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Relationships among monsoon-season circulation patterns, gulf surges, and rainfall within the Lower Colorado River Basin, USA

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Abstract The purpose of this study is to assess the connections between the monsoon anticyclone, gulf surges, and rainfall within the Lower Colorado River Basin (LCRB) during North American monsoon seasons from 1988-2006. The methods involved calculating rainfall characteristics and near-surface humidity for 500-hPa circulation patterns, creating circulation and near-surface humidity composites for rainfall days, and creating near-surface humidity composites for rainfall days occurring under each circulation pattern. The circulation was dominated by the monsoon anticyclone being over or to the immediate east of the basin. The anticyclone was shifted to the northwest (east) of its seasonal mean position on rainfall days in the central portion of the basin (far eastern portion of the basin). Rainfall influenced by gulf surges was most likely when the monsoon anticyclone was shifted westward, especially northwestward, of its typical position. The central portion of the basin received substantially more surge-influenced rainfall than did the far eastern portion of the basin.

1 Introduction

The North American monsoon system (NAMS) dominates the summer circulation over the southwestern United States, which is on the northern periphery of the core monsoon region. The presence of the NAMS in the Southwest is characterized by the following: the development of a pronounced upper-level anticyclone over the Southwest; the development of a thermally induced trough in the Sonoran Desert; northward displacements of the Pacific and Bermuda high-pressure cells, and the formation of southerly low-level jets over the Gulf of California (in Vera et al. 2006). The above circulation changes enable increased atmospheric humidity in the Southwest; deep convection over the Sierra Madre Occidental provides a principal source of upper-level moisture (Anderson and Roads 2001; Berbery 2001), and the Gulf of California is a major direct source of lower-level moisture (Higgins et al. 2004; Mo and Berbery 2004). Consequently, there is a large increase in rainfall from June to July in the southwestern United States (Comrie and Glenn 1998; Higgins et al. 1999). The monsoon season in the Southwest typically dissipates by the end of September (Ellis et al. 2004).

Within the southwestern United States, the NAMS impacts mostly Arizona and New Mexico. Up to one-half of the annual precipitation total for the region occurs during the monsoon season (Douglas et al. 1993; Higgins et al. 1999). Precipitation regionalizations by Comrie and Glenn (1998) and Ellis et al. (2004) indicate that the monsoon region may not include western Arizona, eastern New Mexico, or both. The most intense monsoonal activity exists in southern Arizona (Michaud et al. 1995; Diem 2005), which is part of the northwestward extension of the Sierra Madre Occidental (Fig. 1).

The position of the monsoon anticyclone appears to impact monsoonal activity in the southwestern United States. Wet monsoon seasons in the Arizona/New Mexico region (Higgins et al. 1998, 1999), in the eastern Arizona/western New Mexico region (Comrie and Glenn 1998), and in Arizona (Carleton 1987; Carleton et al. 1990; Adams and

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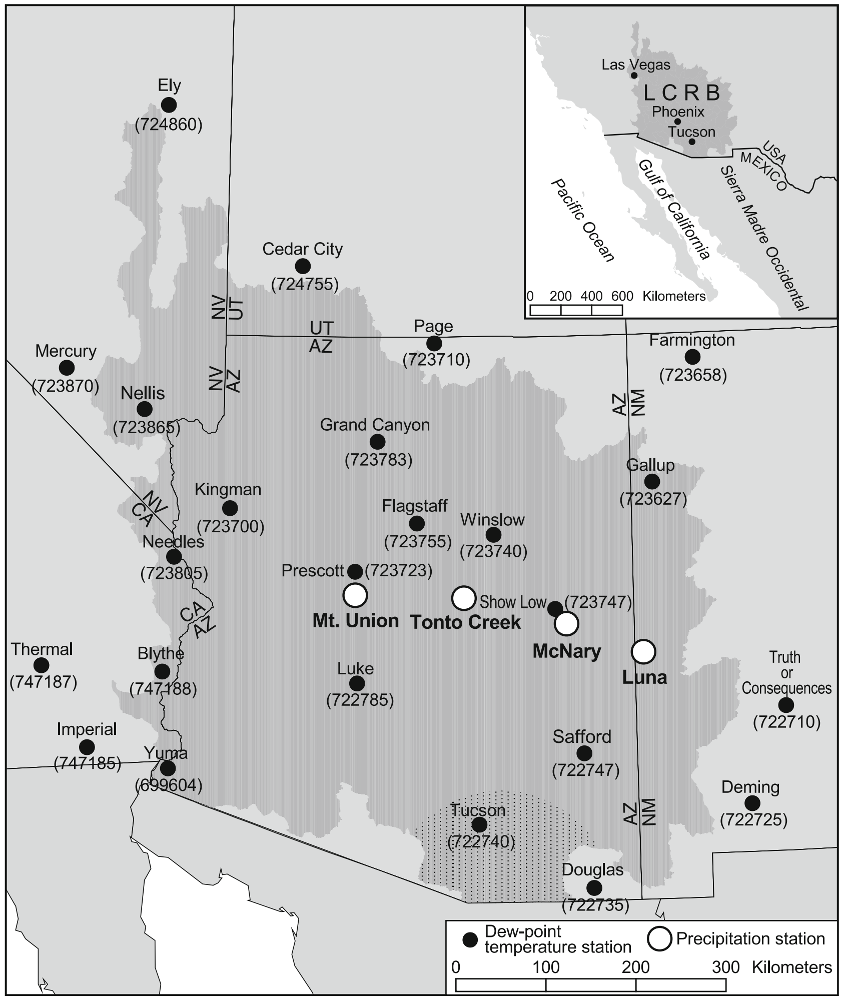

Fig. 1 Locations of the meteorological stations within and proximate to the Lower Colorado River Basin used in this study. World Meteorological Organization identification numbers are shown in *parentheses* below the dew-point temperature stations. The stippling in southern Arizona demarcates the zone with the most monsoonal activity (Michaud et al. 1995; Diem 2005)

Comrie 1997) are characterized by a monsoon anticyclone that is shifted to the northeast, northwest, and north, respectively, of its typical position. The following has been observed within the monsoon season: shifts of the anticyclone both to the northeast and northwest have been linked to severe thunderstorms in central Arizona (Maddox et al. 1995); the location of the anticyclone to the east of and over Arizona has been linked to storm development over the state (Heinselman and Schultz 2006); and extended periods of high lightning totals across Arizona and western New Mexico have been linked to an anticyclone over the region (Watson et al. 1994a).

Gulf surges, which are northward-propagating masses of moist air over the Gulf of California, are common occurrences during the monsoon season that contribute substantially to rainfall totals in portions of the Southwest. Gulf surges are detected typically at Yuma, Arizona, with the defining characteristic of a surge being a sharp increase in near-surface dew-point temperature (Stensrud et al. 1997; Higgins et al. 2004; Dixon 2005). Approximately six surge events occur during July and August (Fuller and Stensrud 2000; Douglas and Leal 2003; Higgins et al. 2004). Since surge events involve multiple days, gulf-surge days comprise over half the days during those months (Higgins et al. 2004). A surge moves the fastest and remains intact the longest as it moves up the Colorado River valley along the western border of Arizona; for example, the near-surface mixing ratio in western Arizona was nearly twice the level in eastern Arizona a day after the onset of two surges in July 1990 (see Fig. 6d of Adams and Stensrud 2007). The largest rainfall rates appear to occur several days after surge onset (see Fig. 6a of Higgins et al. 2004). Over 50% of rainfall during July and August in the Southwest may be linked to gulf surges (Higgins and Shi 2005).

There is limited information on relationships among the position of the monsoon anticyclone, gulf surges, and rainfall in the southwestern United States; therefore, the research presented in this paper is intended to provide some clarity on connections between the monsoon anticyclone and rainfall, the monsoon anticyclone and gulf surges, and gulf surges and rainfall. The chosen study region is the Lower Colorado River Basin (LCRB), which is an ideal geographical domain, because it contains much of the monsoon region within the southwestern United States, it is the destination for gulf surges that reach the United States, and it is populated by many stakeholder groups affected by the monsoon (Ray et al. 2007), such as farmers, fire managers, reservoir managers, air-quality managers, emergency fire response personnel, ranchers, wildlife managers, public-health officials, and urban water managers. The major objectives of the research are to determine the following: (1) the core synoptic-scale circulation patterns over the LCRB; (2) rainfall and near-surface humidity characteristics for the core circulation patterns; (3) circulation and near-surface humidity characteristics for rainfall days; and (4) near-surface humidity characteristics for rainfall days occurring under the various circulation patterns.

2 Data

Middle-troposphere geopotential heights, ground-measured rainfall totals, and near-surface dew-point temperatures were acquired for the 19 monsoon seasons from 1988 to 2006. The starting and ending dates were July 7 and September 14, because, based primarily on daily dew-point temperatures at Phoenix, Arizona, Ellis et al. (2004) identifies those 70 days as the typical monsoon period for central Arizona. Although the onset date, end date, and duration of the monsoon season varies inter-annually (Ellis et al. 2004), it was assumed for this study that in any given year the 70 days from July 7 through September 14 were within the monsoon season. The chosen starting year, 1988, was the earliest year that had data for all the precipitation stations in the study.

Gridded 500-hPa geopotential-height data were extracted from the NCEP/NCAR Reanalysis data set (Kalnay et al. 1996) of the Earth System Research Laboratory of the National Oceanic and Atmospheric Administration (NOAA). The globally gridded data had a spatial resolution of 2.5° and a temporal resolution of one day.

Daily rainfall totals were collected from four precipitation stations situated approximately evenly along a 325-km transect extending across the LCRB (Fig. 1). All stations were located at high elevations within the basin; elevations ranged from 1948 m a.s.l. to 2,285 m a.s.l. Monsoon-season convective systems develop preferably over high-terrain areas (Douglas et al. 1993; Wallace et al. 1999); therefore, the selected stations were ideal for capturing the monsoon signal. The stations also spanned the two monsoon-season precipitation regions (i.e., western region and eastern region) of the Gila River Basin, which constitutes much of the lower half of the LCRB (Diem and Brown 2006); the westernmost and easternmost precipitation stations were firmly in the western and eastern regions, respectively, while the other two stations were close to the border of the two regions but still in separate regions. In addition, the use of four stations, as opposed to a large number of stations, enabled the calculation of mean circulation and near-surface humidity patterns for rainfall days at each of the stations (see Sect. 3). The westernmost station, Mt. Union, was part of the Automated Local Evaluation in Real Time (ALERT) network maintained by the Flood Control District of Maricopa County, Arizona. Unfortunately, there were no high-elevation stations farther west than Mt. Union; thus, the transect could not be extended into the far western portion of the basin. The three other stations, Tonto Creek Fish Hatchery (i.e., Tonto Creek), McNary 2 N (i.e., McNary), and Luna Ranger Station (i.e., Luna), were National Weather Service (NWS) cooperative stations. Mt. Union, Tonto Creek, McNary, and Luna were originally missing 0.5%, 6.7%, 2.3%, and 0.2% of daily observations, respectively. The rainfall records at Mt. Union and Luna were made serially complete by replacing a missing value with the mean rainfall total from two nearby high-elevation stations: Horsethief Basin and Towers Mountain of the ALERT network were used for Mt. Union, while Alpine and Alpine 8 SSE of the NWS cooperative-station network were used for Luna. Horsethief Basin and Towers Mountain were 33 km and 20 km, respectively, from Mt. Union, and Alpine and Alpine 8SSE were 19 km and 18 km, respectively, from Luna. There were no precipitation stations proximate to either Tonto Creek or McNary; thus, rainfall records at those stations remained serially incomplete. Daily rainfall totals at Mt. Union were multiplied by 1.18 to adjust for a reduction in precipitation totals associated with the use of a tipping-bucket gauge (Diem 2005). Since Tonto Creek and McNary had morning observations, rainfall totals at those stations were moved to day $n-1$. Monsoonal activity along the precipitation-station transect peaks between 3 P.M. and 6 P.M. (Balling and Brazel 1987; Watson et al. 1994b). Luna was listed as having 5 P.M. measurements; therefore, the two scenarios for that station involved moving the rainfall total to day $n-1$ and keeping the rainfall total associated with day n.

Mean daily near-surface dew-point temperatures from 24 World Meteorological Organization (WMO) stations within and proximate to the LCRB were acquired from NOAA's Global Summary of the Day data set (Fig. 1). If an additional meteorological station was proximate to one of the aforementioned 24 stations, then data from the nearby station was used to replace missing values at the study station. Therefore, in order to supplement the records at Luke Air Force Base, Safford Municipal Airport, and Yuma Marine Corps Air Station, data were obtained for the WMO Phoenix Sky Harbor Airport station, the AZMET (Arizona Meteorological Network) Safford station, and the WMO Yuma International Airport station, respectively. After the above substitutions, only 1.3% of the daily values were missing for the entire network, and only Page, with 147 missing values and no nearby stations, was missing more than 5% of the daily values.

3 Methods

A manual classification of 500-hPa circulation patterns was used to determine the core synoptic types over the LCRB during the 19 monsoon seasons. Since results from previous studies (e.g., Watson et al. 1994a; Maddox et al. 1995; Higgins et al. 1998, 1999; Heinselman and Schultz 2006) illustrate the importance of the location of the monsoon anticyclone in controlling monsoonal activity in the Southwest, the location of the monsoon anticyclone with respect to the LCRB was a key factor in the synoptic typing. Therefore, a manual classification was chosen over an automated classification. The geographic scale for the typing, which initially was based on a cylindrical equidistant projection, ranged from 22.5°N to 50.0°N latitude and from 92.5°W to 135.0°W longitude; thus, the domain was made as close as possible to that used in Carleton (1986, 1987), which are the only existing manual circulation classifications for the Southwest. The interval for the 500-hPa contour lines was 20 m. All days of the first year (1988), middle year (1997), and last year (2006) as well as a random sample of 133 days (i.e., 10% of the population) were first examined to identify the core synoptic types. The classification was then applied to all 1,330 days in the study period.

Rainfall characteristics at the four precipitation stations were analyzed for all days corresponding to each synoptic type. The variables included the rainfall total and the frequency of rainfall days over the 19 monsoon seasons. Rainfall totals at Tonto Creek and McNary, which were the two stations with missing values, were upwardly adjusted for each synoptic type using the x/y ratio, where x is the total number of days per synoptic type and y is the number of valid daily rainfall totals per synoptic type. Since the minimum observable rainfall total at Mt. Union, the ALERT station, was 2 mm after the application of the adjustment factor (i.e., 1.18) and the minimum observable rainfall total at the NWS stations was 0.254 mm, all days with rainfall totals ≥2 mm were classified as rainfall days.

The typical 500-hPa circulation was determined for rainfall days. Each station had a set of rainfall days; therefore, mean surfaces of 500-hPa geopotential heights were constructed for the four sets of rainfall days.

Surfaces of near-surface humidity were used to detect the possibility of surges of moisture from the Gulf of California into the LCRB. Previous research (e.g., Adams and Stensrud 2007) indicates that a gulf surge should result in a gradient in near-surface dew-point temperature anomalies across the basin, with the western portion of the basin having the largest positive anomalies. Therefore, surfaces of near-surface dew-point temperature anomalies were created for each synoptic type, each set of rainfall days, and each combination of synoptic type and rainfall days. For the synoptic types and rainfall days, one-tailed Student's t-tests ($\alpha=0.01$) were used to test for differences between the mean dew-point temperature of a set of days and the mean value for the other days. Gulf-surge onsets at Yuma were not identified, because there are no widely accepted methods for detecting gulf surges or the associated moisture increases (Dixon 2005).

4 Results

4.1 Synoptic types

The classification of 500-hPa circulation patterns produced six synoptic types, with two types comprising the majority of the days (Table 1). The types, which were named based on the location of the LCRB with respect to circulation features, are as follows: anticyclone (A), northern portion of anticyclone (NPA), southern portion of anticyclone (SPA), eastern portion of anticyclone (EPA), western portion of anticyclone (WPA), and trough (T) (Fig. 2). The types differed from the mean seasonal circulation pattern as follows: type A had an expanded and northwestward-shifted anticyclone; type NPA had a southward-shifted anticyclone; type SPA had an expanded, intensified, and northwestward-shifted anticyclone; type EPA had a westward-shifted anticyclone; type WPA had an expanded and northeastward-shifted anticyclone; and type T had no anticyclone in the domain. The percentage of monsoon-season days that were type A, NPA, SPA, EPA, WPA, and T, respectively, were 34%, 9%, 5%, 4%, 36%, and 9%. Therefore, 70% of the monsoon-season days were either type A or WPA, and only 3% of the days remained unclassified.

4.2 Rainfall characteristics

There were noticeable differences in relationships between rainfall and synoptic types along the precipitation-station transect (Table 1). It needs to be noted that the range in cumulative rainfall was slight: the mean seasonal rainfall totals were 230 mm, 234 mm, 233 mm, and 209 mm at Mt. Union, Tonto Creek, McNary, and Luna, respectively. The two most common synoptic types, A and WPA, had the largest rainfall totals. Major differences between the two types involved Luna, the easternmost station: Luna received twice as much rainfall for type WPA than for type A, and

Table 1 Frequency of the six synoptic types and rainfall characteristics at the four precipitation stations for each synoptic type over the 19 seasons

Type	Days	Total rainfall (mm)				Rainfall days			
		MU	TC	MC	LU	MU	TC	MC	LU
A	450	1,305	1,376	1,362	985	141	121	150	143
NPA	117	407	389	214	182	30	29	26	31
SPA	65	320	202	199	164	31	24	27	21
EPA	54	161	111	93	105	19	14	14	15
WPA	488	1,669	1,924	2,103	2,019	167	153	229	208
T	116	260	293	293	349	24	18	26	30
U	40	245	150	169	171	18	17	20	18
Sum	1,330	4,367	4,445	4,433	3,975	430	376	492	466

The synoptic types are as follows: A (anticyclone), NPA (northern portion of anticyclone), SPA (southern portion of anticyclone), EPA (eastern portion of anticyclone), WPA (western portion of anticyclone), and T (trough). Unclassified days have been assigned to the category "U." "MU" is Mt. Union, "TC" is Tonto Creek, "MC" is McNary, and "LU" is Luna.

that station also received ~30% less rainfall than did the other stations for type A. Much more rainfall occurred at Mt. Union, the westernmost station, than at Luna and McNary, the other eastern station, for types NPA, SPA, and EPA. Under type SPA, Mt. Union received at least 58% more rainfall than did the other three stations. There was little variation in rainfall among the stations for type T days; nevertheless, this was the only type for which Luna had the most rainfall among the stations.

Rainfall was recorded on approximately one-third of the days during the monsoon season, with rainfall days more frequent for the eastern stations than for the western stations and considerable differences in rainfall days existing among the synoptic types (Table 1). The percentages of days with rainfall at Mt. Union, Tonto Creek, McNary, and Luna were 32%, 28%, 37%, and 35%, respectively. Rainfall was most likely under type SPA and least likely under type T: the mean percentages from the

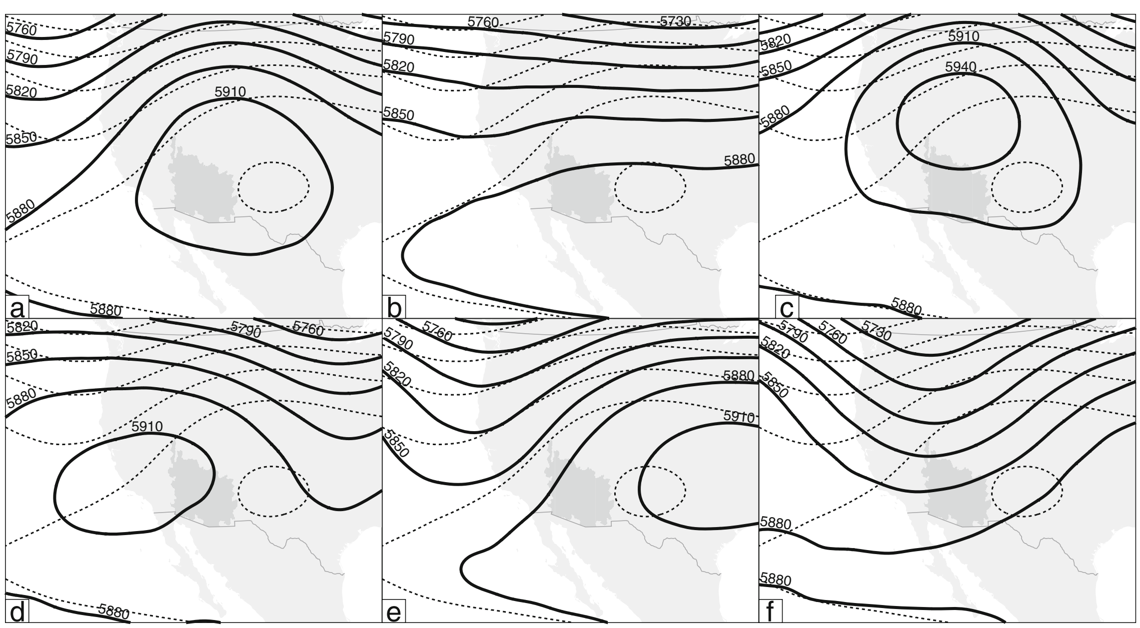

Fig. 2 Mean 500-hPa geopotential heights (in m) for the six synoptic types. The types are **a** anticyclone (A), **b** northern portion of anticyclone (NPA), **c** southern portion of anticyclone (SPA), **d** eastern portion of anticyclone (EPA), **e** western portion of anticyclone (WPA), and **f** trough (T). The *dashed lines* show the mean circulation pattern; maximum and minimum heights are 5,910 m and 5,760 m, respectively. The Lower Colorado River Basin is shown in *darker shading*

four precipitations for types SPA and T were 40% and 21%, respectively. Nearly half the type SPA days had rainfall at Mt. Union, while only 16% of the type T days had rainfall at Tonto Creek. Over 43% of the WPA days had rainfall at either McNary or Luna; one-third of the days were rainfall days at either of the western stations. There were small differences among the stations for types A, NPA, and EPA.

4.3 Circulation on rainfall days

The mean 500-hPa circulation patterns for the sets of rainfall days were all dominated by the presence of the monsoon anticyclone and ridging to the north/northeast of the LCRB (Fig. 3). The intensity of the ridging was greater for the western stations than for the eastern stations. In addition, the position of the monsoon anticyclone relative to its seasonal mean position varied among the stations as follows: the anticyclone was shifted to the northwest, north, northeast, and east on rainfall days at Mt. Union, Tonto Creek, McNary, and Luna, respectively. Therefore, the center of the monsoon anticyclone on Mt. Union rainfall days was ~250 km northwest of the center of the anticyclone on Luna rainfall days.

4.4 Near-surface humidity characteristics

There were substantial differences among the synoptic types with respect to spatial variations in near-surface dew-point temperature anomalies (Fig. 4). Types A, SPA, and WPA were the only synoptic types with significant positive anomalies in dew-point temperature within the basin, and the following major differences existed among those three types: (1) type A had significantly high values primarily in the southwestern portion of the basin and significantly low values in the eastern portion of the basin; (2) type SPA had significantly high values everywhere but the far northeastern and far eastern portions of the basin; and (3) type WPA had significantly high values everywhere but the far western portion of the basin. Type SPA had much larger positive anomalies than did types A and WPA: the western portion of the basin had anomalies exceeding 4.0°C. The three other types, NPA, EPA, and T, had significant negative dew-point temperature anomalies throughout the basin, with types EPA and T having large negative anomalies in the northeastern and southwestern portions of the basin, respectively.

Significant, positive anomalies in near-surface dew-point temperatures occurred throughout the basin for all sets of rainfall days, and there was a consistent change in anomaly patterns when progressing eastward along the precipitation-station transect (Fig. 5). The maximum anomalies for Mt. Union and Tonto Creek, which exceeded 3.5°C for Mt. Union, were in the far western portion of the basin. Maximum anomalies for McNary rainfall days were located over the central portion of the basin and did not reach 2.5°C. The smallest positive anomalies among the four sets of rainfall days occurred for the Luna rainfall days, with the maximum anomalies located in the northeastern portion of the basin. In addition, anomalies in the southwestern portion of the basin were only slightly positive for Luna rainfall days.

For most combinations of synoptic types and rainfall days, the largest positive anomalies in dew-point temperature existed in the far western portion of the basin (Fig. 6). Under types A, SPA, and NPA, rainfall days for all four stations were associated with considerably larger anomalies in the western portion of the basin than in the eastern portion. While for types A and NPA the anomaly magnitudes decreased when moving from the western stations to the eastern stations, there was little change in anomaly magnitude for type SPA. Type EPA was similar to type SPA except that the maximum positive anomalies for Luna were not in the western portion of the basin. There were major differences among the stations for types WPA and T: large positive anomalies in the western portion of the basin existed for type WPA only for Mt. Union and to a lesser degree Tonto Creek, while, for type T, there was a shift from positive anomalies in the western portion of the basin for Mt. Union to large negative anomalies for McNary and Luna.

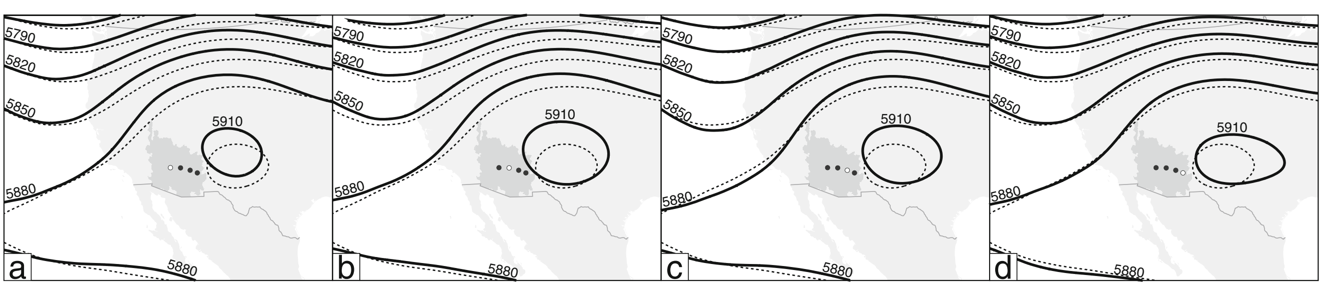

Fig. 3 Mean 500-hPa geopotential heights (in m) for **a** Mt. Union rainfall days, **b** Tonto Creek rainfall days, **c** McNary rainfall days, and **d** Luna rainfall days. The *dashed lines* show the mean circulation pattern; maximum and minimum heights are 5,910 m and 5,760 m, respectively. The Lower Colorado River Basin is shown in *darker shading*. The station to which a panel corresponds is denoted by a *white circle*, while the other three stations are denoted by *black circles*

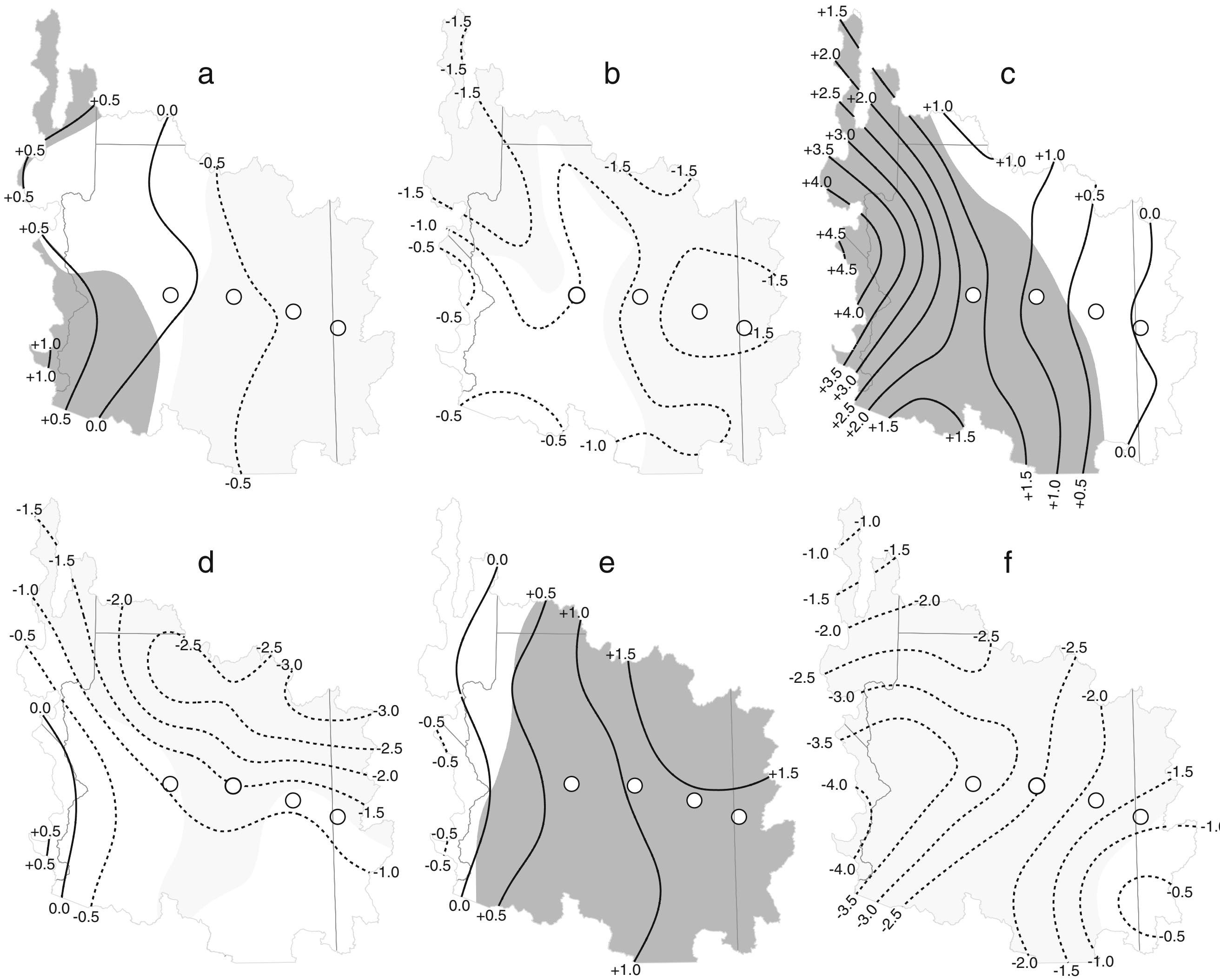

Fig. 4 Mean near-surface dew-point-temperature anomalies for synoptic types **a** A, **b** NPA, **c** SPA, **d** EPA, **e** WPA, and **f** T. Also shown are the following probability values for dew-point-temperature differences: 0.01 with mean value significantly larger than mean of rest of values ( ); and 0.01 with mean value significantly smaller than mean of rest of values ( ). The *circles* are the precipitation stations. State boundaries within the basin also are shown

5 Discussion

The circulation of the NAMS for the LCRB is characterized by the monsoon anticyclone being predominantly over or to the immediate east of the basin. The automated circulation classification of Cavazos et al. (2002), which involved multiple upper-level atmospheric variables, also shows the dominance of the monsoon anticyclone. Most of the circulation modes in Cavazos et al. (2002) are equivalent to either type WPA or a hybrid of types A and WPA, and, similar to the findings in this study, only 10% of the days are troughing days. All the synoptic types presented in this paper have been identified in either Carleton (1986) or Carleton (1987); however, those studies focused on monsoon bursts (i.e., increases in cloudiness throughout the Southwest) and breaks (i.e., decreases in cloudiness throughout the Southwest), thereby making a direct comparison of types between this study and those studies difficult. Nevertheless, since nearly 75% of burst days are linked to troughing and burst days comprise 29% of the days within the monsoon season (see Table 3 of Carleton 1986), one could assume all troughing days are associated with increased cloudiness across the LCRB.

Rainfall days in the LCRB are associated primarily with the monsoon anticyclone displaced slightly northwards of its seasonal mean position. Only in the far eastern portion of the basin (i.e., western New Mexico) is the northward displacement of the anticyclone not linked to rainfall days. Unfortunately, since no other studies have taken an “environment-to-circulation” compositing approach using

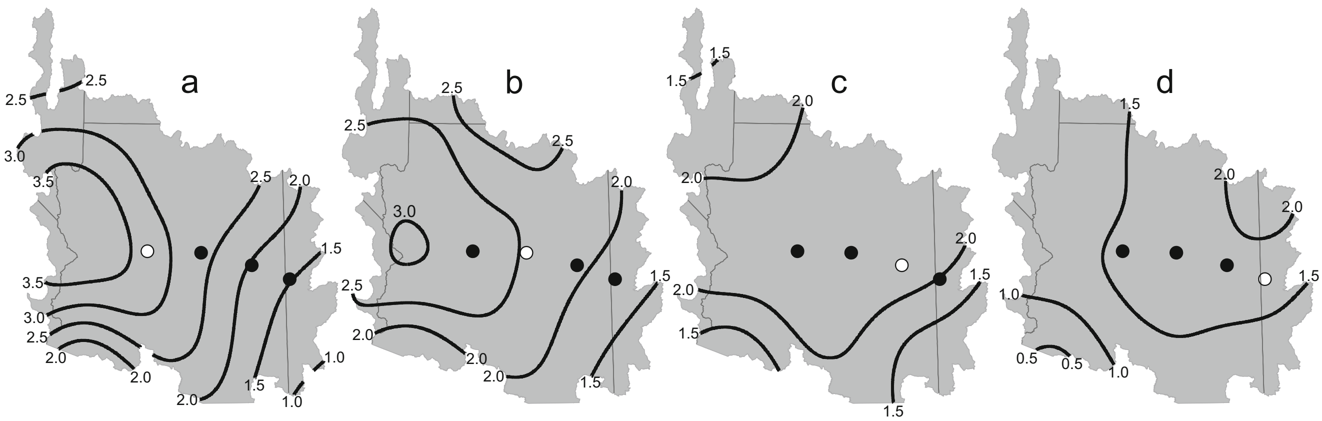

Fig. 5 Mean near-surface dew-point-temperature anomalies (in °C) for **a** Mt. Union rainfall days, **b** Tonto Creek rainfall days, **c** McNary rainfall days, and **d** Luna rainfall days. Shaded areas have mean dew-point temperatures significantly (α=0.01) larger than the mean of the rest of the values. The station to which a panel corresponds is denoted by a *white circle*, while the other three stations are denoted by *black circles*

daily rainfall as the environmental variable, the circulation findings at the daily scale could not be compared directly with other results. Results in this study do converge with the findings of Carleton (1987), Carleton et al. (1990), and Adams and Comrie (1997) that wet summers in Arizona are tied to a northward-shifted anticyclone.

There were connections between gulf surges and synoptic types. As noted earlier in the paper, a gulf surge should result in a gradient in near-surface dew-point temperature anomalies across the basin, with the western portion of the basin having the largest positive anomalies. Therefore, gulf surges are most likely under type SPA, which is centered at ~40°N, and type A and least likely under type T. This confirms the following: light flow aloft is favorable and troughs in the westerlies are unfavorable, respectively, for supporting surges (Hales 1972); and by the end of a gulf surge (i.e., 1 to 2 days after surge onset at Yuma), the anticyclone can be displaced northward to almost 40°N (Douglas and Leal 2003).

Gulf surges can occur under nearly all synoptic types, but there are varying impacts across the LCRB. The synoptic types in descending order based on rainfall evidently influenced by gulf surges are as follows: SPA, EPA, NPA, A, WPA, and T. Therefore, rainfall influenced by gulf surges is most likely when the monsoon anticyclone is shifted westward, especially northwestward, of its seasonal mean position. Surges influencing Mt. Union rainfall are probable under all types with the exception of type T. For Tonto Creek and McNary, surges influencing rainfall are likely under types SPA, EPA, NPA, and A; thus, unlike the situation for Mt. Union, surges do not appear to impact rainfall at the two middle stations when type WPA is present. Surges that might influence Luna rainfall are confined to types SPA, NPA, and A.

As might be expected, rainfall at Mt. Union, the westernmost station, is considerably more impacted by gulf surges than is rainfall at Luna, the easternmost station. Mt. Union is ~150 km closer to the Gulf of California than is Luna, and no substantial topographic barriers exist between Mt. Union and the Gulf of California. Gulf surges have been tied to 60-70% of seasonal rainfall in central Arizona and 50-60% of seasonal rainfall in western New Mexico (see Fig. 12a of Higgins and Shi 2005). The above information coupled with the synoptic type/gulf surge relationships as well as the rainfall totals in Table 1 indicate that Mt. Union receives at least 20% more surge-influenced rainfall than does Luna. This research supports the conclusion of Diem and Brown (2006) that the Bradshaw Mountains, within which Mt. Union is located, are impacted strongly by moisture from the Gulf of California. The lack of surge activity at Luna is balanced by typically higher amounts of middle-troposphere moisture over western New Mexico than over Arizona: 700-hPa specific humidity over Luna is typically ≥1 g kg^{-1} greater than specific humidity over Mt. Union (see Fig. 10b of Diem and Brown 2006), and for seven of the nine summer circulation modes in Cavazos et al. (2002) there was higher 700-hPa specific humidity over New Mexico than Arizona. The Sierra Madre Occidental and the Gulf of Mexico are the most likely sources of moisture on rainfall days in the White Mountains (i.e., Luna) (Diem and Brown 2006).

6 Conclusions

This paper presented an assessment of connections between the monsoon anticyclone, gulf surges, and rainfall within the Lower Colorado River Basin (LCRB) during North

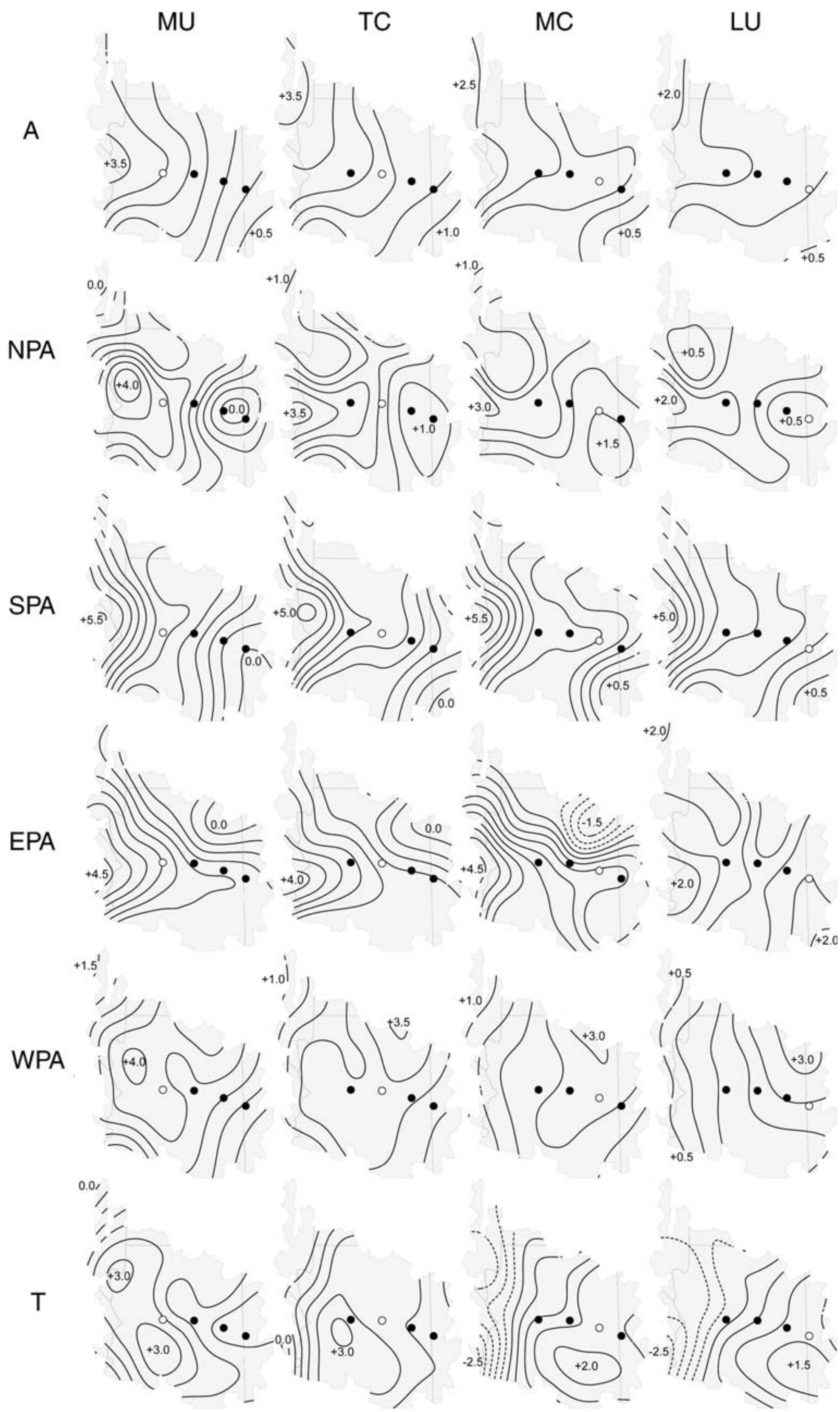

Fig. 6 Mean dew-point-temperature anomalies (in °C) for the 24 combinations of sets of rainfall days and synoptic types. The columns are the precipitation stations (Mt. Union, Tonto Creek, McNary, and Luna), and the rows are the synoptic types. The station to which a panel corresponds is denoted by a *white circle*, while the other three stations are denoted by *black circles*

American monsoon seasons from 1988-2006. Instead of using rainfall values from dozens of precipitation stations across the LCRB, rainfall totals came from four high-elevation stations along a 325-km transect extending across the basin. The four stations were chosen for the following reasons: the topographic settings of the stations made them ideal for capturing the monsoon signal; the stations had nearly identical rainfall totals over the 19 seasons; and the four stations enabled an "environment-to-circulation" approach to be used to determine mean circulation and near-surface humidity patterns for rainfall days. The methods involved a classification of synoptic-scale circulation patterns over the LCRB, calculating rainfall characteristics and near-surface humidity for the circulation patterns, creating circulation and near-surface humidity composites for rainfall days, and creating near-surface humidity composites for sets of rainfall days occurring under each circulation pattern. The circulation classification revealed that the monsoon anticyclone was predominantly over or to the immediate east of the basin. A westward shift of the monsoon anticyclone was associated generally with a westward shift in rainfall and surface humidity across the LCRB. The mean position of the monsoon anticyclone on rainfall days relative to its seasonal mean position shifted from northwest, to north, to northeast, and finally to east when moving among the four precipitation stations from the westernmost station to the easternmost station. Rainfall influenced by gulf surges was most likely when the monsoon anticyclone was shifted westward, especially northwestward, of its mean position. The central portion of the basin received substantially more surge-influenced rainfall than did the far eastern portion of the basin.

Future research in the LCRB should investigate the spatio-temporal complexity of monsoonal activity within the basin. These investigations should encompass the history of the NCEP/NCAR Reanalysis dataset (1948–present); classify synoptic circulation patterns using manual typing, automated typing, or both approaches; employ a sound technique for identifying gulf-surge days; continue to use the network of near-surface dew-point temperature measurements; and make use of daily rainfall totals for precipitation stations throughout the basin.

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