INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **33**: 2274–2279 (2013)
Published online 15 August 2012 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.3576

Short Communication

Multi-decadal changes in the North American monsoon anticyclone

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ABSTRACT: The purpose of this study was to assess trends in the intensity of the North American monsoon anticyclone over multiple decades from 1948 to 2010 during July and August, with a focus on the Lower Colorado River Basin (LCRB). The methodology included a 500 hPa geopotential-height regionalization of the monsoon-anticyclone domain (i.e. a large portion of the western United States and northern Mexico), a typing of 500 hPa circulation patterns over the LCRB, and an examination of multi-decadal trends as well as inter-epochal differences in geopotential heights and frequencies of synoptic types. Three regions (i.e. Northwest, Northeast, and South) were revealed that differed based on inter-annual variations in 500 hPa geopotential heights. The Northwest and South regions had significant increases in geopotential heights from 1948–1978 to 1980–2010. The synoptic types reflected the location of the monsoon anticyclone over the LCRB. The monsoon anticyclone intensified primarily over the northwestern region, which includes the LCRB, since the mid- to late 1970s. The anticyclone has thus been expanding over the LCRB. The anticyclone has been in a northern position, specifically a north-central position, over the basin more frequently over the past 30 years; conversely, the anticyclone has been in southern and eastern positions over the basin less frequently.

KEY WORDS synoptic; North American monsoon system; circulation; anticyclone

Received 5 May 2012; Revised 11 July 2012; Accepted 15 July 2012

1. Introduction

The North American monsoon affects northwestern Mexico and parts of the southwestern United States mostly during July and August. The monsoon is centred over the Sierra Madre Occidental (SMO) (e.g. Higgins *et al.*, 1999), and up to 75% of the annual rainfall there occurs in July and August (Higgins *et al.*, 1997). The part of the southwestern United States most impacted by the monsoon is south-central and southeastern Arizona (Diem, 2005). Middle-troposphere moisture over southern Arizona and the rest of the Lower Colorado River Basin (LCRB) typically can be traced back to the SMO (Diem and Brown, 2006). Gulf surges, which are northward-propagating masses of moist air over the Gulf of California, occur at Yuma, Arizona on approximately half the days during July and August (Higgins *et al.*, 2004). As a result, over 60% of rainfall in the southern portion of the LCRB during those months may be linked to gulf surges (Higgins and Shi, 2005). Direct impacts on rainfall from gulf surges probably are confined to the western portion of the LCRB (Diem and Brown, 2006).

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The dominant atmospheric feature of the North American monsoon is an anticyclone in the middle- to upper-troposphere (Figure 1). Westerly circulation over the southwestern United States retreats northward at the end of June, coincident with the northward migration of the monsoon-ridge over northwestern Mexico (Cavazos *et al.*, 2002). Therefore, the monsoon anticyclone reaches its mature phase in July and August; it is centred typically over New Mexico [see Figure 2 in *Cavazos et al.* (2002)]. The rapid onset of monsoonal rains accompanies the establishment of the anticyclone in July (e.g. Higgins *et al.*, 1997). The monsoon begins to decay in September, and this entails the retreat of the monsoon anticyclone and the return to circulation patterns similar to those in June (Higgins *et al.*, 1997; Cavazos *et al.*, 2002).

A meridional displacement of the monsoon anticyclone appears to be a major cause of disparities in rainfall among monsoon seasons for the LCRB as a whole or parts of it. The anticyclone is displaced either northward (e.g. Carleton *et al.*, 1990; Cavazos *et al.*, 2002; Diem and Brown, 2009), northeastward (e.g. Higgins *et al.*, 1998; Higgins *et al.*, 1999; Cavazos *et al.*, 2002; Diem and Brown, 2009), or northwestward (e.g. Comrie and Glenn, 1998) of its mean climatological position for wet monsoons or for rainy periods within the season. The

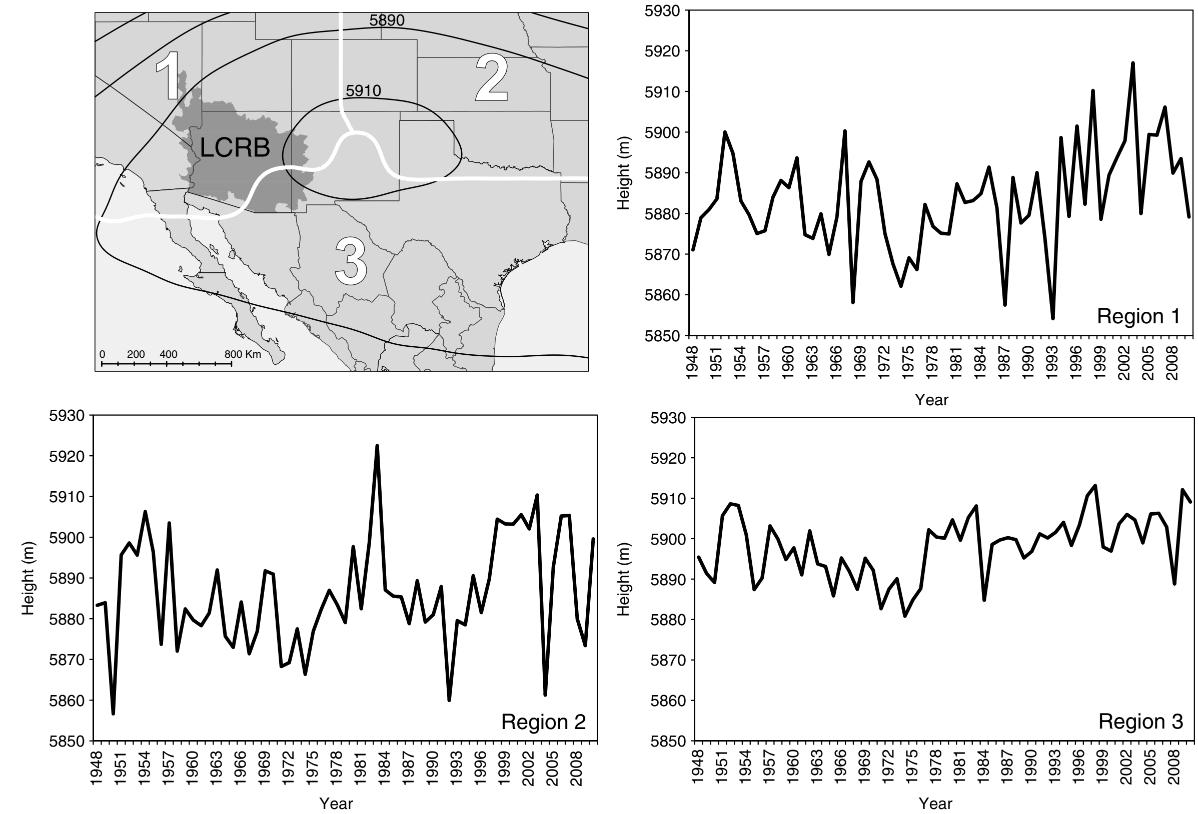

Figure 1. The North American monsoon anticyclone domain showing mean 500 hPa heights during July–August of 1948–2010, the three 500 hPa height-change regions, and the Lower Colorado River Basin (LCRB) along with time series of mean July–August 500 hPa geopotential heights for the three regions.

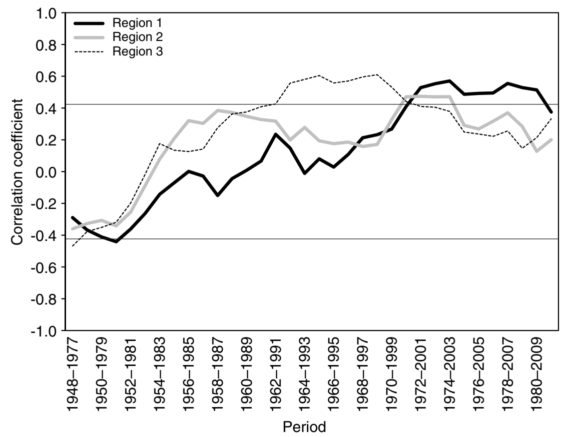

Figure 2. Trends in regional 500 hPa geopotential heights within 34 over-lapping climate periods. Each of the 34 periods has a Spearman's ρ correlation coefficient. Significant positive trends are above the upper horizontal line and significant negative trends are below the lower horizontal line. The significance level is 0.01 for a one-tailed test.

anticyclone is displaced southward for dry monsoons (e.g. Carleton *et al*., 1990; Higgins *et al*., 1998, 1999; Castro *et al*., 2001; Johnson *et al*., 2007). The anticyclone is enhanced/strengthened during wet monsoons and suppressed/weakened during dry monsoons (Higgins *et al*., 1998, 1999).

The monsoon anticyclone appears to shift northward during gulf surges. Douglas and Leal (2003) report a northward-displacement of the anticyclone during surge events. Diem and Brown (2009) are more specific and speculate that the anticyclone is displaced primarily to the northwest during gulf surges. Higgins *et al*. (2004) note that the anticyclone is displaced northeastward during wet surges and northwestward during dry surges.

Despite the monsoon anticyclone being an important feature of the North American monsoon system, there is scarce published material on multi-decadal changes in the anticyclone. Therefore, the purpose of this article is to assess trends in the intensity of the North American monsoon anticyclone over multiple decades from 1948 to 2010 during July and August, with a focus on the LCRB. The LCRB is selected because it represents the region of the southwestern United States most impacted by the monsoon (e.g. Diem, 2005; Diem and Brown, 2006) and previous synoptic-circulation research has focused on the basin (Diem and Brown, 2009).

2. Data and methods

2.1. Regionalization

A regionalization of middle-troposphere heights over the monsoon-anticyclone domain (i.e. a large portion of the western United States and northern Mexico) was needed to enable further analyses of temporal variations within the domain. The time period was July–August from 1948 to 2010. Gridded 500 hPa geopotential-height data were extracted from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis data set (Kalnay *et al.*, 1996) of the Earth System Research Laboratory of the National Oceanic and Atmospheric Administration. The data had a spatial resolution of 2.5°; seasonal means were calculated from daily values.

Standardized principal components analysis was used to determine the regions. The input S-mode matrix consisted of 63 rows (i.e. years) and 108 columns (i.e. grid cells). A Scree plot of log-transformed eigenvalues was used to determine the number of components to retain; the components represented the regions. The loadings matrix was orthogonally rotated using the VARIMAX technique to enable a proper examination of the loadings (e.g. Richman and Lamb, 1985). Each cell was assigned to the component (i.e. region) on which it had the highest loading; thus, the maximum-loading rule was used.

2.2. Synoptic typing

A manual classification of 500 hPa circulation patterns was used to determine the synoptic types over the LCRB during July and August. The classification focused on the position and intensity of the monsoon anticyclone. The typing domain extended from 22.5 °N to 50.0 °N latitude and from 92.5 °W to 135.0 °W longitude; thus, the domain was nearly identical that used by Carleton (1986, 1987). The synoptic typing was performed with daily Reanalysis data (Kalnay *et al.*, 1996). The contour interval of each map was set to 20 m, with a minimum of 5500 m and maximum of 6000 m to match the interval and range of a previous synoptic classification performed by Diem and Brown (2009).

The typing scheme presented in this study is a more objective version of the classification presented in Diem and Brown (2009). The location of the 5880 m contour for each day was identified with respect to the LCRB, and a day was classified as 'north,' 'central,' or 'south.' The 5880 m contour was present in each of the synoptic types of Diem and Brown (2009). The contour was located north of the LCRB on 'north' days, within the LCRB on 'central' days, and south of the LCRB on 'south' days. The monsoon-ridge axis was then determined to be west of, over, or east of the LCRB, and those days were classified as 'west,' 'central,' and 'east,' respectively. Consequently, the classification scheme forced the creation of the following nine synoptic types: northwest (NW), north-central (NC), northeast (NE), central-west (CW), central-central (CC), central-east (CE), southwest (SW), south-central (SC), and southeast (SE). Finally, the types also were grouped according to whether they were 'north,' 'south,' east,' or 'west' types.

2.3. Multi-decadal trends and differences

One-tailed Spearman's ρ correlation tests were used to detect significant ($\alpha = 0.01$) trends in anticyclone-related variables. Testing was done for 34 over-lapping 30 year periods (i.e. 1948–1977, 1949–1978, ..., and 1981–2010). The variables were 500 hPa geopotential heights for each region, frequencies of synoptic types, and frequencies of groups of types.

Inter-epochal differences in middle-troposphere heights and synoptic-type frequencies also were examined. Student's t-tests were used to detect significant ($\alpha = 0.01$) changes in heights and type frequencies from 1948–1978 to 1980–2010. The geopotential heights pertained to the monsoon-anticyclone regions.

3. Results and discussion

Three height-change regions were identified in the monsoon-anticyclone domain (Figures 1 and 2), and those regions differed substantially with respect to multi-decadal changes in 500 hPa geopotential heights. Over 90% of the variance in the original dataset was retained in the first three components of the analysis; therefore, it was a parsimonious and thorough regionalization. The anticyclone was centred typically over New Mexico and northern Texas, and all three regions were present within the centre of the anticyclone. Region 1 (i.e. Northwest), which contained within it most of the LCRB (i.e. Arizona), was characterized by a significant decrease in heights from 1951 to 1980 and significant increase in heights within nine consecutive periods beginning with 1972–2001 and ending with 1980–2009. This region also had significant increases in heights from 1948–1978 to 1980–2010. Region 2 (i.e. Northeast), which was centred over Kansas, was characterized by a significant increase in heights within four consecutive periods beginning with 1971–2000 and ending with 1974–2003. Region 3 (i.e. South), which was centred over northern Mexico, was characterized by a significant decrease in heights from 1948 to 1977 and a significant increase in heights within ten consecutive periods beginning with 1961–1990 and ending with 1971–2000. Along with Region 1, this region also had significant increases in heights from 1948–1978 to 1980–2010.

The nine circulation patterns produced by the synoptic typing varied substantially in frequencies (Figure 3). Five types (i.e. NE, NC, NW, CE, and SE) had over 300 occurrences each. The NE type occurred on 39% of the days and was thus by far the most prevalent type. The percent occurrences for the NC, NW, CE, and SE types were 20%, 12%, 11%, and 8%, respectively. Four types (CW, SW, CC, and SC) had fewer than 40 occurrences each; each type occurred on less than 1% of the days. None of the types of groups of types experienced significant differences in frequencies from 1948–1978 to 1980–2010.

The northern types generally experienced decreases in frequencies during the first half of the study period and significant increases during the second half of the period (Figures 4 and 5). The NC type decreased significantly in frequency for 11 consecutive periods beginning with 1951–1980 and ending with 1961–1990. Northern types

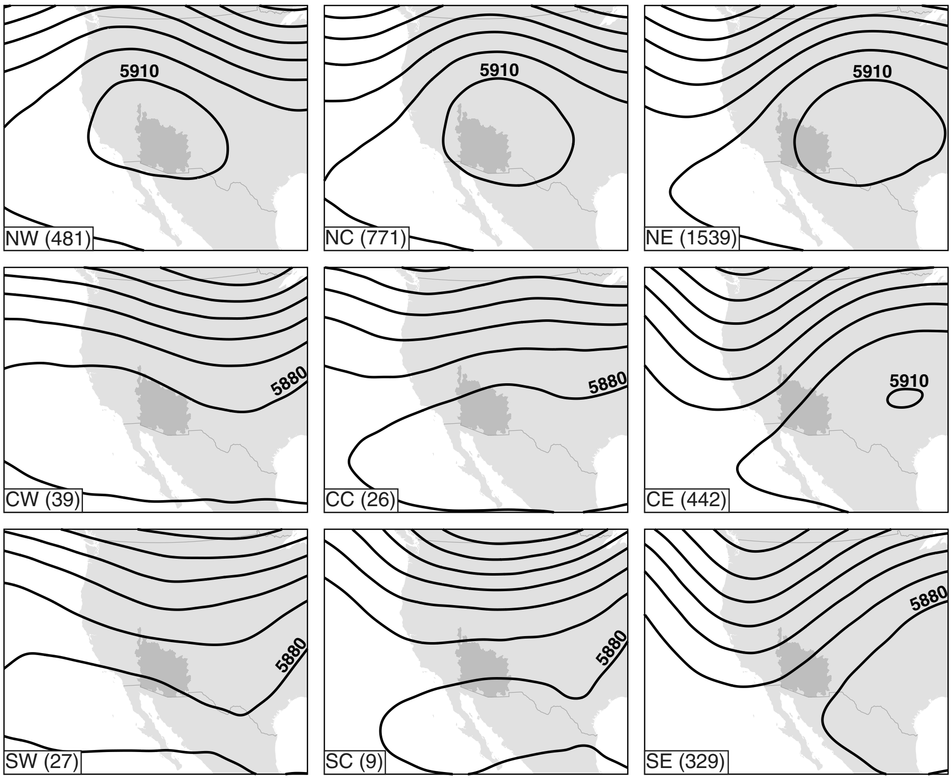

Figure 3. Mean 500 hPa geopotential heights during July–August of 1948–2010 for the nine synoptic types. The frequency of each type is shown in parentheses. Only the highest heights for each type are labelled. The contour interval is 30 m. The shaded region is the Lower Colorado River Basin.

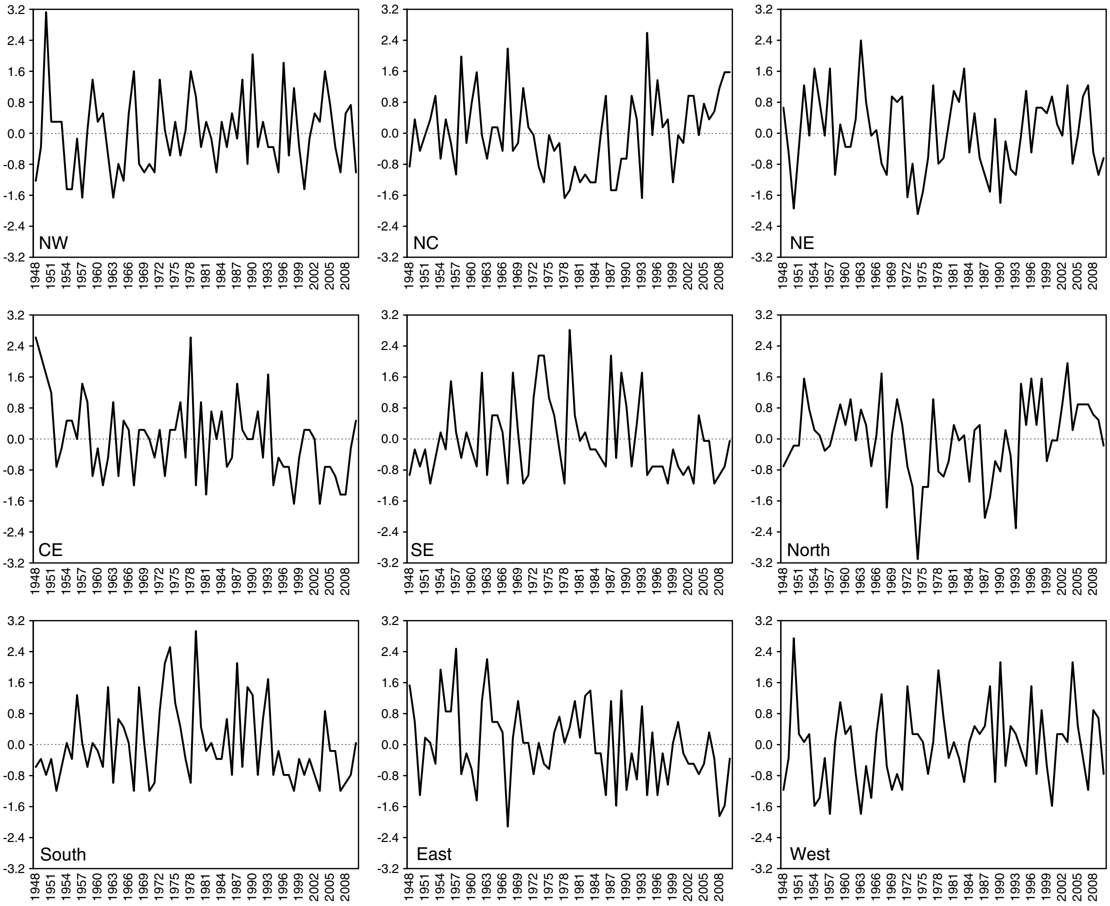

Figure 4. Standardized frequencies of synoptic types and groups of synoptic types during July–August of 1948–2010. Synoptic types with low frequencies are not shown.

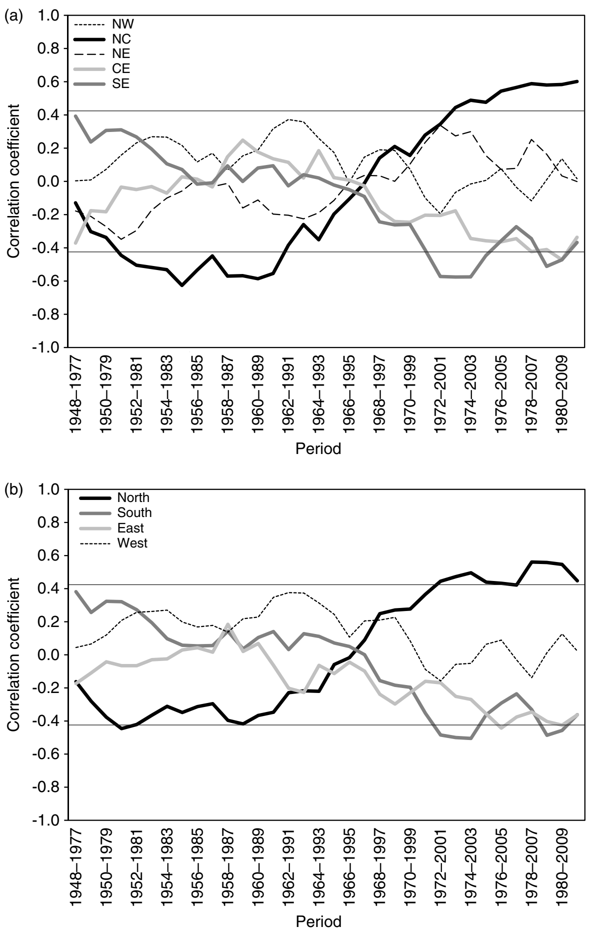

Figure 5. Trends in (a) synoptic types and (b) groups of types for 34 over-lapping climate periods. Each of the 34 periods has a Spearman's ρ correlation coefficient. Significant positive trends are above the upper horizontal line and significant negative trends are below the lower horizontal line. The significance level is 0.01 for a one-tailed test.

collectively decreased significantly in frequency from 1951 to 1980. The NC type increased significantly in frequency within nine consecutive periods beginning with 1973–2002 and ending with 1981–2010. Northern types collectively increased significantly in frequency within ten consecutive periods beginning with 1972–2001 and ending with 1981–2010.

The southern and eastern types generally experienced decreases in frequencies during the second half of the period (Figures 4 and 5). The SE type decreased significantly in frequency within four consecutive periods beginning with 1972–2001 and ending with 1975–2004; there also were significant decreases from 1979–2008 to 1980–2009. The CE type decreased significantly in frequency from 1978–2007 to 1980–2009. Southern types collectively decreased in frequency within five periods beginning with 1972–2001 and ending with 1980–2001. Eastern types collectively decreased in frequency from 1976–2005 to 1980–2009.

The above results indicate that the monsoon anticyclone weakened or was relatively weak or both over the southern and northwestern portions of the domain from the late 1940s to the late 1970s. This period was characterized by the southern region having much lower heights compared to 1980–2010. The centre of the monsoon anticyclone also occurred less frequently over the LCRB (i.e. the northern synoptic types became less frequent) during the period.

The monsoon anticyclone intensified primarily over the northwestern portion of the domain, which includes the LCRB, since the mid- to late 1970s. The anticyclone has thus been expanding over the LCRB. The anticyclone has been in a northern position, specifically a north-central position, over the basin more frequently over the past 30 years; conversely, the anticyclone has been in a southern and eastern position over the basin less frequently. Therefore, troughing over the basin has become less frequent.

The monsoon anticyclone intensified from 1948–1978 to 1980–2010 and it has been intensifying since the 1970s; this intensification may be associated with changes in summer rainfall north of the monsoon region. Using precipitation data from 1930 to 2000, Anderson *et al.* (2010) report no multi-decadal trends in July–September rainfall in the LCRB; however, positive trends in seasonal precipitation amounts and number of daily rainfall events are reported for a region north of the LCRB (e.g. Utah) from 1975 to 2000. The increased rainfall north of the LCRB suggests a northward expansion of the North American monsoon (Anderson *et al.*, 2010).

4. Conclusions

This article presented an examination of multi-decadal changes in the North American monsoon anticyclone from 1948 to 2010 during the mature phase of the system (i.e. July and August). The geographic scales involved the anticyclone domain (i.e. the western United States and northern Mexico) and associated regions as well as the LCRB. Trends in 500 hPa geopotential heights and frequencies of 500 hPa circulation patterns were assessed for 34 over-lapping 30 year periods. In addition, changes in heights and type frequencies from 1948–1978 to 1980–2010 were examined. The only significant changes involved the northwestern and southern regions of the anticyclone domain: both regions had significant increases in geopotential heights from the earlier period to the latter period. The following generally occurred from the late 1940s to the late 1970s: a significant decrease in 500 hPa geopotential heights over the northwestern and southern regions; and a significant decrease in frequencies of northern synoptic types associated principally with a decrease in the north-central type. The following generally occurred over the following 30 years beginning in the late 1970s: a significant increase in 500 hPa geopotential heights over the northwestern and southern regions; a significant increase in frequencies of northern synoptic types as a whole, with one specific type, the north-central type, having a significant increase in frequency; and a significant decrease in southern and eastern synoptic types as a whole, with two specific types, the southeast and central-east types, having significant decreases in frequency.

Future research needs to investigate connections since the 1970s between circulation and rainfall throughout the southwestern United States and northwestern Mexico. For example, detailed analyses of trends in rainfall characteristics for zones within the LCRB are needed, since there are marked differences in monsoon-related processes within the basin (e.g. Diem and Brown, 2006, 2009). In addition, it is essential that future research place much more emphasis on changes in the monsoon anticyclone when projecting changes in monsoonal rainfall for the remainder of the century.

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