% of fires over the entire study period. The second value is much lower than the 94% that Westerling et al. (2003) report for the entire western United States, which is indicative of the regional variation in seasonal precipitation patterns. The wet season for much of the West occurs during the winter months, whereas southern Arizona records much of the annual precipitation (45 to 60%) during July, August, and September (Douglas et al. 1993, Glueck 1997).

A small late-year increase in wildland fire occurrence appears in October and/or November during some years. These months represent a brief dry period between monsoon retreat and the beginning of the winter wet season (Glueck 1997). During the two-month dry spell, fuel moisture levels decrease, leading to the heightened potential for fire activity. Natural fires in this period could result from lightning produced by thunderstorms associated with decaying eastern North Pacific tropical cyclones or synoptic-scale weather systems in the westerly flow. A greater number of wildland fires in October and November may also be human-caused as recreational activity increases during this relatively cooler period.

The mean weekly fire count from late April/early May through late October/early November for 1977-2001 is shown in Figure 3. The five-week running mean reveals a wildland fire increase through May and early June, a peak in late June to early July, and a downward trend through early fall. Week 26 (late June/early July) represents the peak in mean weekly wildland fires at 14.36. There is an initial rapid decline of approximately four fires per week after week 26, especially through week 30 (late July/early August), followed by a drop in the rate of decrease. This weekly pattern is consistent with the general descriptions provided in previous studies (Swetnam and Betancourt 1990, Swetnam and Betancourt 1998, Grissino-Mayer and Swetnam 2000, Westerling et al. 2003).

End of the Wildland Fire Season and the Onset of the NAMS

Analysis of wildland fire occurrence on a weekly scale reveals more detail about the relationship between the decrease in fire frequency and the monsoon than previous monthly comparisons (Figure 3). A downward trend in wildland fires occurs after monsoon onset. The rate of pre-monsoon fire increase from late April through early July is more gradual than the decrease after monsoon onset. The trend decreases from approximately 14 fires per week before mean onset to approximately 3 fires per week around the mid-monsoon period (mid-August), followed by low fire occurrence (< 3 fires per week) through the monsoon retreat. This pattern can be explained in large part by the fuel moisture characteristics. The increase in atmospheric moisture and precipitation during the monsoon raises fuel moisture, which is sufficient to preclude a continued high fire frequency.

The largest number of fires occurs approximately one week prior to the mean onset of the monsoon. Since averaging the fire frequency for the 25-year period smoothes the finer temporal scale (annual) variation in fire count, we also analyzed individual years. In 80% (20 of 25) of the years, the peak wildland fire frequency occurs within three weeks of monsoon onset. The difference is likely attributable to: (1)

precipitation/moisture conditions prior to the monsoon, but not necessarily limited to the preceding winter, (2) number, frequency, and location of pre-monsoon dry thunderstorms, (3) synoptic-scale or smaller-scale atmospheric circulation, (4) ocean-atmosphere teleconnections, (4) wildland fire activity in previous years, or (5) landscape modifications and other human factors. Variation in any or all of these factors can influence patterns in subsequent years. Such distinctions are beyond the scope of this study.

Wildland Fire and Monsoon Breaks

Some years containing early breaks have only a 3-day period that reached monsoon onset criteria, followed by breaks of varying duration. An increase in wildland fires occurs, apparently related to the break, during some of these years (e.g., 1989), but not in others (e.g., 1988; not shown). The breaks in these years tend to be much shorter than the breaks in 1991 and 1995 (Figures 4a-b), which are discussed in more detail below. A similar pattern is seen in years with short breaks later in the monsoon, such as 1987 and 1998 (not shown). When an increase in wildland fires occurs with the late breaks, it is not as dramatic as in the early break cases. Therefore, break timing, i.e., early versus late, has varying impacts on wildland fire activity.

Wildland fire occurrence and rate of change in the fire count also vary with break duration; longer breaks tend to result in increased wildland fire occurrence in most cases. We use four years – 1991, 1995, 2000, and 2001 – to illustrate the complicated relationships for long breaks (Figures 4a-d). All years show an increase in wildland fires during or after a long break, although the magnitude varies. For example, 2001 (Figure 4d) has only a small increase, despite being of similar duration to 1995 (Figure 4b). Years with short-duration breaks tend to show little, if any, increase in wildland fires. Additional drying time for fuels during longer breaks can explain this variation. The duration of the long breaks is also longer than anticipated. While some years do have increased fire activity with breaks as short as five days, more substantial increases and higher peaks in the number of fires occur when breaks are at least 8-10 days long.

These findings suggest that long breaks require further analysis, specifically with respect to break timing. We examine 1991, 1995, 2000, and 2001 to determine the influence on wildland fire activity of both early and late long breaks. Early, long breaks occur during 1991 and 1995, while late, long breaks occur during 2000 and 2001.

The break in 1991 begins five days into the monsoon (onset date = 4 July) and continues for 10 days (9-18 July; Figure 4a). In 1995 the break starts ten days after monsoon onset (onset date = 11 July) and persists for 17 days (21 July-6 August; Figure 4b). The two years are different in terms of total reported fires (198 in 1991 vs. 438 in 1995) and weekly fire count, but they show similar patterns in the response of wildland fire to extended breaks. An increase of 10 fires per week occurs in 1991, while 1995 has an increase of 14 fires per week.

A late, long break (9 days from 1-9 September) in 2000 takes place after a 42-day burst (Figure 4c). This break occurs over a month prior to monsoon retreat. In 2001, a late, long break continues for 14 days (18 September-1 October). A 6-day burst precedes it, and the monsoon retreats six days later (8 October; Figure 4d). These two years are fairly similar in number of fires (342 in 2000 and 251 in 2001), with the main differences being 85 more fires from January through April in 2000 and a slight variation around weeks 29 and 30 (mid- to late July). The late monsoon wildland fire patterns are similar, with a slight increase after the break. The rate of increase is much less substantial (only four fires per week) than during the early, long breaks in 1991 and 1995, potentially due to the accumulated precipitation and fuel moisture. Relatively longer breaks would be necessary later in the season to reduce fuel moisture to levels recorded just after the monsoon onset.

The combination of timing and duration of monsoon breaks is therefore much more important in producing an increase in wildland fires than either timing or duration alone. Early, long breaks produce the greatest increase in intra-monsoon wildland fire occurrence. While other scenarios (early, short breaks, late, short breaks, or late, long breaks) may result in an escalation in fires, no consistent pattern exists within each division.

The fire pattern within a break follows the expected model of an initial decrease, followed by an increase near the end of the break or during the subsequent burst. Details, such as fire count per week and magnitude and timing of decrease or increase, differ however. The variations may result from a combination of different fuel types, fuel moisture levels, atmospheric moisture levels, previous precipitation, thunderstorm activity, length and timing of the break, or prior fire activity in the area.

Post-monsoon Wildland Fire Occurrence

On average, no post-monsoon wildland fire increase occurs at the monthly level (Figure 2), and only a very slight increase is present in the weekly data (Figure 3). It occurs during weeks 41 and 42 (early to mid-October), which is 3-4 weeks after the mean monsoon ending date. The cause of this increase, which takes place after wildland fires decrease during the first two weeks following the monsoon retreat is unclear. It may result from a longer fuel drying time and could be related to natural or human factors.

A slight upswing in wildland fires is seen during some years. Fire data for an example year, 1991, are shown in Figures 4a (weekly) and 5 (monthly). The increase occurs in October and represents a difference of only 7 fires between September and October. (November also has a higher fire count than September.) The weekly data show that fire count decreases to zero near the end of the monsoon. After a five-day break, the monsoon ends (23 September) with a seven-day burst. The increase in fires after the end of the monsoon occurs during the first three weeks of October, followed by a drop to zero fires during the last week of the month and a low number thereafter. The reason for the increase is uncertain, but post-monsoon drying of fuels combined with human-caused ignitions are likely factors. Other years with a post-monsoon upswing in wildland fires show similar patterns.

In all cases when an increase in wildland fire occurrence is present, it is small relative to other periods. The month of incidence varies, with the most cases in November, followed closely by October. October, however, accounts for a higher percentage of increase. These months represent a brief dry period between the monsoon and the winter wet season (Glueck 1997). During October and November, fuel moisture levels decrease, leading to the higher fire potential. Natural fires during this period may result from thunderstorms associated with either decaying eastern North Pacific tropical cyclones or synoptic-scale weather systems in the westerly flow. Many of these late-year fires likely begin in smaller fuels as a result of human ignition.

Conclusions and Recommendations

The relationships between the wildland fire season and the NAMS in southern Arizona are quite complex. Because of the impacts of wildland fire, both beneficial and detrimental, previous research has attempted to characterize wildland fire-climate relationships for the entire western U.S. These studies provide useful results, but smaller scale investigations, such as Mohrle (2003), Crimmins and Comrie (2004), and the current one, are needed to understand the regional climate controls on wildland fire season duration and severity.

This research uses fire data for AZCD 7 and T_d recorded at Tucson International Airport to study relationships between the wildland fire season in southern Arizona and the NAMS. After an initial analysis of temporal wildland fire patterns, we investigate (1) the connection between the end of the wildland fire season and monsoon onset, (2) the intra-seasonal and interannual wildland fire response to breaks, and (3) the nature of post-monsoon fire occurrence and activity.

The peak in mean wildland fires typically occurs approximately one week prior to the mean monsoon onset date. In 20 of the 25 years, the peak occurs within three weeks of onset. After onset, the average fire count decreases from 14 fires per week at the monsoon onset to approximately 3 fires per week at the mid-monsoon period, followed by a slight decrease or steady frequency through the end of the monsoon. The decrease in fire activity can be attributed in part to higher fuel moisture.

Break timing and duration have diverse effects on wildland fire activity. The timing of breaks shows no consistent impact on wildland fire occurrence, perhaps related to the lack of correlation between break timing and mean break T_d. Break duration, however, does affect wildland fire. Long breaks, i.e., more than 8-10 days, tend to result in both a more substantial increase and a higher peak in wildland fires, while short breaks tend to show little or no increase in wildland fires. The additional drying time for fuels during longer breaks may explain this conclusion.

The combination of break timing and duration is the most important factor on intra-monsoon wildland fires, with early, long breaks producing the greatest wildland fire increase. Early, long breaks occur before strong moisture advection and precipitation impact fuel moisture levels (timing). If fuel moisture does increase, the length of the break (duration) will affect moisture loss. Other combinations of timing and duration – early, short breaks, late, short breaks, and late, long breaks – have inconsistent effects.

The fire pattern within a break generally involves an initial decrease, followed by an increase toward the end of the break or during the subsequent burst, likely due to the increase in thunderstorms. Weekly fire and magnitude and rate of decrease or increase differ due to any combination of factors.

A slight increase in wildland fires in early to mid-October is present in the weekly data. On average, there is no monthly increase in post-monsoon wildland fires, despite upswings during October and/or November in individual years, which is a climatologically dry period between the monsoon and a secondary wet season during the winter.

This study focuses on a specific relationship between the monsoon and wildland fire, i.e., dewpoint temperature as a control of wildland fire frequency, and it, therefore, is not intended to represent the full complexity of the relationship. Rather, it is a stepping-stone to further investigations. One prospective direction is to consider how multiple factors, such as dewpoint, monsoon-period precipitation amount and intensity, burst or pre-break precipitation amount and intensity, soil moisture, and fuel moisture, affect monsoon-wildland fire frequency and size. Delineating fires by cause – natural versus human – in future research is also important to understand more completely the intricacies of the relationship between the monsoon and fire.

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Table 1. Break count and percentage by type for 1977-2001. Early breaks occur in the first half of the monsoon, while late breaks occur in the second half. Duration refers to short (≤ 6 days) and long (> 6 days).

Type of Break	Count	Percent of Period Total
Early short	25	32%
Early long	7	9%
Late short	31	40%
Late long	15	19%

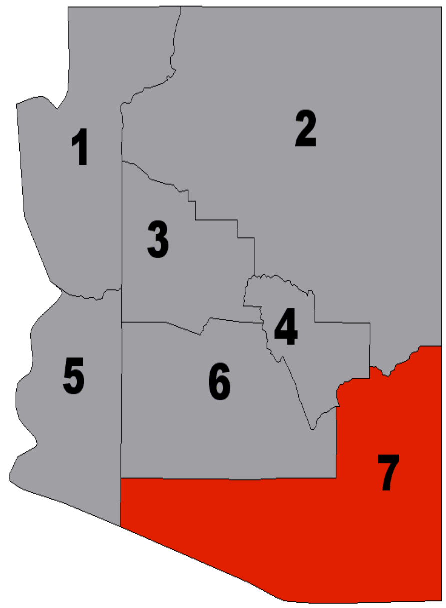


Figure 1. Climate divisions in Arizona. The study area, Arizona Climate Division 7 (AZCD 7), is highlighted.

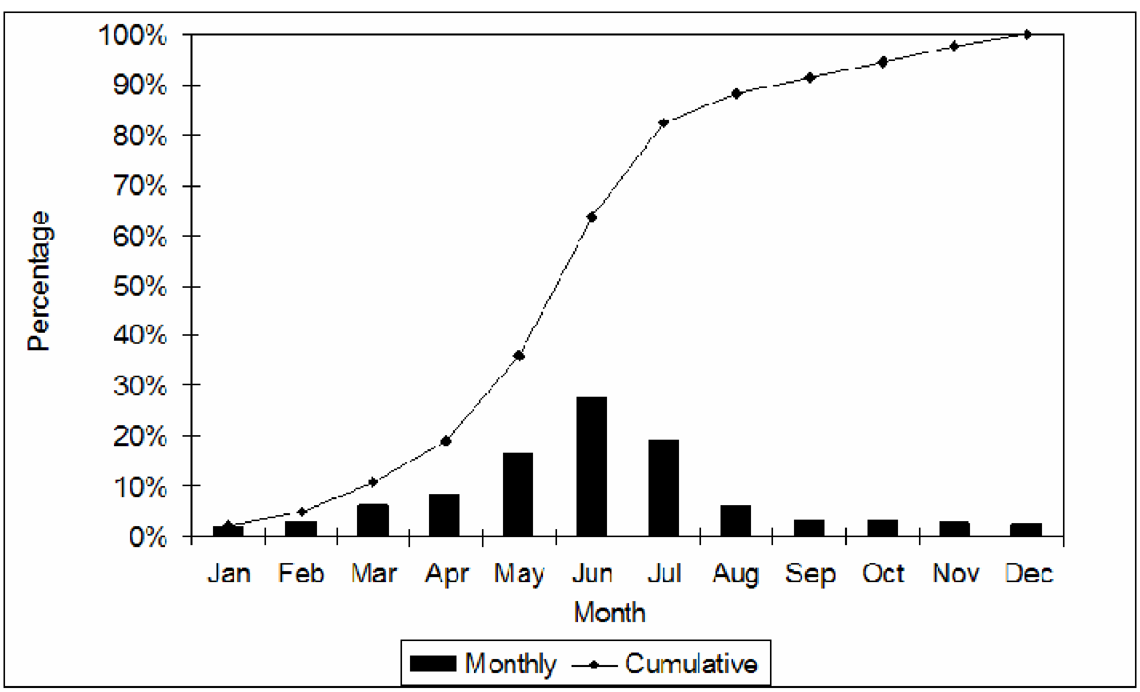


Figure 2. Monthly (bars) and cumulative (line) percentage of wildland fires (1977-2001) in AZCD 7.

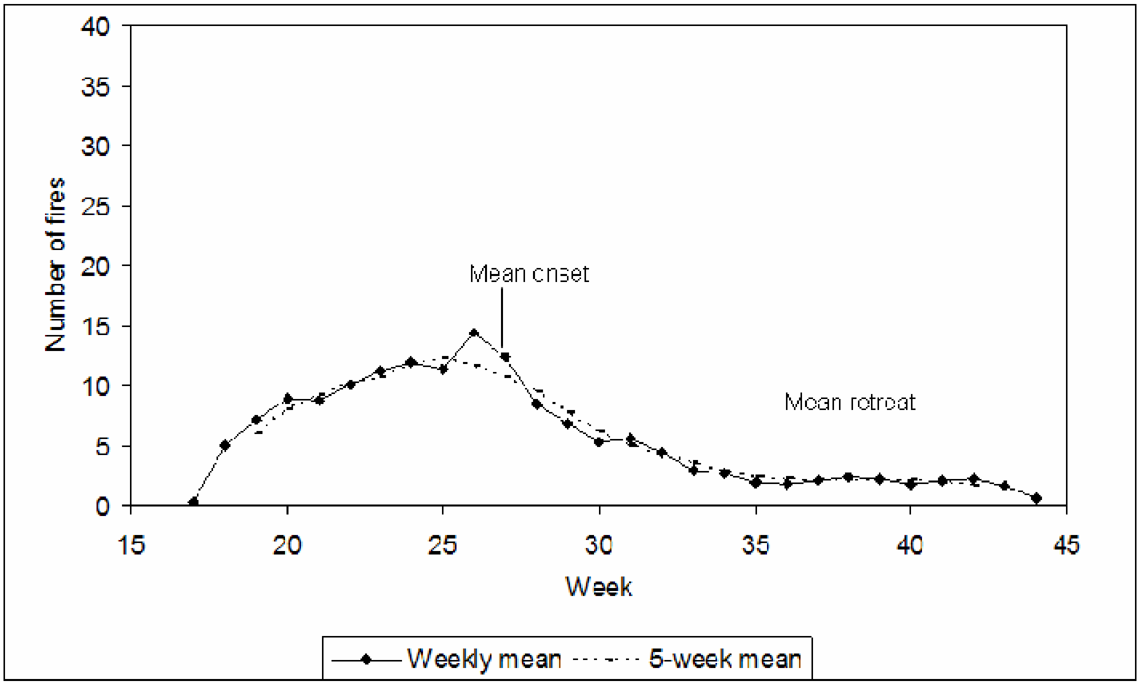
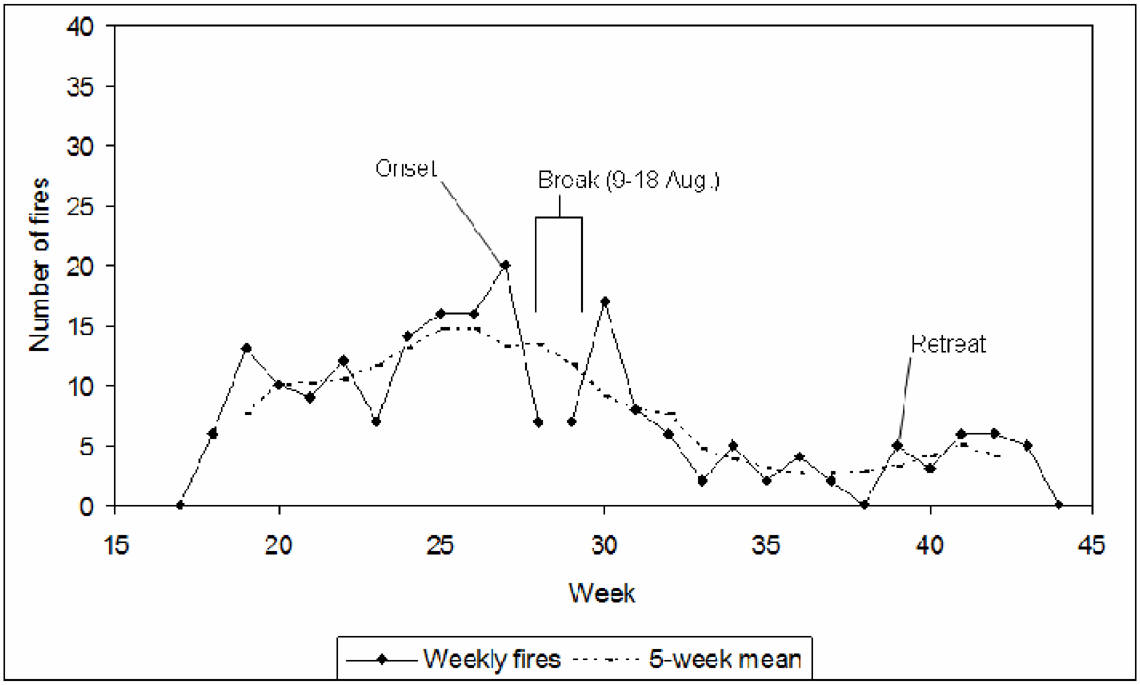
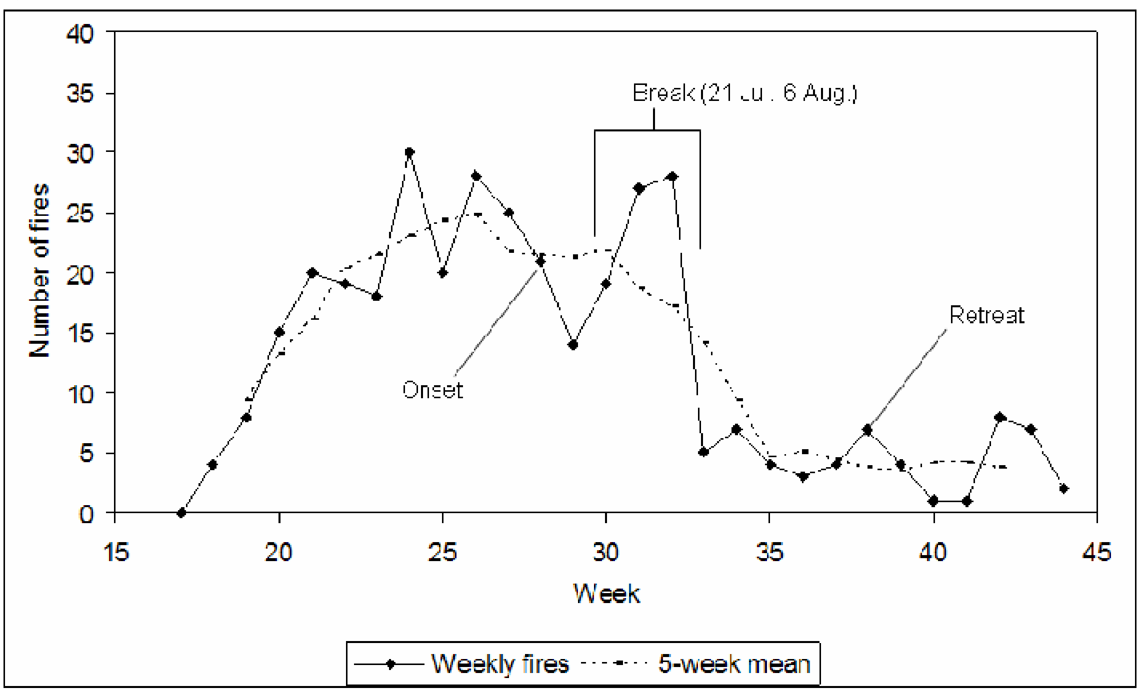


Figure 3. Mean wildland fire count by week of year from late April through early November (1977-2001) in AZCD 7. The solid line indicates the mean number of wildland fires per week. The dotted line indicates the 5-week running mean. Mean monsoon onset and retreat are labeled.

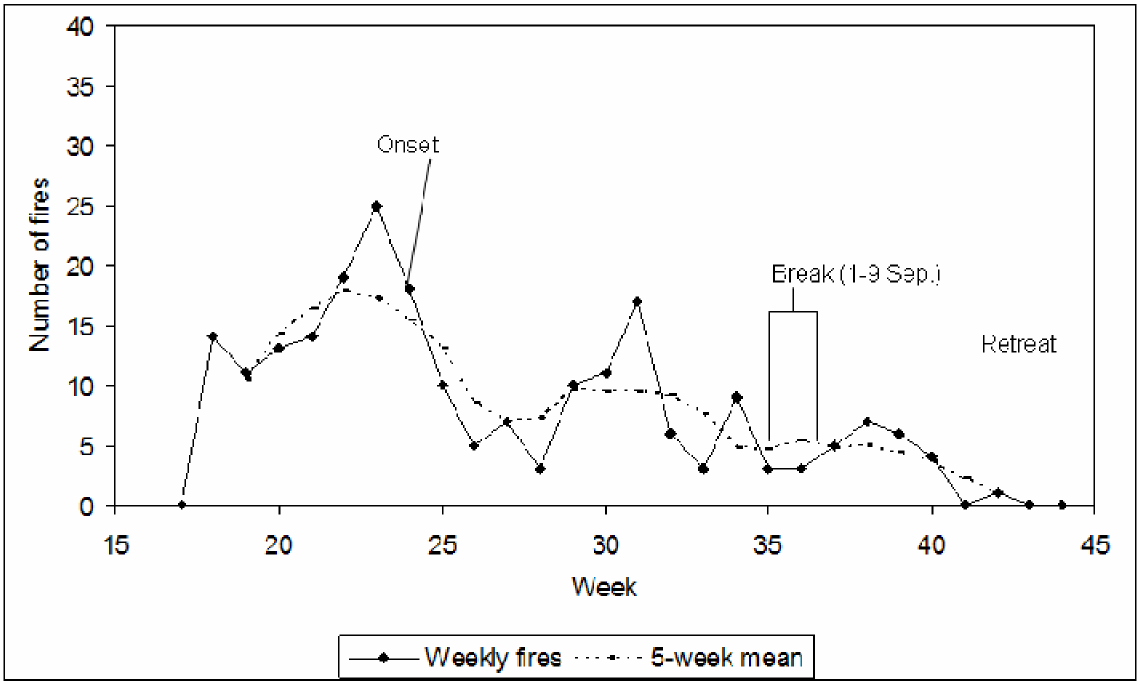
(a)


Number of fires
Week
Onset
Break (9-18 Aug.)
Retreat
Weekly fires
5-week mean

(b)


Number of fires
Week
Break (21 Ju . 6 Aug.)
Onset
Retreat
Weekly fires
5-week mean

(c)


40
35
30
25
20
15
10
5
0
Number of fires
15
20
25
30
35
40
45
Week
Onset
Break (1-9 Sep.)
Retreat
Weekly fires
5-week mean

(d)

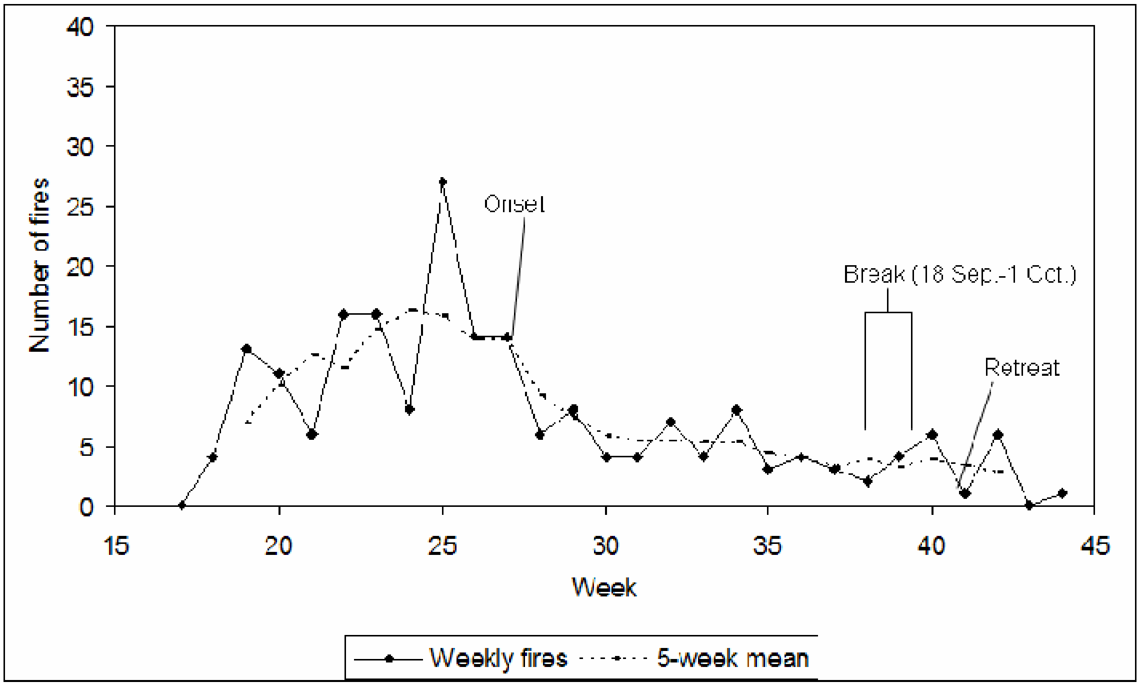


Figure 4. Wildfire count by week of year from late April through early November during *(a)* 1991, *(b)* 1995, *(c)* 2000, and *(d)* 2001 in AZCD 7. The solid line indicates the mean number of wildland fires per week. The dotted line indicates the 5-week running mean. Mean monsoon onset and retreat and break periods are labeled.

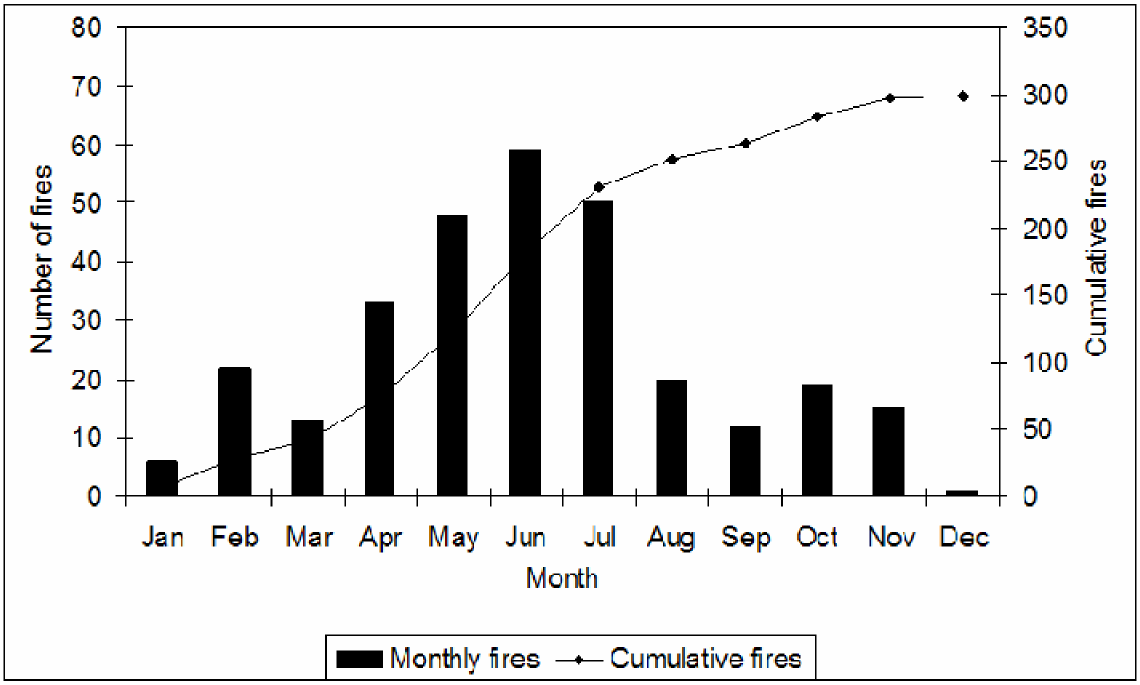


Figure 5. Temporal fire pattern for during 1991 in AZCD 7. The bars indicate monthly count. The line indicates cumulative count.