Spatio-Temporal Variability of the North American Monsoon

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Abstract

Analysis is performed on the spatio-temporal attributes of North American Monsoon rainfall in the southwestern USA. Results show a significant delay in the initiation, peak and closing stages of the monsoon in recent decades. Consequently, there is a decrease in rainfall during July and a corresponding increase in rainfall during August and September. Relating these attributes of the summer rainfall to antecedent winter/spring land and ocean conditions leads us to propose the following hypothesis: warmer tropical Pacific SSTs and cooler northern Pacific SSTs (i.e., a warm Pacific Decadal Oscillation (PDO)/ El Niño-Southern Oscillation (ENSO) pattern) in the antecedent winter/spring leads to wetter than normal conditions over the desert southwest (and drier than normal conditions over the Pacific Northwest). This enhanced antecedent wetness delays the seasonal heating of the North American continent that is necessary to establish the monsoonal land-ocean temperature gradient. The delay in seasonal warming in turn delays the monsoon initiation, thus reducing rainfall during the typical early monsoon (July) period and increasing rainfall during the later months (August and September) of the monsoon season. While the rainfall during the early monsoon appears to be most modulated by antecedent winter/spring Pacific SST patterns (PDO/ENSO), the rainfall in the later part of the monsoon seems to be driven largely by the SST conditions surrounding the monsoon region along the coast of California and the Gulf of California. The role of antecedent land and ocean conditions in modulating the following summer monsoon appears to be quite significant. This enhances the prospects for long-lead forecasts of monsoon rainfall over the southwestern US, which could have significant implications for water resources planning and management in this water-scarce region.

Introduction and Background

The North American Monsoon System (NAMS) is the large-scale atmospheric circulation system that drives the dramatic increase in rainfall experienced in the desert southwest U. S. and northwestern Mexico during the summer months of July, August and September. These summer thunderstorms typically begin in early July and last until mid-September and can account for as much as 50-70 percent of the annual precipitation in the arid region (Carleton et al. 1990; Douglas et al. 1993; Higgins et al. 1997; Mitchell et al. 2002; Sheppard et al. 2002). The variability of this important moisture source is of particular concern for watershed managers, ranchers, and planners of southwestern North America. Too little summer rainfall has negative agricultural and environmental impacts, while heavy summer thunderstorms present the danger of flash floods. Predicting the variability in the strength, location, and timing of monsoonal precipitation is understandably very important for local communities.

The North American Monsoon is established when the winds shift from a generally westerly direction in winter to southerly flow in summer. These southerly winds bring moist air from the Gulf of California, eastern Pacific Ocean and Gulf of Mexico northward to the land during the summer months (Adams and Comrie 1997). This shift in the winds is brought about by the landmass heating up in summer, thus increasing the land-ocean temperature gradient and bringing the winds from the relatively cooler ocean in over the land. The combination of moist air and warm land surfaces causes convective instability, thus producing frequent summer precipitation events (Adams and Comrie 1997; Barlow et al. 1998). The seasonal shift in the winds depends primarily upon the relative location of the subtropical jet, which typically migrates northward during the summer months. Several studies have shown that a more northward displacement of the subtropical ridge is associated with a wetter monsoon over the southwestern U. S. In years when the ridge stays in a more southerly position, the transport of tropical moisture is inhibited (Carleton 1986; Carleton et al. 1990; Adams and Comrie 1997; Comrie and Glen 1998; Ellis and Hawkins 2001; Hawkins et al. 2002).

Geographically speaking, the North American Monsoon is centered over the Sierra Madre Occidental, a mountain range in northwestern Mexico (Douglas et al. 1993; Barlow et al. 1998), however it extends into New Mexico, Arizona, southern Colorado and Utah (e.g., Hawkins et al. 2002; Douglas et al. 1993; Lo and Clark 2002). Several researchers (e.g., Brenner 1974; Hales 1974; Houghton 1979; Tang and Reiter 1984; Reiter and Tang 1984) have defined the North American Monsoon region to be much larger covering the entire plateau of western North America.

For several decades scientists have debated whether North American monsoonal moisture comes from the Gulf of Mexico or from the Gulf of California (e.g., Bryson and Lowry 1955; Rasmussen 1967; Hales 1972; Brenner 1974; Mullen and Schmitz 1998) Determining the source of monsoonal moisture is particularly important for prediction purposes. The general consensus today is that while the Gulf of California and eastern Pacific provide a large portion of total monsoonal moisture, the Gulf of Mexico also introduces an important component. Anderson et al. (2004) found that the western monsoon region receives more moisture from the Gulf of California and eastern Pacific while the eastern region receives most of its moisture from the Gulf of Mexico.

The complex nature of the moisture source and transport mechanism combined with extremely varied topography in the region make it extremely difficult to understand the variability of the North American Monsoon. Regionally, the intensity of the North American Monsoon decreases as one moves northward of the Sierra Madre Occidental. Not only is the intensity of the monsoon much weaker in the southwestern United States, but the variability of the monsoon is also much larger in these regions, sometimes larger than the mean summer rainfall itself (Higgins et al. 1998).

Temporal variability of the North American Monsoon ranges from diurnal to seasonal, to interannual, to interdecadal. Diurnal variability is dominated by precipitation peaking in the afternoon and early evening (Dai et al. 1999; Berbery 2001; Trenberth et al. 2003; Anderson and Kanamaru 2004). On an intra-seasonal scale, particularly the northern parts of the monsoon region experience wet and dry spells within a monsoon season. This is likely related to a gulf surge phenomenon that brings moisture up the Gulf of California in intermittent bursts (Hales 1972; Brenner 1974). Carleton (1986, 1987) demonstrated that periods of convective activity across the southwestern U. S. are associated with passing upper-level troughs in the westerlies. Also, as noted earlier, the position of the subtropical ridge significantly affects convective activity (Carleton 1986; Carleton et al. 1990; Adams and Comrie 1997; Comrie and Glen 1998; Ellis and Hawkins 2001; Hawkins et al. 2002).

Interannual variability is presumed to result from variability in certain synoptic-scale patterns as well as variability in the initial conditions of the landmass and Pacific Ocean SSTs. Carleton et al. (1990) observed that shifts in the subtropical ridge are related to the phase of the Pacific/North American (PNA) pattern (which is related to ENSO), where a positive (negative) PNA pattern in winter is typically followed by a northward (southward) displacement of the subtropical jet and a wet (dry) summer monsoon. Higgins et al. (1999) found that cold (warm) tropical Pacific SST anomalies appear near the dateline prior to wet (dry) monsoons and that the anomalies increase in amplitude during the spring. Other studies (Higgins and Shi 2000; Mo and Paegle 2000) found that anomalously cold SSTs in the northern Pacific and anomalously warm SSTs in the subtropical northern Pacific contribute to a wetter and earlier monsoon season. Castro et al. (2001) observed similar relationships with Pacific SSTs linking a high (low) PDO phase and El Niño (La Niña) with a southward (northward) displaced monsoon ridge and a late (early) monsoon onset and below (above) average early monsoon rainfall. Mitchell et al. (2002) determined certain threshold SST values for the northern Gulf of California that are associated with the regional onset of the North American Monsoon.

Land surface conditions also play an extensive role in the onset and intensity of the North American Monsoon. Within a monsoon season increased soil moisture impacts evapotranspiration between storm events, thus enhancing future storm systems and precipitation (Matusi et al. 2003). On an interseasonal scale, several studies have demonstrated an inverse relationship between winter precipitation, particularly snowfall, and subsequent summer precipitation (Gutzler 2000; Higgins and Shi 2000; Lo and Clark 2002). This relationship is thought to result from snowfall acting as an energy sink. Greater amounts of snowfall in winter require more energy to melt and evaporate the moisture by summer. Larger snow cover areas also increase the albedo in spring, thus reinforcing the relationship. The resulting delayed and decreased warming of the North American landmass upsets the land-ocean heating contrasts necessary for monsoonal circulation patterns, thus delaying and decreasing the intensity of the North American Monsoon. The relationship between winter snowfall and monsoonal precipitation, however, appears to vary spatially and temporally (Lo and Clark 2002). Relationships between monsoonal precipitation and runoff have not been extensively studied, though Gochis et al. (2003) found that runoff depends more on precipitation rates in individual local storms than on monthly total, basin-averaged precipitation.

The North American Monsoon system is very complex. While several synoptic-scale, topographic, and mesoscale relationships have been recognized, these relationships are not fully understood. Furthermore, there has been relatively little research on the variability of the seasonal cycle of the monsoon, which has important implications for water management. While several recent studies have illustrated an earlier onset of spring in the western United States (e.g., Dettinger and Cayan 1995; Cayan et al. 2001; Mote 2003; Stewart et al. 2004; Regonda et al. 2005), this has not been studied in relation to the NAMS.

This research sets out to investigate the space-time variability of the North American Monsoon in Arizona and New Mexico and its large-scale drivers. The paper is organized as follows: Data sets and the analysis methodology are first presented. Variability in the monsoon seasonal cycle and rainfall amounts are described, followed by their links to antecedent land and ocean conditions. A hypothesis for the relationships is also presented.

Data and Methods

The data sets and the methodology used in this study are described below:

Climate division data

Monthly precipitation, temperature, and Palmer Drought Severity Index (PDSI) data from 8 climate divisions covering New Mexico (NM) and 7 divisions for Arizona

(AZ) for the years 1948-2004 were used. The climate divisions and data sets are obtained from www.cpc.ncep.noaa.gov.

NWS COOP data

Daily precipitation data were obtained from the National Weather Service cooperative network (COOP). Most COOP stations have records beginning from the mid-1900s. Stations with continuous daily records from 1948-1999 across NM and AZ were selected - 219 stations in total.

NCEP/NCAR re-analysis data

Monthly values of large-scale ocean atmospheric variables, e.g., sea surface temperature (SST), geopotential heights, precipitable water, winds, etc., from the NCEP/NCAR re-analysis data (Kalnay et al. 1996) were obtained from http://www.cdc.noaa.gov.

Methodology

To understand the seasonal cycle and 'timing' of the monsoon, we first identify the Julian day when 10, 25, 50, 75, and 90 percent of the monsoonal (July-September) precipitation occurred for each year at all the COOP stations. The Julian day at these five thresholds helps capture the entire monsoon cycle. Nonparametric trend analysis based on Spearman rank correlation (Helsel and Hirsch 1995) is performed on these Julian days at all the stations. The Spearman rank correlation is similar to Pearson's R, except that it doesn't require that data be normally distributed, the values are converted to ranks before computing the correlation coefficient, and it is robust against outliers. The slope of the regression fit is used to calculate the magnitude (number of days) and direction (earlier or later) of the shift. The estimated trends in 'timing' are then spatially mapped. Similar analysis is performed on the monsoon monthly and seasonal rainfall amounts as well as the precipitable water.

To understand the physical mechanisms driving the trends, we analyze the relationship between antecedent (December-May) land/ocean conditions and summer rainfall. First, we perform the Spearman rank correlation analysis to detect trends in antecedent precipitation and soil moisture (Palmer Drought Severity Index, PDSI, is used as a proxy for this). Next, the leading modes of timing and rainfall amounts from the summer season are correlated with the antecedent ocean, atmosphere and land conditions. The leading modes are obtained by performing a Principal Component Analysis (PCA) on the Julian day and monthly rainfall timeseries. PCA is widely used in climate research. This method decomposes a space-time random field into orthogonal space and time patterns using Eigen decomposition and effectively reduces the dimensions of the data (e.g., von Storch and Swiers 1999). In PCA the patterns are automatically ordered according to the percentage of variance captured, i.e., the first space-time pattern, also called the leading mode or first principal component, captures the most variance present in the data, and so on. Typically, the first few modes capture most of the variance present in the data. In this research, we use the time component also known as Principal Component (PC) of the leading mode as an average spatial index. The leading modes were found to have similar magnitude and sign across the spatial locations and are highly correlated with the spatial average time series.

Composites of ocean/atmosphere variables (vector winds, 500mb geopotential heights and SSTs) during high and low monsoon precipitation years are created to provide corroborative evidence. We define high years as having monsoonal precipitation above the 90th percentile and low years as having monsoonal precipitation below the 10th percentile. The differences between the high and low composites are spatially mapped.

Analysis of the rainfall amount is performed using the monthly climate division data since, unlike the COOP data, this data set extends until the present. The COOP and climate division data, however, are quite consistent, and preliminary analysis found that the results are insensitive to the data set. For the timing analysis, the daily COOP data is required.

Results

The results from the trend analysis of the timing and rainfall amounts are presented first, followed by the relationships to antecedent large-scale climate variables and the physical mechanisms. Based on these results we put forth a hypothesis for the monsoon variability.

Monsoon Cycle

Julian day trends at the five threshold levels (10th, 25th, 50th, 75th, and 90th percentile) are shown in Figure 1. It can be seen that there is a significant delay in the entire monsoon cycle over the monsoon region. The shifts are on the order of 10 to 20 days. To put these shifts in perspective, the median Julian days, i.e., the median of all historical data for all stations, for these thresholds are also shown in Figure 1. Climatologically, the monsoon begins in early July, reaching 10% of the total precipitation by (or on) July 19th; the peak of the monsoon (when 50% of the precipitation has fallen) occurs around August 13th (roughly a week earlier in Arizona than in New Mexico) and the monsoon typically nears its end (when 90% of the total precipitation has fallen) roughly at the end of August and into the beginning of

September. The timing shift that delays the monsoon cycle would suggest an increase in August and September rainfall and a corresponding decrease in July rainfall. For supporting evidence, we look at the annual cycle of the rainfall using the monthly climate division data. The annual cycle of the rainfall at four representative climate divisions from the region for the period 1948-1975 and 1976-2004 are shown in Figure 2. A general decrease in precipitation in July and an increase in August and September in the recent period can be seen. Other climate divisions, particularly those in the lower regions, show similar changes to the annual cycle. These shifts are consistent with the shifts identified in Figure 1.

Monsoon Rainfall

Spatial trends in the monthly rainfall amount (July to September) are shown in Figure 3. It can be seen that precipitation is generally decreasing in July and increasing in August and September, with NM exhibiting a stronger trend. Also, a general increase in total monsoonal precipitation (July-September) is evident largely for NM – consistent with the increasing trend in August and September. The daily COOP station data showed very similar results (figure not shown). To further corroborate this result, we computed the trends in the July to September precipitable water (Figure 4). The precipitable water shows trends similar to the rainfall results. We note that the trends seen in the timing and rainfall amount should not be used for predictive purposes in and of themselves, but rather as diagnostic tool to help shed light on the key drivers of monsoon variability.

Hypothesis

The key question that emerges from the above analysis is: what is driving the delay in the monsoon cycle? For answers, we turn to the 'basics' of the monsoon process, i.e. the pre-monsoon land-ocean gradient. We hypothesize that there is increased antecedent (pre-monsoon) soil moisture in the southwestern U. S. that requires longer summer heating and delays the development of the necessary land-ocean temperature gradient, consequently delaying the summer monsoon. It is reasoned that the wetter winter and spring conditions in the southwestern U. S. are largely driven by winter ocean-atmospheric conditions, especially Pacific SSTs, the PDO/ENSO pattern and the observed increase in ENSO activity in recent decades (Trenberth and Hoar 1996; Rajagopalan et al. 1997). Links to the antecedent land, ocean, and atmosphere conditions offer hope for long-lead forecasts of the summer monsoon. This hypothesis is tested in the following sections.

Antecedent Land Conditions

To determine whether the antecedent land conditions are getting wetter, we examined the trends in the precipitation and PDSI for the December – May season (Figure 5). The PDSI is an integrated measure of rainfall and temperature and is thus, a good indicator of the soil moisture. A significant increasing trend in the winter/spring precipitation and PDSI over the desert southwest can be seen. Also, a corresponding decreasing trend over the Pacific Northwest is apparent. Increased precipitation in the southwest and decreased precipitation in the northwest is typical of PDO/ENSO teleconnections in the western U. S. identified by several researchers (Ropelewski and Halpert 1986; Redmond and Koch 1991; Cayan and Webb 1992; Cayan et al. 1999).

To further demonstrate the strength of the link between antecedent land conditions and the timing of the monsoon, we correlate the leading mode of the monsoon timing with the pre-monsoon land conditions. Figure 6 a, b shows the correlations between the first PC for the monsoon peak, i.e., the Julian day when 50 percent of the total seasonal rainfall has occurred, and the winter/spring (December-May) precipitation and PDSI. The first PC explains 28% of the total variance, has similar magnitude and sign across all stations and is highly correlated with the spatial average, hence it can be regarded as the regional monsoon "timing index". Significant positive correlations exist between the regional monsoon timing index and antecedent precipitation and PDSI over the monsoon region. These positive correlations indicate that an increase in the monsoon peak's Julian day (i.e., a late shift in the monsoon) occurs with increased rainfall and soil moisture during the preceding winter/spring, thus supporting the proposed hypothesis. A negative correlation over northwestern U. S. is also evident– this is typical of the PDO/ENSO teleconnection pattern noted in the previous paragraph. When the timing of the onset of the monsoon is considered, this correlation pattern becomes even stronger. Figure 6 c, d presents the correlations between the first PC of the monsoon onset (i.e., the Julian day when 10 percent of the seasonal rainfall has occurred) and the antecedent conditions. This PC captures 31% of the total variance and can be thought of as the leading mode of the monsoon onset. It is noted that the relatively low values of 28% and 31% of the total variance accounted for by the first PC's can be explained by the noise in the daily data. The leading PC in all the cases, however, provides a robust measure of the spatial average.

Correlations between the leading mode of the summer (July – September) monsoon rainfall amount and antecedent precipitation (Figure 7a) show a negative correlation pattern over the monsoon region and positive over northwestern U. S. The results are similar for the antecedent PDSI (figures not shown). Interestingly, the correlation pattern for the leading mode of the July rainfall amount (Figure 7b) is even stronger, indicating that the onset of the monsoon is most affected by antecedent conditions. These results are consistent with the timing results presented above: as pre-monsoon land moisture increases the monsoon is delayed, thus decreasing monsoonal precipitation in July. The negative relationship between winter/spring precipitation and summertime precipitation over the southwestern U. S. has also been noted in previous studies (e.g., Gutzler 2000). Similar results were obtained when the PCA was performed separately for Arizona precipitation and New Mexico precipitation and each of these leading PCs were correlated with antecedent land conditions. In general, correlations with Arizona tended to be slightly stronger. Table 1 shows the percent of total variance captured by the leading PCs.

These results indicate that the preceding winter/spring land conditions (i.e., precipitation, soil moisture) tend to most strongly affect the timing of the monsoon initiation and the early monsoon rainfall amount (i.e., July rainfall). That is, a wetter winter/spring tends to delay the monsoon cycle and decrease the early monsoon rainfall, and vice-versa.

Antecedent Ocean Conditions

It is generally accepted that the enhanced wet (dry) conditions over the southwestern (northwestern) U. S. in winter and spring seasons are largely due to warm

PDO/ENSO conditions (Ropelewski and Halpert 1986; Redmond and Koch 1991; Cayan and Webb 1992; Cayan et al. 1999). Consequently, the winter/spring ocean conditions should also be related to the following monsoon. To investigate this explicitly, we relate the monsoon attributes (timing and rainfall amount) to the antecedent ocean conditions.

Correlations between the winter/spring (December-May) SSTs and the leading mode of the following monsoon's peak Julian day exhibit strong negative values in the northern Pacific Ocean in a pattern similar to the warm PDO phase (Mantua et al. 1997) (Figure 8a). This pattern is stronger with the leading mode of the early monsoon Julian day (Figure 8b). This suggests that cooler than average SSTs in the northern Pacific during winter/spring are associated with a delay in the following monsoon cycle. Though not as strong, the opposite correlation pattern is seen for the tropical Pacific SSTs, also reminiscent of the PDO pattern or a broad ENSO pattern. The PDO is generally believed to be the low frequency expression of ENSO and independence of the two from each other is still in question (Newman et al. 2003). These correlations indicate that below average SSTs in the north Pacific and above average tropical SSTs (warm PDO/ENSO) in winter/spring tend to increase (i.e., delay) the monsoon timing. We propose that this occurs via the increased winter/spring precipitation over the monsoon region resulting in a weaker land-ocean gradient which delays the monsoon initiation.

We correlated the leading mode of the monthly and summer seasonal monsoon rainfall amount with the antecedent ocean conditions (Figure 9). The SST correlations with the July rainfall (Figure 9a) exhibit a clear PDO/ENSO connection. That is, warmer northern Pacific SSTs and cooler tropical Pacific SSTs (i.e., cool PDO/ENSO conditions) during winter/spring are related to increased monsoon rainfall during July. The cool

PDO/ENSO conditions result in decreased winter/spring precipitation over the southwest U. S. increasing the land-ocean temperature gradient and the resulting monsoonal precipitation in July. The correlation pattern reverses and is much weaker (Figures 9b, c, d) for the August, September, and total seasonal precipitation. This indicates that the antecedent winter/spring ocean conditions have a stronger impact on the early monsoon (July) rainfall. This is consistent with the results obtained for the antecedent land conditions described in the previous section.

This leaves us to question what large-scale features, if any, affect the late monsoon (August-September) rainfall. To explore this, we correlated the leading modes of August and September rainfall with the near term and concurrent ocean conditions. Figure 10 (a, b) shows the correlation between the leading mode of the August rainfall and the preceding July SST and concurrent August SST, respectively. Figure 10 (c, d) similarly presents the SST correlations with the leading mode of the September rainfall. We notice that the leading mode of rainfall in these months is related to SSTs near the California coast and Gulf of California. These SSTs could be part of the larger tropical Pacific SST pattern (such as the case for August rainfall – Figure 10a,b) or much more localized as in the case of September rainfall. We hypothesize that the September correlations are weaker due to the monsoon ending sometime in mid-September.

Composite maps of the average SST difference between high and low rainfall years during the three monsoon months (Figure 11) corroborate the previous results by showing a cool PDO/ENSO pattern for July and more localized warm SSTs in the California cost and gulf region for August and September. The 500mb geopotential height and vector wind composites are consistent with the SST patterns (Figure 11). The geopotential height composite also shows the typical PNA pattern known to modulate monsoonal precipitation (Carleton 1986; Carleton et al. 1990; Adams and Comrie 1997; Comrie and Glen 1998; Ellis and Hawkins 2001; Hawkins et al. 2002).

Summary and Conclusions

A systematic analysis of the spatio-temporal attributes of North American Monsoon in Arizona and New Mexico was performed in this study. Trends in the Julian day of the 10^{th} and 50^{th} percentiles of summer rainfall indicate a significant delay (approx. 10-20 days) in both the initiation and peak of the summer monsoon in Arizona and New Mexico. This delay in the monsoon cycle leads to a decrease in rainfall during the early monsoon (July) and corresponding increase during the later period (August and September). The antecedent (winter/spring) rainfall and soil moisture (PDSI) show an increasing trend over the southwestern U. S. monsoon region and a decreasing trend over the northwestern U. S. – this is consistent with the well-known PDO/ENSO teleconnections in the western U. S. Combining these observations we proposed the following hypothesis: increased antecedent (pre-monsoon) soil moisture in the monsoon region will take longer summer heating to set up the land-ocean gradient and consequently delay the monsoon cycle. The wetter antecedent conditions in the southwestern U. S. are largely driven by winter ocean-atmospheric conditions, especially PDO/ENSO (Ropelewski and Halpert 1986; Redmond and Koch 1991; Cayan and Webb 1992; Cayan et al. 1999). Enhanced ENSO activity in recent decades (Trenberth and Hoar, 1996; Rajagopalan et al., 1997) seems to be a contributor to the space-time trends in monsoon rainfall observed in this study. These antecedent links offer hopes for long-lead forecasts of the summer monsoon. The proposed hypothesis needs further testing using climate models. Analysis of the space-time variability of streamflow in the monsoon region is underway to investigate the consistency of the proposed hypothesis and to help in developing long-lead streamflow forecast tools.

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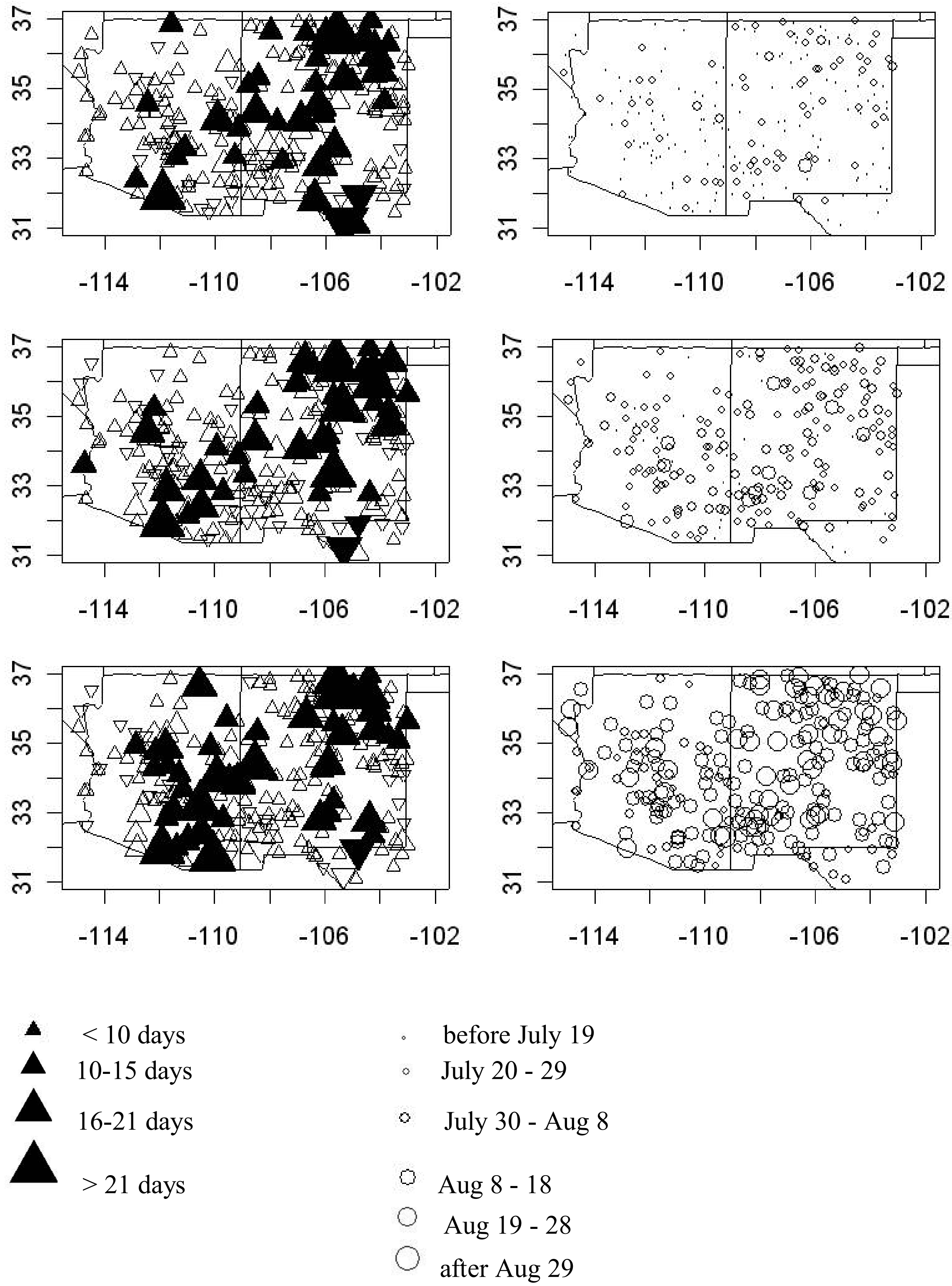
Figures


37
35
33
31
-114
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> 21 days
before July 19
July 20 - 29
July 30 - Aug 8
Aug 8 - 18
Aug 19 - 28
after Aug 29

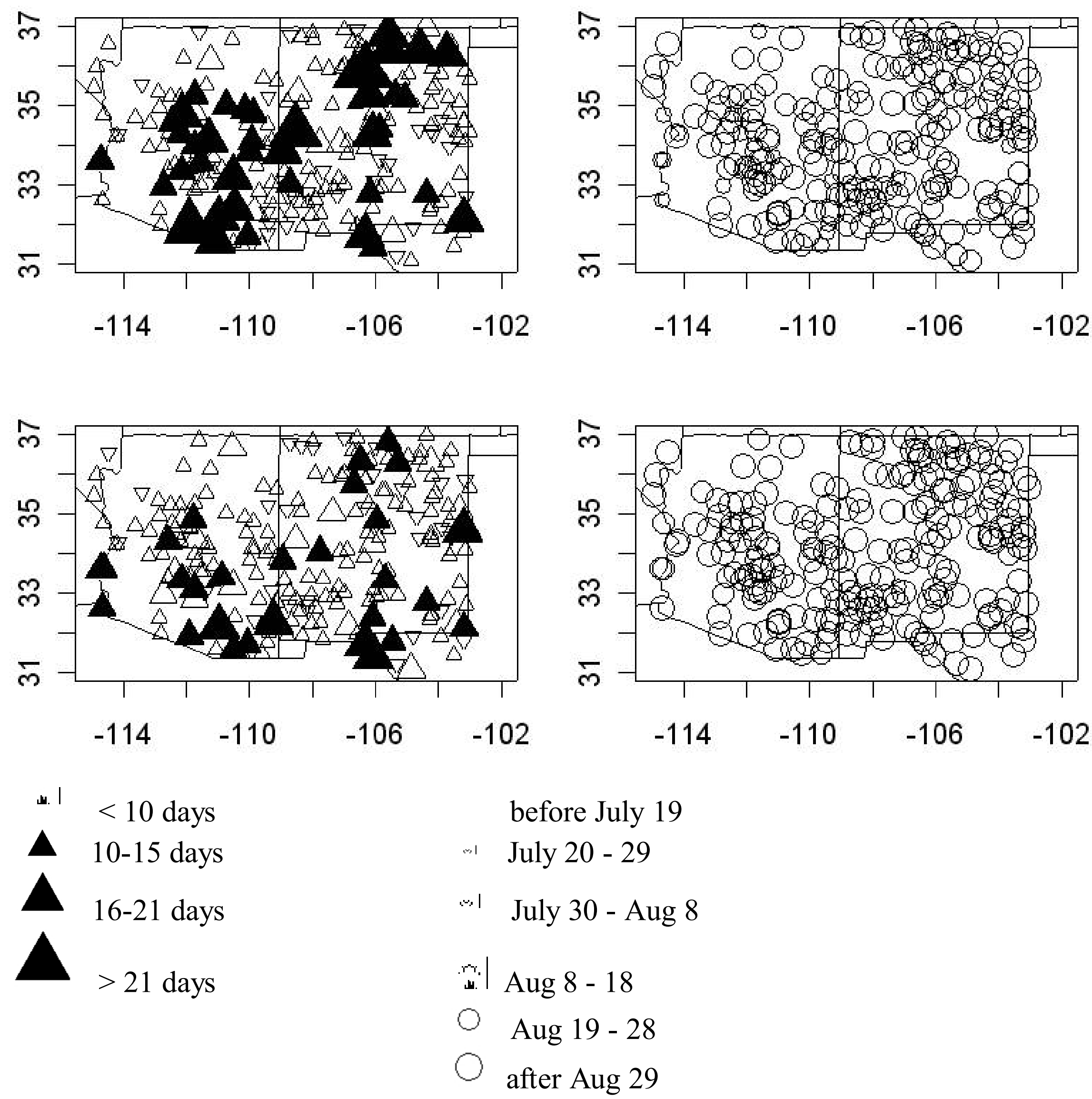


Figure 1 Trends in Julian day of summer (July-Sep) seasonal rainfall accumulation at five thresholds (10th, 25th, 50th, 75th, and 90th percentile) (left column, top to bottom, respectively) and the corresponding climatological Julian days (right column, top to bottom, respectively). For the Julian day trends, point-up triangles indicate delay and point-down triangles indicate advancement. Triangle size indicates the magnitude of the trend. Filled triangles indicate statistically significant trends at 90% confidence. For the climatological Julian days, the six circle sizes represent six Julian day windows.

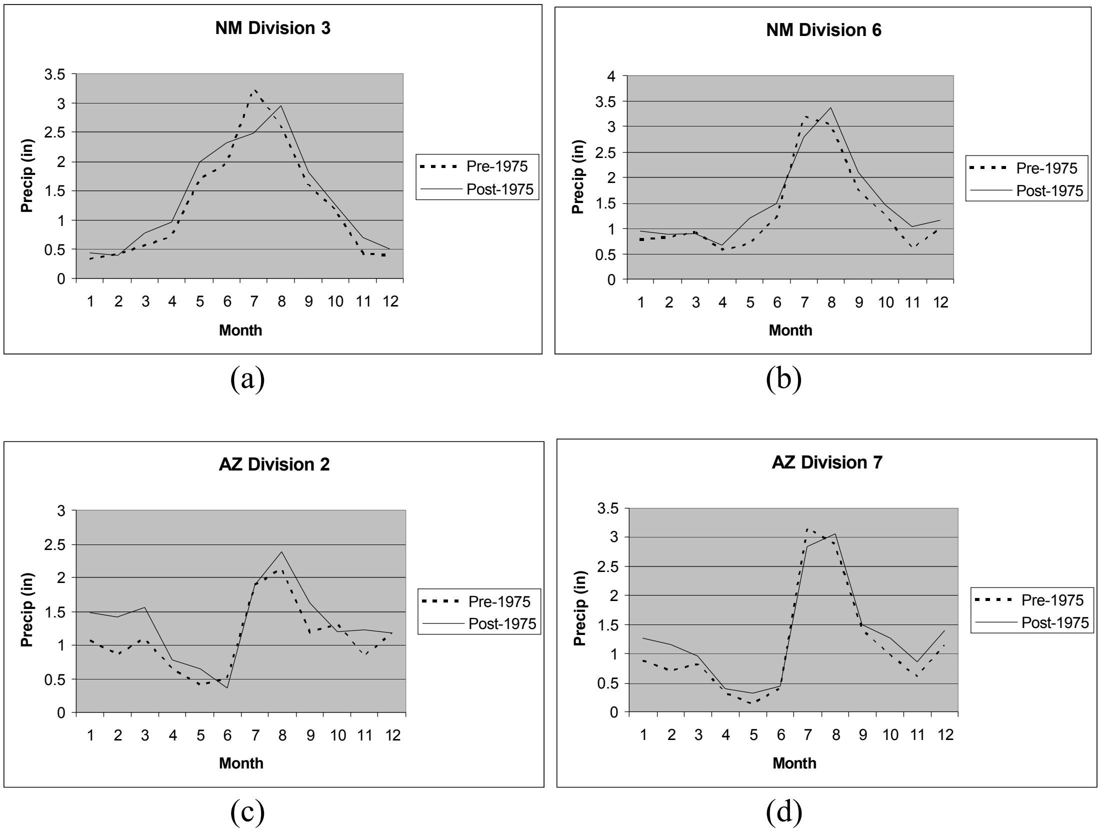


Figure 2 Annual cycle of precipitation during 1948-1975 (dashed line) and 1976-2004 (solid line) at two climate divisions in New Mexico (a, b) and two climate divisions in Arizona (c, d)

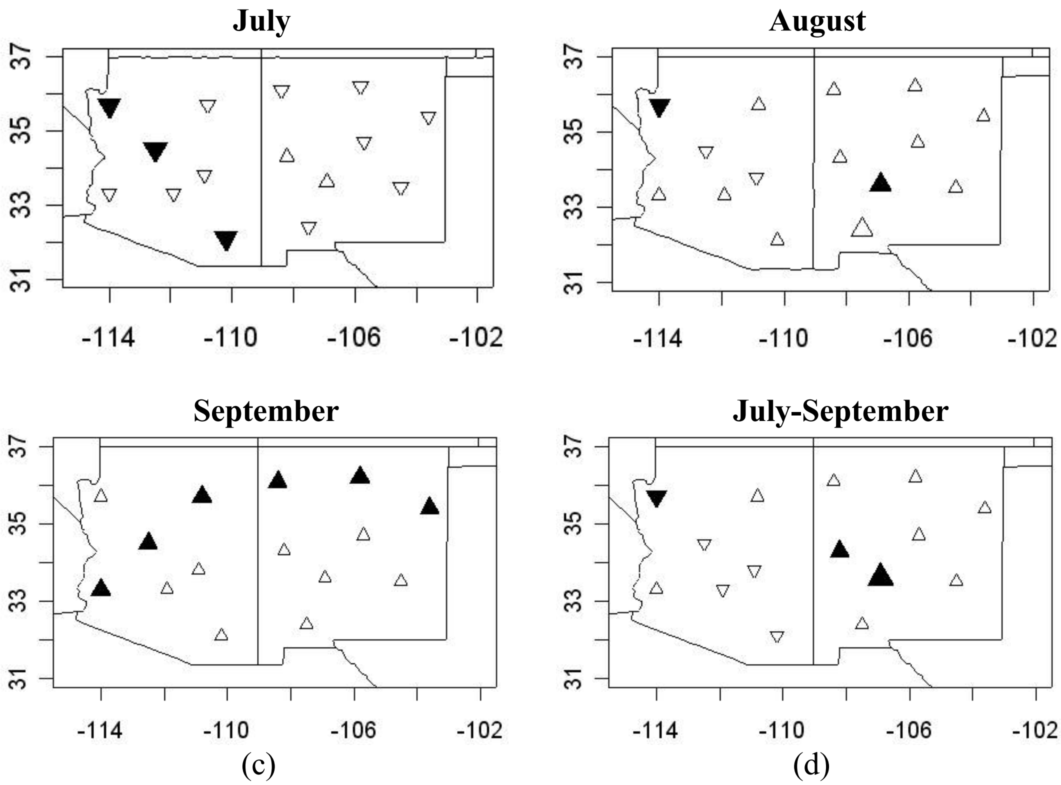


Figure 3 Trends in summer monthly and seasonal rainfall. Point-up triangles indicate an increasing trend and point-down triangles indicate a decreasing trend. Size indicates the relative magnitude of the trend. Filled triangles indicate statistically significant trends at 90% confidence.

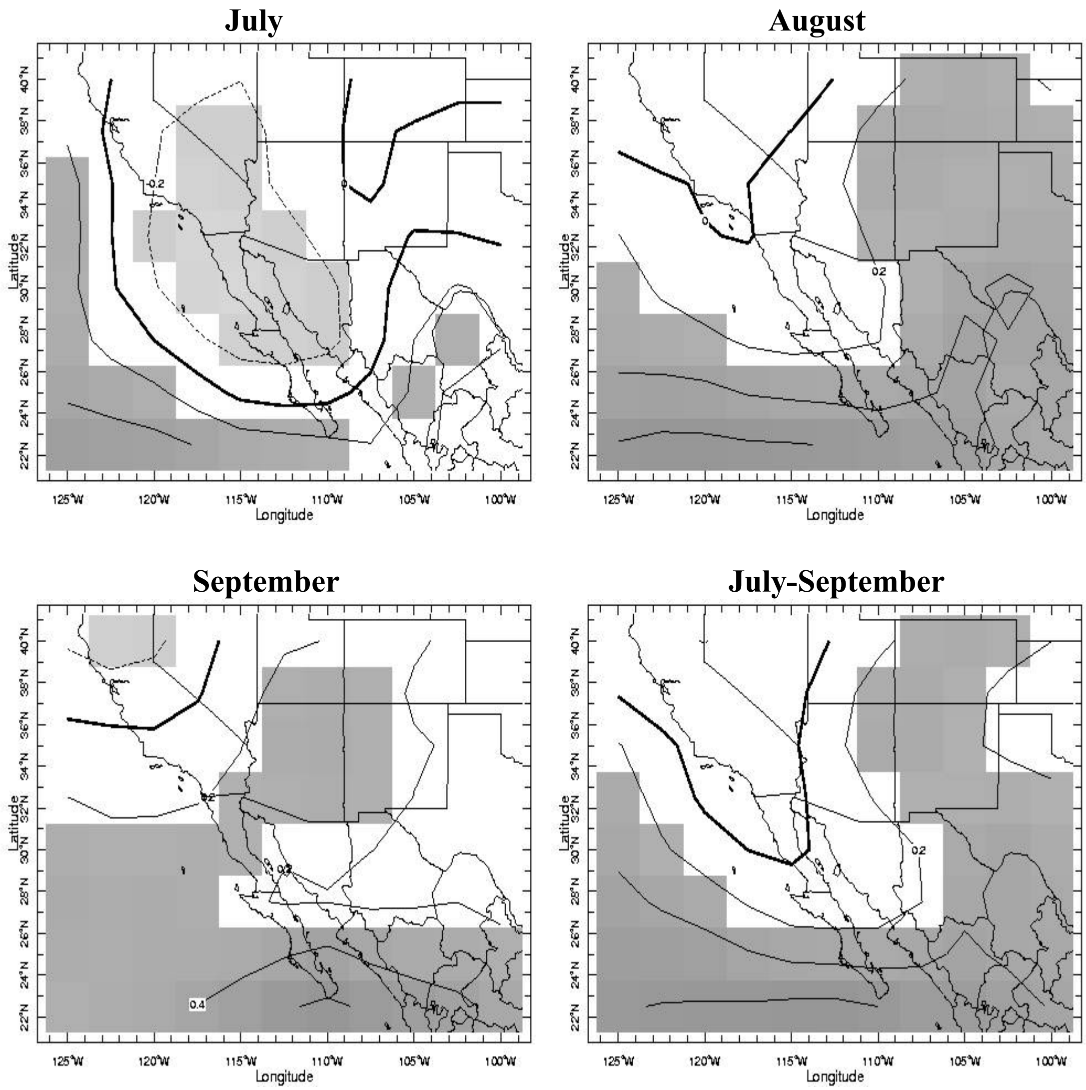


Figure 4 Trends in monthly and seasonal precipitable water. Shaded regions are statistically significant at 90% confidence.

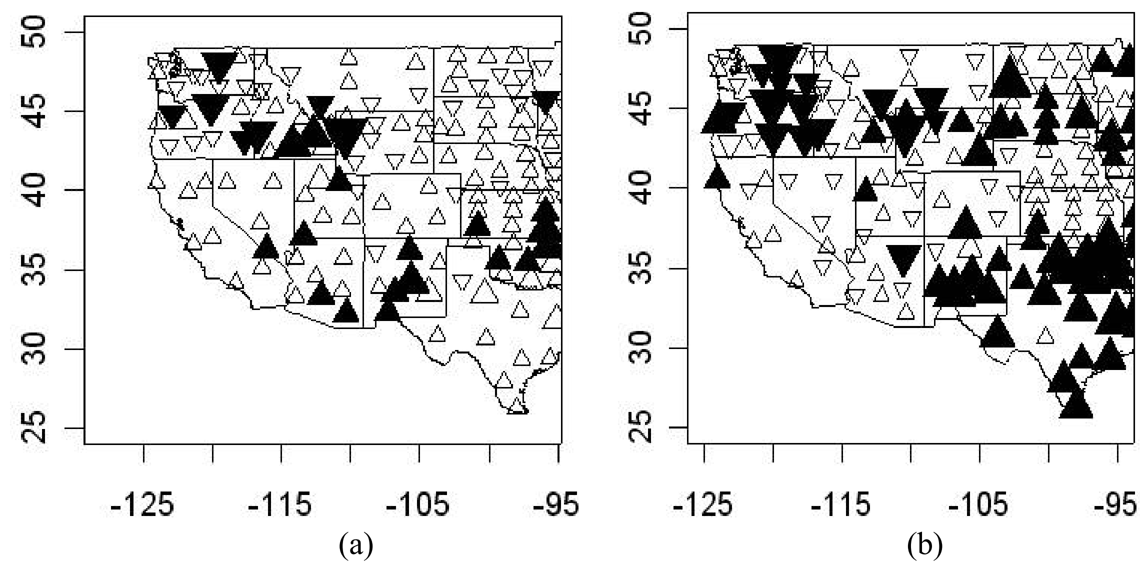


Figure 5 Same as Figure 3 but for antecedent winter/spring (December-May) land conditions – (a) precipitation and (b) PDSI.

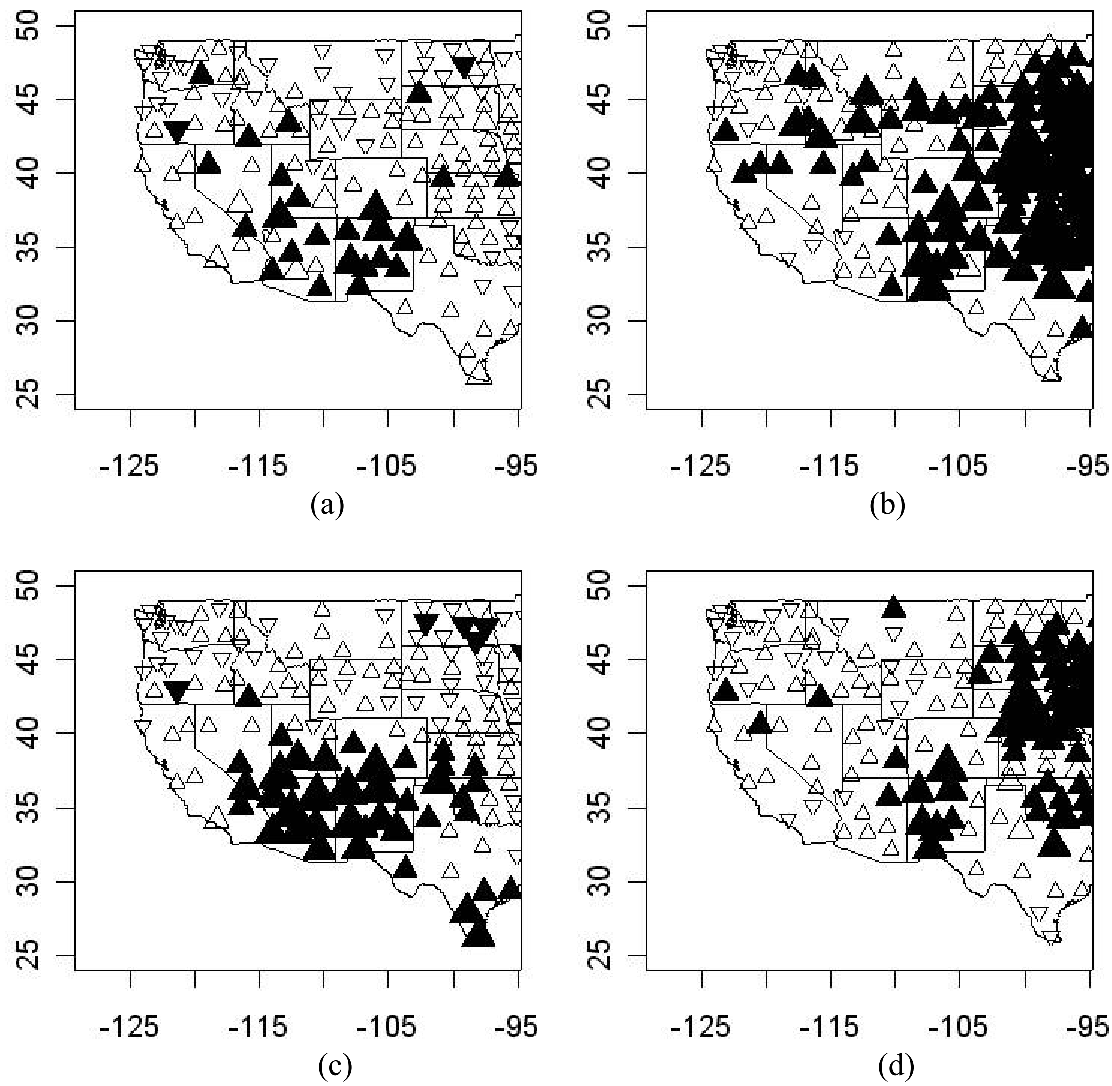


Figure 6 Correlation map of the 50^{th} percentile (a,b) and 10^{th} percentile (c,d) of the timing PC with antecedent winter/spring (Dec-May) precipitation (a,c) and PDSI (b,d). Point-up triangles indicate a positive correlation, point-down indicate a negative correlation. Symbol size indicates the relative magnitude of the correlation and filled symbols indicate statistically significant correlations at 90% confidence.

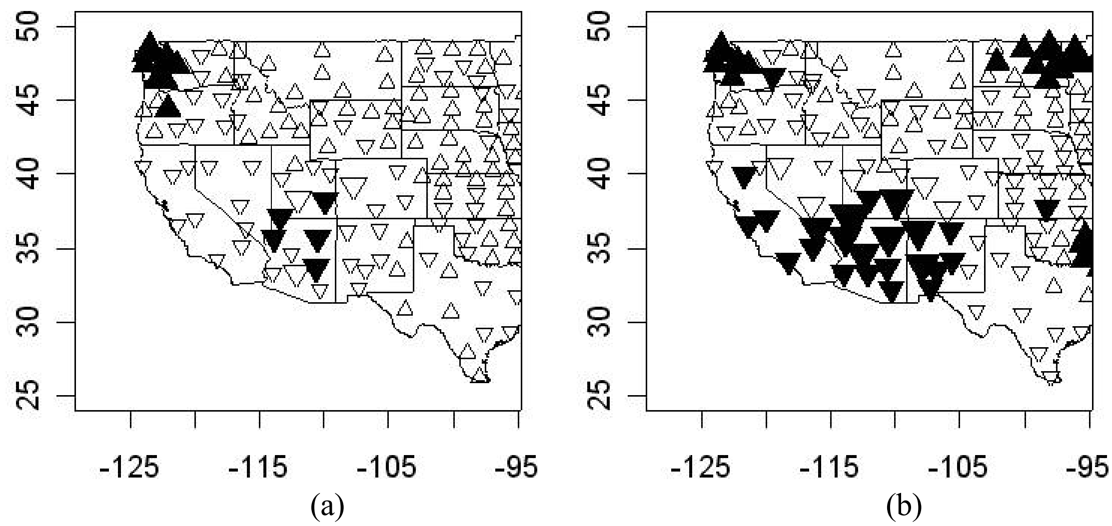
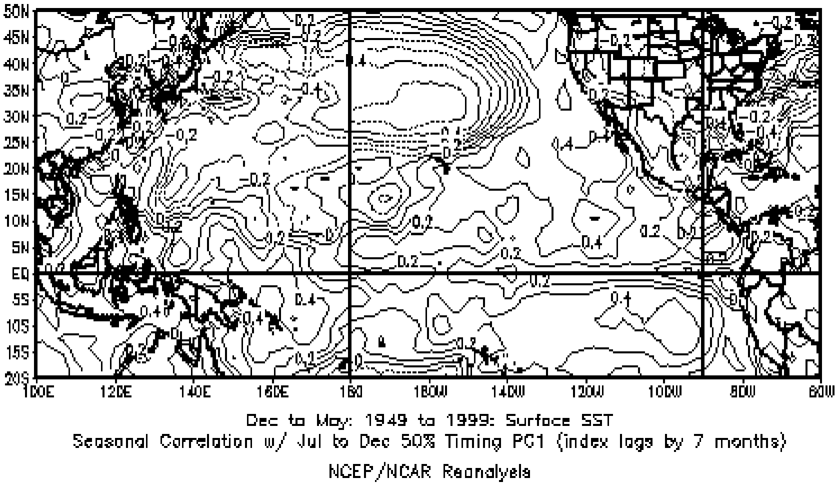
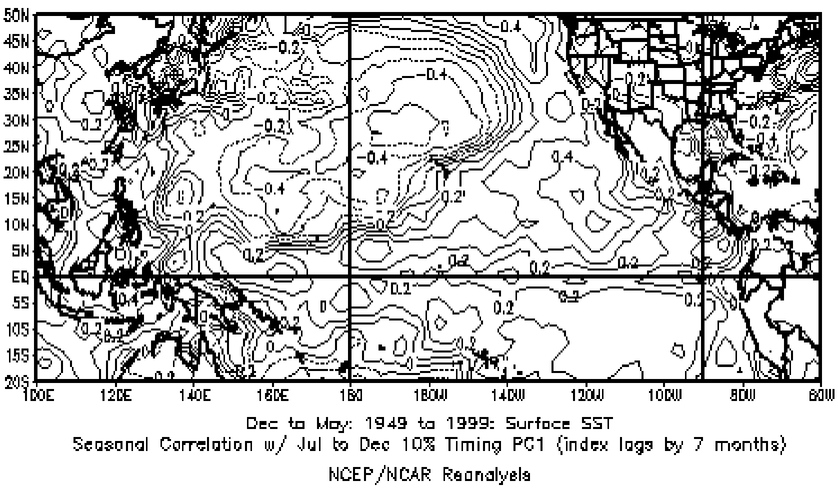


Figure 7 Same as Figure 6 but with antecedent winter/spring precipitation and (a) the first PC of seasonal (Jul-Sep) rainfall amount and (b) the first PC of July rainfall.

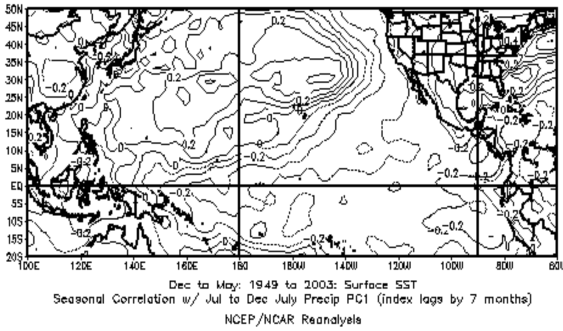


(a)

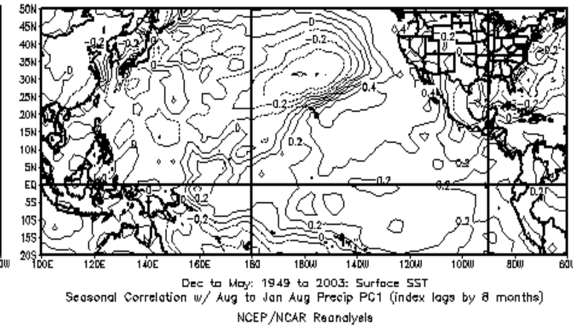


(b)

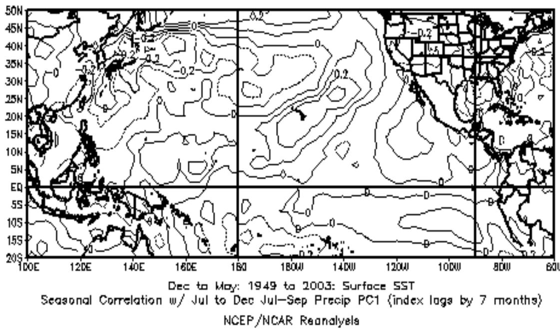
Figure 8 Correlations between the antecedent winter/spring (Dec-May) SSTs and the first PC of the Julian day of the 50th percentile (a) and 10th percentile (b). Correlations above 0.25 and below -0.25 are statistically significant at 90% confidence.



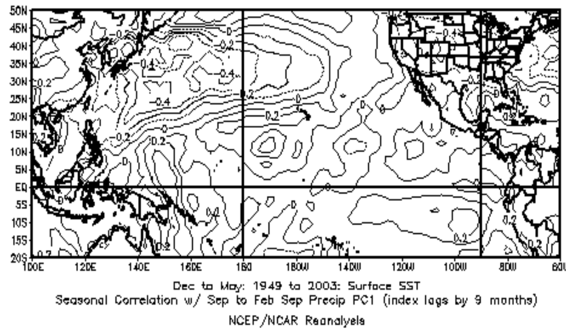
(a)



(b)



(c)



(d)

Figure 9 Same as Figure 8 but with antecedent winter/spring (Dec-May) SSTs and the first PC of monthly rainfall (a) July, (b) August and, (c) September.

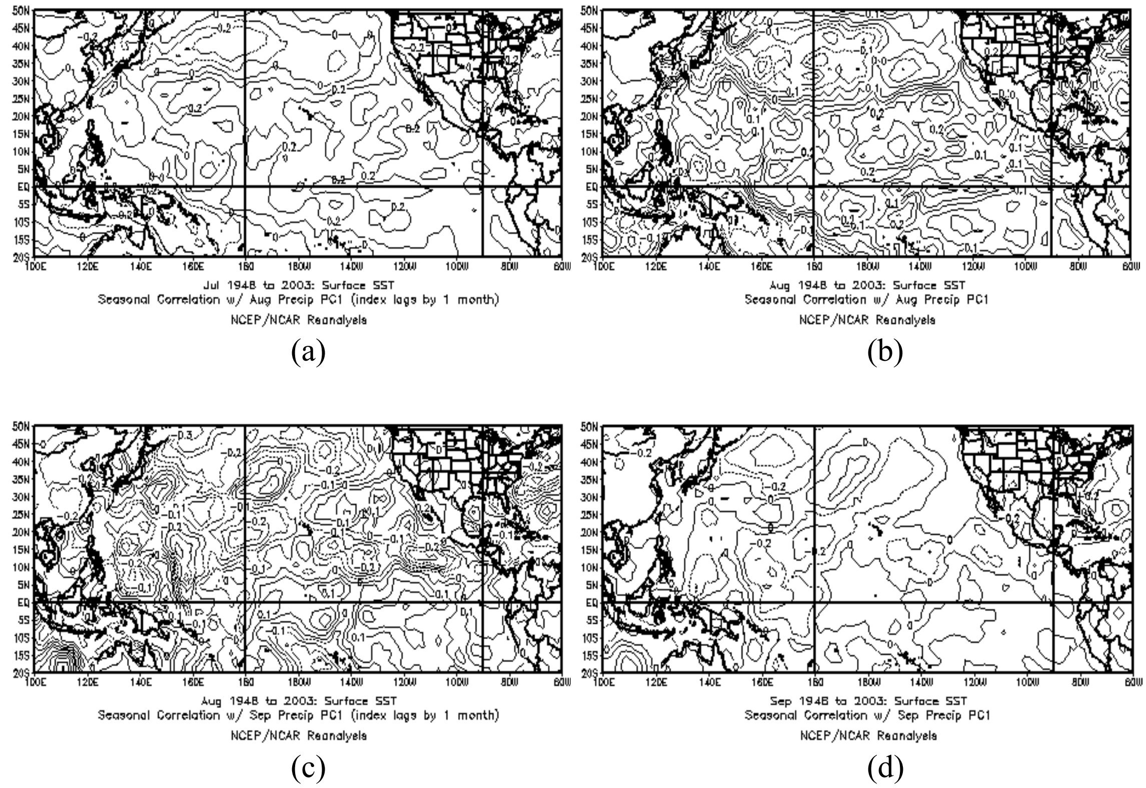


Figure 10 Correlations between the preceding month's and coincident SSTs and the first PC of the August (a,b) and September (c,d) rainfall. Correlations above 0.25 and below -0.25 are 90% significant.

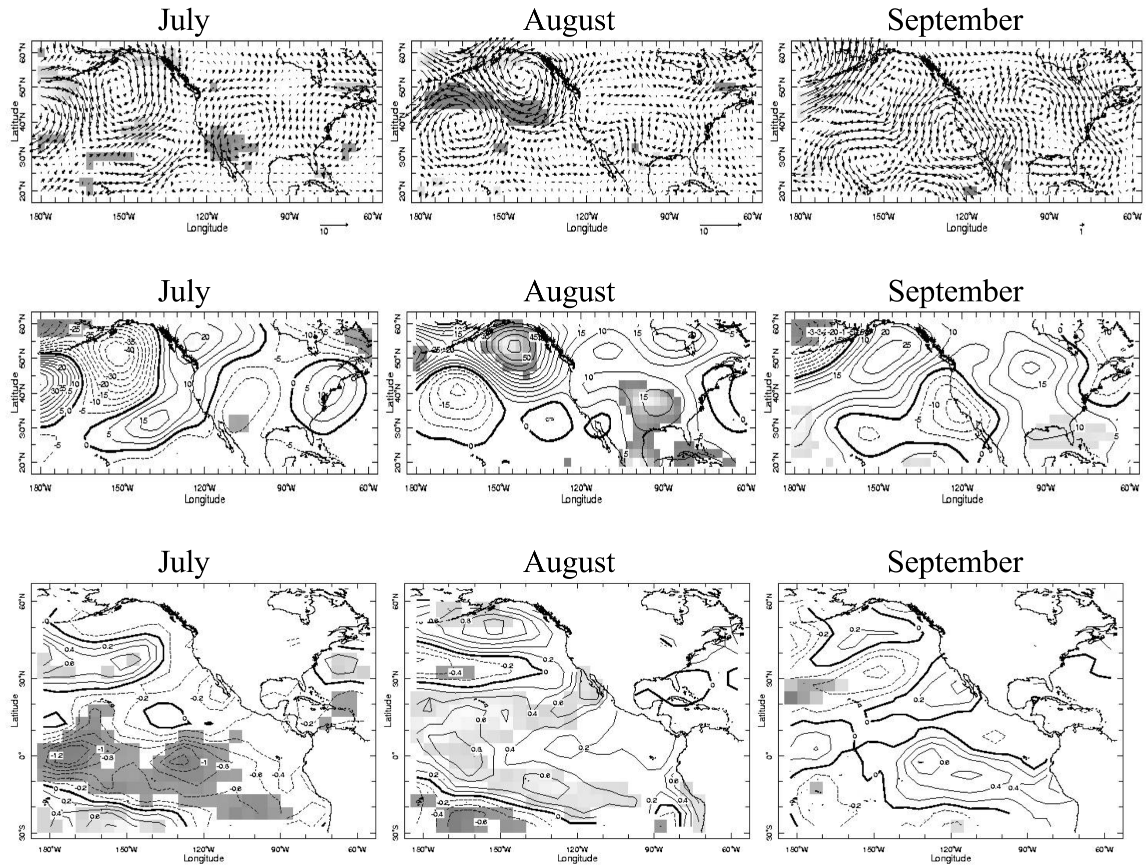


Figure 11 Composite differences between high and low precipitation years of vector winds (top row), 500 geopotential heights (middle row), and SSTs (bottom row). Shaded regions are statistically significant at 90% confidence.

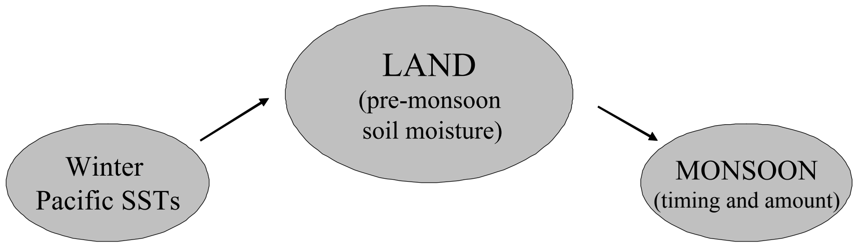


Figure 12 Schematic of proposed hypothesis

Tables

Table 1 Percent of total variance captured by each leading PC of monsoonal precipitation in varying months and regions

State	Month	variance
NM and AZ	July	45%
NM and AZ	August	53%
NM and AZ	September	58%
NM and AZ	July-September	43%
AZ	July	80%
AZ	August	78%
AZ	September	75%
AZ	July-September	77%
NM	July	61%
NM	August	64%
NM	September	71%
NM	July-September	63%