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Nature and causes of the 2002 to 2004 drought in the southwestern United States compared with the historic 1953 to 1957 drought

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ABSTRACT: The 1950s drought (1953 to 1957) and the recent drought (2002 to 2004) are 2 of the longest and most severe droughts to affect the southwestern USA since 1895. The 1953 to 1957 drought was longer, more severe, and more spatially extensive than the 2002 to 2004 drought. Although the 1953 to 1957 drought was centered over New Mexico, it was quite severe over much of the southwestern USA, while the impact of the 2002 to 2004 drought was mostly felt in Arizona. Both of these droughts were associated with multi-year La Niña events, the cold phase of the Pacific Decadal Oscillation (PDO), the warm phase of the Atlantic Multidecadal Oscillation (AMO), and the positive phase of the Eastern Pacific Oscillation (EPO). These conditions resulted in anomalous atmospheric ridging over the southwestern USA, which prevented Pacific moisture from entering the study region. Therefore, both droughts were associated with increases in the number of dry tropical days and decreases in the number of dry moderate and moist tropical days. These statistically significant changes in air mass frequencies were relatively consistent across the southwestern USA and during both drought events. Generally, it appears that the occurrence of major droughts in the southwestern USA is associated with a cold PDO and warm AMO, conditions seen during both the 1950s and the recent drought.

KEY WORDS: Drought · Southwestern USA · Atlantic Multidecadal Oscillation · Pacific Decadal Oscillation · Eastern Pacific Oscillation · El Niño/Southern Oscillation

1. INTRODUCTION

A prolonged drought has affected portions of the southwestern USA for more than a decade (1996 to the present). Tree-ring records reveal that the ongoing drought is one of the 10 most severe droughts in the southwestern USA since 1500 AD (Piechota et al. 2004). This drought has coincided with a large increase in the regional population, most notably in the Phoenix metropolitan area, and has raised concerns about sustainability in a region known for its complex system of water management (Morehouse et al. 2002). This combination of factors led to the creation of the Arizona drought preparedness plan which addresses issues of drought vulnerability and drought mitigation (GDTF 2004). Much uncertainty regarding the future of water resource management remains, and there is growing concern about increases in the seasonal variability of winter precipitation. Goodrich & Ellis (2008) demonstrated that the recent reversal in southwestern USA winter precipitation from 2005 (the second wettest winter since 1895) to 2006 (the driest winter since 1895) is representative of a statistically significant trend of increasing variability in winter-season precipitation since 1960. Enhanced seasonal precipitation variability has also led to increased variability in spring run-off and storage in some of the larger reservoirs in the region. While brief wet periods during decadal droughts in the western USA are not uncommon (Meko & Woodhouse 2005), these wet periods can lead to a false sense of security among water resource managers and government officials if they think that the drought has ended.

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Recent research suggests that persistent La Niña-like conditions in the tropical Pacific coupled with local soil-moisture feedbacks are responsible for many of the persistent droughts that have occurred since 1850 (Seager et al. 2003, 2005, Schubert et al. 2004, Herweijer et al. 2006). Other studies have also identified sea surface temperatures (SST) in the Atlantic, Indian, and extratropical Pacific Oceans as the dominant forcing mechanism for long-term drought (Hoerling & Kumar 2003, Seager 2007). Persistent SST patterns can produce seasonal patterns of low-frequency variability in the atmosphere (i.e. teleconnections) that cause below normal precipitation in some regions. Two of the most important SST patterns are the Atlantic Multidecadal Oscillation (AMO) and the Pacific Decadal Oscillation (PDO).

The AMO is a 65 to 80 yr cycle in North Atlantic SSTs. It is believed that these multidecadal SST anomalies in the North Atlantic are caused by natural variations in the strength of the thermohaline circulation and meridional overturning (Collins & Sinha 2003, Sutton & Hodson 2003). This hypothesis was further refined by Dima & Lohmann (2007), who suggested a deterministic mechanism, the memory of which is driven by the thermohaline adjustment to freshwater fluxes and the subsequent meridional overturning of Atlantic SSTs that results from sea ice response to wind stress. The negative feedback of the AMO results from exchanges between the Arctic and Atlantic basins, with amplification from the Pacific basin. This causal relationship that results in multidecadal signals being transferred between the Atlantic and Pacific basins is supported by the time sequence of the climate shifts that occurred in the Atlantic and Pacific during the 1970s. The AMO is associated with SST differences between warm and cold phases that are on the order of 0.4°C throughout the North Atlantic basin (Enfield et al. 2001). AMO warm (or positive) phases occurred from 1860 to 1880 and 1940 to 1960, and cool (or negative) phases occurred from 1905 to 1925 and 1970 to 1990 (Enfield et al. 2001). The warm phase of the AMO is associated with negative precipitation anomalies in the central and western USA such as the droughts of the 1930s and 1950s (Enfield et al. 2001, Hidalgo 2004, McCabe et al. 2004). Since 1995, the AMO has returned to the warm phase and drought has returned to the western/southwestern USA (in particular during 1996 and 1999 to 2002) (Enfield et al. 2001, Hidalgo 2004, McCabe et al. 2004).

The PDO represents low frequency variability in extratropical SSTs in the northern Pacific, with a period of approximately 50 yr (Mantua et al. 1997). Warm phases of the PDO occurred from 1925 to 1946 and from 1977 to at least 1998, while cold phases of the PDO occurred from 1890 to 1924 and 1947 to 1976. There remains uncertainty as to the current phase of the PDO (Mantua & Hare 2002, Chavez et al. 2003). The warm phase of the PDO is associated with cooler than normal SSTs in the northern-central Pacific and warmer than normal SSTs along the west coast of North America, while the cold phase is associated with the opposite SST patterns. The PDO, which influences precipitation patterns in a manner similar to El Niño/Southern Oscillation (ENSO), is positively correlated with winter precipitation in the southwestern USA. In fact, it is well established that the relationship between winter precipitation in the western USA and ENSO has varied in the past several decades, primarily due to changes in PDO phase (Gershunov & Barnett 1998, McCabe & Dettinger 1999, Gutzler et al. 2002, Goodrich 2007). Barlow et al. (2001) found that summertime precipitation, drought, and streamflow were positively correlated with both ENSO and PDO over the western United States such that drought conditions were most likely to occur during the cold phase of the PDO. In addition, the PDO is also linked to decadal drought patterns in the western USA (McCabe et al. 2004). As with the AMO, there is some uncertainty regarding the physical mechanisms that drive the PDO. Some believe that ENSO may force the PDO and that the PDO is a low frequency manifestation of ENSO in the North Pacific (Gedalof et al. 2002, Newman et al. 2003, Schneider & Cornuelle 2005). Regardless of the relationship between the PDO and ENSO, it has been established that the usefulness of ENSO as a seasonal predictive tool varies with the phase of the PDO.

There is evidence of decadal and multi-decadal variability in the western USA drought record. For example, a strong 51 yr drought periodicity has been identified within the 500 yr record of reconstructed moisture conditions in the USA (Hidalgo 2004). This suggests that low frequency modes of variation, such as the AMO and PDO, may be responsible for modulating drought occurrence. In particular, many of the major episodes of wetter than normal conditions in the southwestern USA during the 15th, 16th, and 20th centuries appear to be associated with the cold phase of the AMO (Hidalgo 2004).

With the uncertainty in the physical mechanisms that lead to decadal drought, there is a need to develop a better understanding of the nature and causes of recent droughts in the southwestern USA. The first objective of the present paper was to characterize the severity, spatial extent, and duration of droughts in the southwestern USA since 1895. The second objective was to compare and contrast the weather-type variability associated with the recent drought and the 1950s drought. The third objective was to investigate the causal mechanisms that have allowed these droughts to persist by examining upper air data and atmospheric and oceanic teleconnection indices. The 1950s drought and the recent drought were selected for analysis because they were the 2 most severe droughts that have occurred in the southwestern USA during the period for which upper air data are available.

2. DATA

2.1. Drought data

The Standardized Precipitation Index (SPI) was used to quantify the spatial and temporal nature of droughts in the southwestern USA (1895 to 2006). The SPI was designed to be a spatially invariant indicator of drought (e.g. spatially and temporally comparable), and the mean SPI for any location is zero (McKee et al. 1993, 1995). Positive (negative) SPI values indicate greater (less) than median precipitation. The SPI can quantify precipitation on multiple scales (i.e. weeks, months, years), and therefore it can be used to measure different types of drought (i.e. meteorological, agricultural, hydrological), since each has a unique time scale (McKee et al. 1993, 1995). The SPI is calculated by fitting a probability density function (PDF) to a long precipitation record. There are 2 probability distributions that are commonly used to calculate the SPI (i.e. Pearson Type III and Gamma). This is important to note because each probability distribution will produce different SPI values, even with the same input data. Guttman (1999) experimented with a number of probability distributions and concluded that the Pearson Type III distribution provides the best model for calculating the SPI. However, this remains a matter for debate since other studies disagree with Guttman's (1999) findings. For example, the National Drought Mitigation Center (NDMC) uses the 2-parameter gamma PDF to fit the frequency distribution of precipitation and calculate the SPI (Wu et al. 2007). The calculation of all SPI values in the present study will be carried out using Guttman's (1999) algorithm.

The SPI was calculated using precipitation data obtained from the National Climatic Data Center (NCDC) for Arizona and New Mexico climate divisions. Data from each climate division represents an unweighted average of all representative stations within that division (Guttman & Quayle 1996). From 1895 to 1930 a regression technique was used to calculate the divisional averages based on available United States Department of Agriculture (USDA) statewide averages (Guttman & Quayle 1996). Thus, the pre-1930 climate division data should be treated with caution since it cannot fully account for intra-state climatic variability. The climate division precipitation data can be accessed at www.cdc.noaa.gov/Timeseries/.

The 12 mo SPI was used to characterize the duration, severity, and spatial extent of droughts for the 7 climate divisions in Arizona and 8 climate divisions in New Mexico (1895 to 2006). A drought event was initiated when the mean area-weighted water-year SPI for the study region (i.e. all 15 climate divisions) was less than –1.0 for 3 consecutive months and a drought event was terminated when it returned to a positive value (McKee et al. 1993, 1995). The mean spatial extent of a drought event was calculated by determining the percentage of the study region that had an SPI value of less than –1.0 for each month and then averaging over the entire drought duration. The duration, severity, and spatial extent rankings are based on a comparison of all drought events that have occurred in the region since 1895.

2.2. Spatial Synoptic Classification

Weather-type (air mass) variability associated with drought in the southwestern USA is characterized using the Spatial Synoptic Classification (SSC). The SSC is a hybrid classification scheme that is based on manual initial identification of air masses, or weather types, followed by automated classification based on these identifications (Kalkstein et al. 1996, Sheridan 2002). The SSC utilizes surface weather data (e.g. temperature, dew point, sea-level pressure, wind speed and direction, cloud cover) to classify a given day into one of the following weather types: dry polar (DP), dry moderate (DM), dry tropical (DT), moist polar (MP), moist moderate (MM), moist tropical (MT), and transitional (TR).

DP is a cool or cold and dry air mass similar to the traditional continental polar (cP) air mass. It is typically associated with clear skies and northerly winds. Northern Canada and Alaska are the primary source regions for DP, and it is advected into the rest of North America by a cold-core anticyclone that migrates out of the source region (Sheridan 2002).

DM is a mild and dry air mass that has no traditional source region. In the eastern and central portions of North America, DM usually occurs as a result of zonal flow aloft which adiabatically modifies air masses from the Pacific Ocean as they traverse the Rocky Mountains (Sheridan 2002). DM can also result from a significantly modified DP weather type or from a mixture of influences from multiple air masses. DM is similar to the Pacific air mass identified by Schwartz (1991).

DT is associated with the hottest and driest conditions. It is analogous to the traditional continental tropical (cT) designation, and it is associated with high pressure and clear skies. The primary source region for DT is the deserts of the southwestern USA and north-western Mexico, but it can also be created by strong downsloping winds, where rapid compressional heating produces a hot dry air mass (Sheridan 2002).

MP is associated with cool, cloudy, and humid weather conditions, and it is often accompanied by light precipitation. It is analogous to the traditional maritime polar (mP) designation, and it typically forms over the North Pacific or North Atlantic before being advected onto land. MP can also result from a cP air mass that acquires moisture as it passes over a large water body (Sheridan 2002).

MM is warmer and more humid than MP air. It is commonly formed by modifying either an MP or MT weather type. MM can also form south of MP air near a warm front (Sheridan 2002).

MT air is warm and very humid, cloudy in winter and partly cloudy in summer. Convective precipitation is quite common in this weather type, especially in summer. MT is analogous to the traditional maritime tropical (mT) designation, and it typically forms either over the Gulf of Mexico, tropical Atlantic, or tropical Pacific Ocean (Sheridan 2002). MT is found in the warm sector of a mid-latitude cyclone and on the western side of a surface anti-cyclone (e.g. Bermuda High).

TR is used to represent days where there is a transition from one weather type to another, based on large changes in dew point, pressure, and wind. A complete discussion of all of the weather types and the development of the SSC (including maps) is provided in Sheridan (2002, 2003) and Kalkstein et al. (1998).

Daily SSC data are available for 2 stations in New Mexico (Albuquerque and Roswell) and for 5 stations in Arizona (Prescott, Tucson, Winslow, Yuma, and Phoenix; data available at http://sheridan.geog.kent.edu/ssc.html). Only stations with a record >50 yr and with <5% missing data were used in this study. The 3 stations that met these criteria were Albuquerque, New Mexico (1948 to 2005), Tucson, Arizona (1949 to 2003), and Phoenix, Arizona (1948 to 2004).

2.3. Oceanic and atmospheric indices

The Niño-3.4 index, which is calculated as the average of monthly SST anomalies for the area 5°N to 5°S, 120 to 170°W, was used to represent ENSO. According to the National Oceanic and Atmospheric Administration (NOAA), an El Niño (La Niña) event is said to occur when the 3 mo moving average of Niño-3.4 anomalies exceeds +0.5 (–0.5) for 3 consecutive months. All other periods are considered to have neutral ENSO conditions. Since most El Niño and La Niña events tend to develop during the summer and persist through the spring of the following year, the impact of ENSO on southwestern USA precipitation is greatest during the winter months (Redmond & Koch 1991). Each water year was classified with the appropriate ENSO category if the ±0.5 threshold of the 3 mo moving average occurred anytime during the October to December period. The Niño-3.4 dataset used in the present study was obtained from the International Research Institute for Climate prediction (IRI) data library (available online at http://iridl.ldeo.columbia.edu/SOURCES/.Indices/.nino/.EXTENDED/.NINO34/). A small adjustment was made to the time series to change the base period climatology from 1951–1980 to 1971–2000.

Other teleconnections that are known to influence precipitation in the southwestern USA were also considered in this study. Monthly data for the Eastern Pacific Oscillation (EPO) were obtained from the Climate Diagnostics Center (ftp://ftp.cdc.noaa.gov/Public/gtb/teleconn/epo.jan1948-dec2005.asc). The EPO is based on centers of action of 500 hPa height fields where values from 55 to 65° N, 160 to 125° W are subtracted from values from 20 to 35° N, 160 to 125° W, such that the positive phase of the EPO is represented by a ridge east of Hawaii and a trough in the Gulf of Alaska. This subtropical ridge that occurs during the positive phase of the EPO is associated with below average precipitation in the southwestern United States. The EPO index for any day is centered on a 3 d moving average to emphasize low frequency variability. Monthly data for the PDO were obtained from the Joint Institute for the Study of the Atmosphere and Ocean at the University of Washington (http://jisao.washington.edu/pdo/PDO.latest). The AMO index is calculated based on detrended SST anomalies in the North Atlantic between 0° and 70° N, and the index is then smoothed using a 20 yr moving average (Hidalgo 2004, McCabe et al. 2004). Monthly data for the AMO were obtained from the Earth Science Research Laboratory Physical Sciences Division (www.cdc.noaa.gov/Correlation/amon.us.data).

3. RESULTS

3.1. Historical comparison

A total of 17 drought events were identified in the southwestern USA between 1895 and 2006 (Table 1). The average drought lasted 17.9 mo (range 5 to 53 mo), the mean severity was –0.82 (range –0.49 to –1.11), and the mean spatial extent was 40% of the study region (range 19 to 63%). The turn-of-the-century drought that persisted from 1899 to 1905 was the worst drought to affect Arizona and New Mexico since 1895. In addition to being the longest drought (53 mo), it was also extremely severe (ranked second) and spatially extensive (ranked second). The 1953 to 1957 drought was the second longest (49 mo), and the 2002 to 2004 drought was the third longest (31 mo) to affect the region. The 1953 to 1957 drought ranked fourth in terms of severity and seventh in terms of spatial extent. The 2002 to 2004 ranked eighth in terms of severity and ninth in terms of spatial extent. The 1950s drought was centered over New Mexico and was characterized by hot, dry summers followed by mild, dry winters (Fig. 1A). In contrast, the 2002 to 2004 drought was more severe in Arizona (Fig. 1B) and, although 1996 to 2006 was generally dry, there was more intra-decadal variability than during the 1950s drought, as demonstrated by the wet winters of 1998 and 2005 (Fig. 2).

The methodology (e.g. drought index and threshold) used to identify drought events has an impact on the results. Fig. 2 shows the 12 mo SPI values that were used to calculate the drought statistics shown in Table 1 and the same data smoothed using a 5 yr moving average. Using the 12 mo SPI data to characterize drought, results in the identification of more drought events, but events are usually of shorter duration and greater severity than those identified using a 36 mo time period. For example, based on the 12 mo SPI the period from 1946 to 1957 is broken into 4 distinct drought events that range in length from 8 to 49 mo, while the 36 mo smoothed SPI identifies 1946 to 1957 as a single uninterrupted drought event. Therefore, depending on the methodology employed, this period can be either described as a quasi-decadal drought, or as a series of shorter drought events punctuated by periods of near-normal or wetter-than-normal conditions. The 12 mo SPI was used for defining droughts in the present paper since it has been shown to be appropriate for monitoring hydrological drought conditions (Quiring et al. 2007). Annual (water year) data are also commonly used for making policy and water resource management decisions (Goodrich & Ellis 2006). Using periods longer than a year suppresses variability to the point where brief wet episodes (i.e. breaks in the drought) can be lost.

Table 1. Duration, severity, and spatial extent of drought events (1895 to 2006) in southwestern USA (and their respective ranks). Severity is the mean 12 mo Standardized Precipitation Index (SPI); spatial extent is the percentage of the study region with SPI < 1.0

Drought	Duration (mo)	Duration rank	Severity	Severity rank	Spatial extent (%)	Spatial extent rank
Aug 1899 to Jan 1905	53	1	−1.10	2	54	2
Sep 1910 to Jul 1911	11	11	−0.85	8	38	8
Dec 1924 to Oct 1925	11	11	−1.11	1	63	1
Sep 1928 to Aug 1929	12	9	−0.53	16	24	16
Sep 1934 to Aug 1935	12	9	−0.58	15	33	13
Mar 1946 to Nov 1946	8	15	−0.78	11	34	12
Sep 1947 to Jan 1949	16	5	−0.75	12	36	10
Oct 1950 to Apr 1952	16	5	−0.91	7	52	5
Sep 1953 to Oct 1957	49	2	−1.00	4	44	7
Jul 1963 to Jun 1965	24	4	−0.49	17	19	17
Mar 1971 to Jun 1972	16	5	−0.63	14	27	15
Mar 1974 to Mar 1975	13	8	−0.94	5	53	3
Nov 1989 to Sep 1990	11	11	−0.85	8	35	11
Mar 1996 to Jan 1997	11	11	−0.94	5	47	6
Aug 2000 to Jan 2001	5	17	−0.64	13	32	14
Mar 2002 to Sep 2004	31	3	−0.85	8	37	9
Feb 2006 to Aug+ 2006	6	16	−1.02	3	53	3

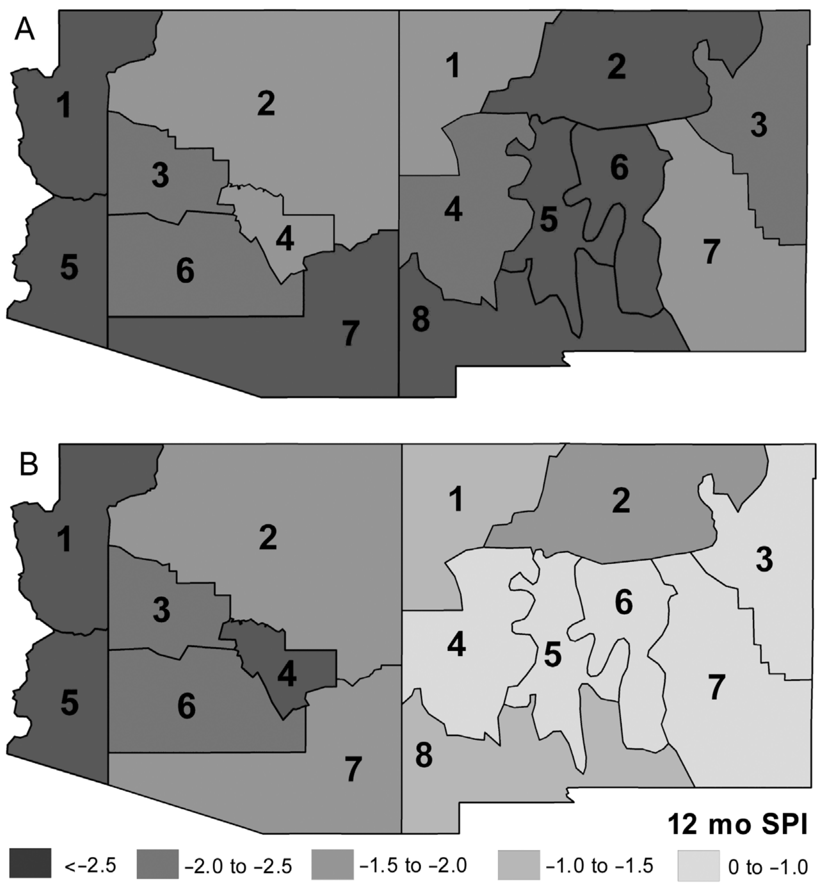

Fig. 1. Severity of drought conditions (based on 12 mo Standardized Precipitation Index, SPI) in Arizona and New Mexico in the water years of (A) 1956 and (B) 2002. Climate division boundaries and numbers for Arizona and New Mexico are shown

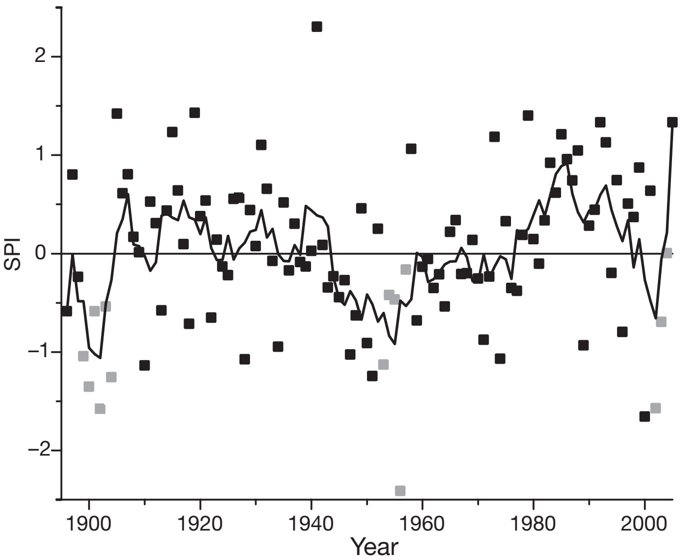

Fig. 2. Mean 12 mo Standardized Precipitation Index (SPI) (squares) and 5 yr moving average (thick black line) for southwestern USA (1896 to 2006). Grey squares are used to identify the 3 major droughts: 1899 to 1904, 1953 to 1957, and 2002 to 2004

Since air mass, teleconnection, and atmospheric reanalysis data are not available for the 1899 to 1905 drought, this paper will focus on comparing the nature and causes of the 1950s (second worst) and 2002 to 2004 (third worst) droughts. Unlike the turn-of-the-century drought, both the recent and mid-century droughts consisted of a series of dry years interspersed with very wet years, which mitigated the impact of the dry years somewhat. Both droughts also had a 'peak' drought year marked by an extremely low SPI (Fig. 2). The driest water year in the mid-century drought occurred in 1956, which had the lowest 12 mo SPI ever recorded for New Mexico and the second lowest ever recorded for Arizona (after 2002). The driest water year in the recent 2002 to 2004 drought occurred in 2002; the 12 mo SPI ranks 2002 as the driest in Arizona and the thirteenth driest in New Mexico since 1895. Based on an area-weighted average of Arizona and New Mexico climate divisions, 1956 was the driest for the study region (mean 12 mo SPI was –2.41) since 1895, and 2002 was the fourth driest (mean 12 mo SPI was –1.57).

3.2. Air mass variability associated with the 1956 and 2002 drought events

3.2.1. Air mass climatology

The 3 most common air masses in Phoenix, Arizona (1948 to 2004), are DT, DM, and MT (Fig. 3A). DT is the most frequent air mass during the warm half of the year, and it is especially dominant during April to June (pre-monsoon) and September to October (post-monsoon). MT air masses occur relatively infrequently between October and June, but MT is much more common during the peak monsoon months of July and August as a result of the influx of moisture from the Gulf of California (and to a lesser extent the Gulf of Mexico). DM is the most frequent air mass during the cold half of the year (November to March). The other air masses are relatively infrequent (frequencies of <10%) in all months, with the exception of TR air masses which occur during 10 to 15% of the days between March and July as a result of increased frontal passages.

On average, the 3 most common air masses in Tucson, Arizona (1949 to 2003), are also DT, DM, and MT (Fig. 3B). DT is the most frequent air mass in all months of the year except December to January and July to August. DT is especially dominant during April to June (pre-monsoon) and September to October (post-monsoon). MT frequencies increase greatly during the peak monsoon months of July and August (and are also somewhat higher in June and September), but MT occurs relatively infrequently between October and June. DM air masses are the dominant air mass during the coldest months of the year (December and January). As in Phoenix, the other air masses occur relatively infrequently, although DP peaks in spring and fall (associated with shifts in storm tracks due to the changing seasons) and MM increases in July and August.

In Albuquerque, New Mexico, the 3 most common air masses (1948 to 2005) are DM, DT, and DP (Fig. 3C). DM is the most frequent air mass in all months of the year, except June, and it peaks in importance during July and August. DT is especially dominant during April to June (pre-monsoon) and September to October (post-monsoon), but it occurs less frequently than in Phoenix and Tucson. DP is the second most frequent air mass during the cold season (November to March), and it occurs less frequently during the warm season as the frequency of DT increases. In Albuquerque, MM air masses are generally more common than MT air masses. MT air masses are absent, except during August and September. TR air masses appear to be more important in Albuquerque than at the other 2 locations, and they occur most frequently between March and June. Unlike at the other 2 locations, the onset of the North American Monsoon is not associated with large increases in the occurrence of moist air masses. Instead, the monsoon (July to September) is associated with a dramatic increase in the occurrence of DM. This is due to the increased distance between Albuquerque and the Gulf of California (the primary source of low-level moisture).

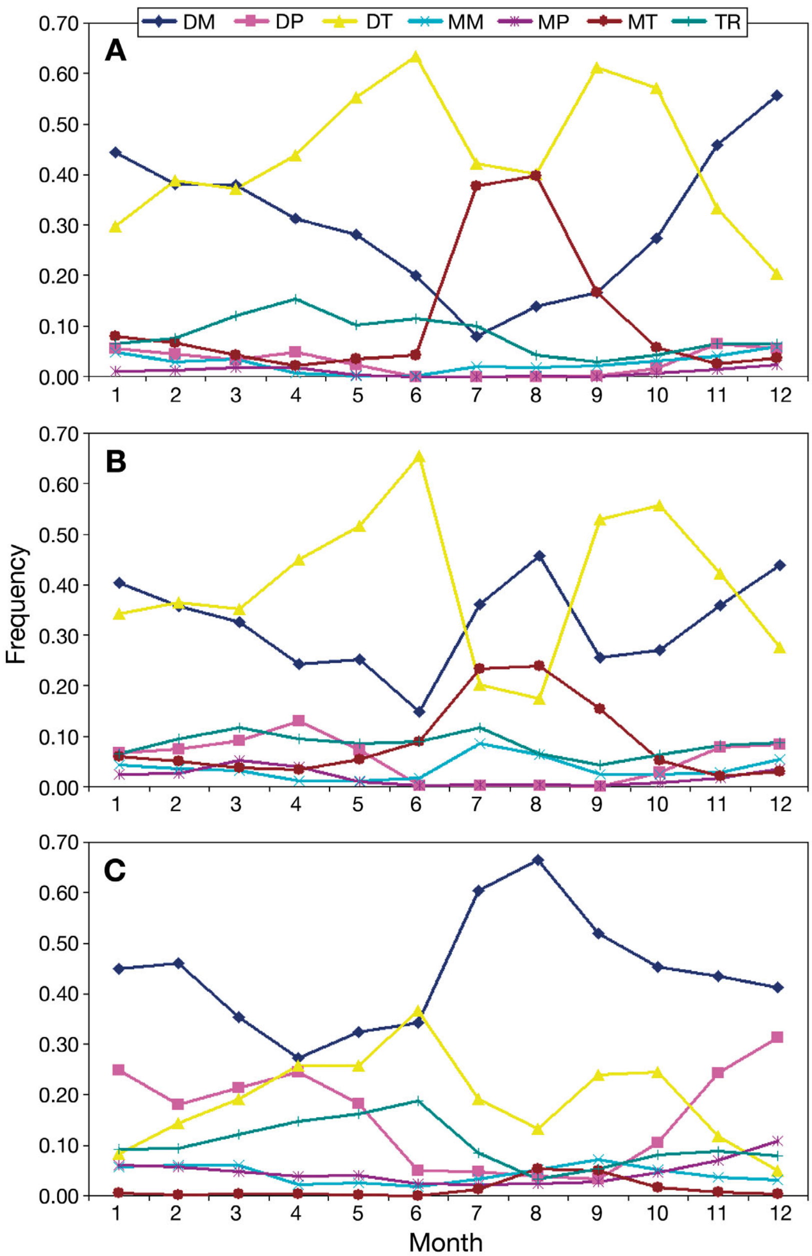

Fig. 3. Mean monthly air mass frequencies for (A) Phoenix, AZ, (B) Tucson, AZ, and (C) Albuquerque, NM. Air mass types: DM: dry moderate, DP: dry polar, DT: dry tropical, MM: moist moderate, MP: moist polar, MT: moist tropical, TR: transitional (see Section 2.2)

3.2.2. Air mass anomalies associated with the 1956 and 2002 droughts

The water year droughts of 1956 and 2002 were associated with relatively large and consistent changes in air mass frequencies across the southwestern USA (Table 2). Both droughts were associated with an increased number of dry air mass (DP, DM, and DT) days and a decreased number of moist air mass (MM, MP, and MT) days. In 1956, the region experienced an average of 21 more days of dry air masses and 17 fewer days of moist air masses, as compared to normal. In 2002, the region experienced an average of 13 more days of dry air masses and 20 fewer days of moist air masses, as compared to normal. However, in 2002 the changes in air mass frequencies were most pronounced at Tucson and Phoenix. This is not surprising given that this drought was more severe in Arizona than in New Mexico (Fig. 1B). The observed changes in air mass frequencies are statistically significant at all 3 stations (based on χ^2 test, $\alpha = 0.01$) (Fig. 4).

In addition to examining the overall changes in dry and moist air masses, the changes in individual air mass types were also evaluated. In 1956 there were large decreases in the frequency of DM at both Tucson and Albuquerque (Fig. 4B,C). In Tucson, the number of DM days was approximately 70% of normal, and in Albuquerque the number of DM days was 74% of normal. This corresponds to 35 and 42 fewer DM days in Tucson and Albuquerque, respectively. In 2002 there were also similar decreases in the number of DM days in Tucson (70% of normal) and Albuquerque (84% of normal). Phoenix also experienced fewer DM days during the 2002 drought (57% of normal or 48 fewer DM days); however, Phoenix actually experienced about 38 more DM days than normal in 1956 (Fig. 4A).

The 1956 and 2002 droughts were also associated with large increases in the number of DT days. In Tucson, DT days were approximately 140% of normal during 1956 and 2002 (Fig. 4B). This means that there were about 60 additional DT days during each drought. Albuquerque also experienced large increases in DT days. In 1956, DT days were 193% of normal (e.g. approximately 65 additional DT days), and in 2002, DT days were 141% of normal (e.g. approximately 29 additional DT days) in Albuquerque (Fig. 4C). Phoenix also experienced more DT days during the 2002 drought (138% of normal or 61 more DT days); however, Phoenix actually had about 38 fewer DT days than normal in 1956 (Fig. 4A). The main reason for the difference between Phoenix and Tucson/Albuquerque in 1956 is due to a known issue with the SSC methodology. The SSC is based on seed days that are selected from 1961 to 1990, and it assumes station-

Table 2. Changes (observed number of days – normal number of days) in air mass frequencies associated with the 1956 and 2002 droughts. Dry includes DP, DM, and DT air masses and wet includes MP, MM, and MT air masses. TR: the transition air mass type. Air mass frequencies are rounded to the nearest whole day. For definition of air mass types see Fig. 3

		Phoenix	Tuscan	Albuquerque	Mean
1956	Dry	22	27	15	21
	Wet	−9	−19	−23	−17
	TR	−13	−7	8	−4
2002	Dry	17	26	−4	13
	Wet	−29	−28	−3	−20
	TR	12	3	6	7

arity in the climate (e.g. the seed days are appropriate for the whole period 1948 to present). This can be a problem in locations where there has been a significant increase in the urban heat island over time (e.g. Phoenix). This means that an air mass would tend to be classified as DM during the early part of the record (pre-1960) and as DT during the later part of the record (S. C. Sheridan pers. comm.). Therefore, the differences between Tucson and Phoenix in 1956 are likely a result of this known issue with the SSC methodology.

Both droughts were also associated with decreases in the number of MT days. During the 1956 drought, MT days were 20, 57, and 85% of normal at Albuquerque, Tucson, and Phoenix, respectively. The decreased occurrence of MT days was particularly pronounced during the monsoon season (July and August). There were also decreases in MM and MP air masses. When all the moist air masses (i.e. MT, MM, and MP) are considered together, there were 23 fewer moist air mass days in Albuquerque, 9 fewer in Phoenix, and 20 fewer in Tucson in 1956. Although these changes involve fewer days than the changes in DM and DT, they are extremely important because during the moist air mass days precipitation is most likely to occur. During the 2002 drought, MT days were 122, 47, and 51% of normal at Albuquerque, Tucson, and Phoenix, respectively. The higher than normal frequency of MT days in Albuquerque is likely because the drought was more intense in Arizona than in New Mexico. When all the moist air masses are considered together, there were 3 fewer moist air mass days in Albuquerque, 30 fewer in Phoenix, and 29 fewer in Tucson in 2002.

At all 3 locations DM and DT are clearly the 2 most common air mass types, and therefore the largest absolute changes in the number of air mass days are associated with these 2 air masses. However, the moist air mass types are important, particularly during the monsoon season, when MT is present during, on average, 40 and 25% of the days in July and August for Phoenix and Tucson, respectively.

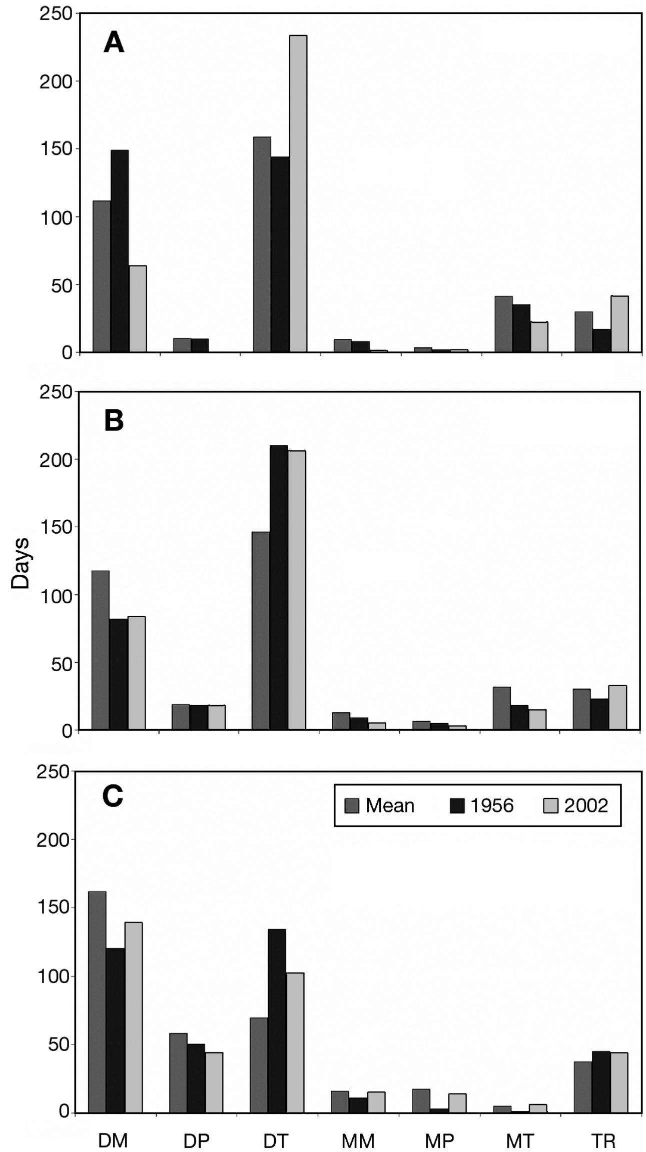

Fig. 4. Air mass frequencies for mean conditions (e.g. a normal year) (dark grey bars), 1956 water year (black bars), and 2002 water year (light grey bars) in: (A) Phoenix, AZ, (B) Tucson, AZ, and (C) Albuquerque, NM. For definition of air mass types see Fig. 3

A separate analysis of 2 anomalously wet years, 1979 and 1992, also revealed statistically significant changes in air mass frequencies. In particular, these 2 anomalously wet years in the southwestern USA were associated with increases in the number of MM days (120 to 220% of normal) and decreases in the number of DP days (28 to 88% of normal) (results not shown). Anomalously wet years also tend to be associated with decreases in DT and increases in DM air masses (in 6 out 8 cases). However, the changes in air mass frequencies associated with these wet years were much less consistent (both spatially and temporally) than the changes during the drought years.

Overall, it appears that major drought events in the southwestern USA are associated with statistically significant changes in air mass frequencies. In particular, major drought events were associated with increases in the occurrence of DT air masses and decreases in the occurrence of DM and MT air masses. These patterns were relatively consistent across the 3 locations and during the 2 drought events. This suggests that both of these drought events were caused by changes in atmospheric circulation over the region. The reasons for these changes will be examined by looking at the upper-level flow and atmospheric circulation indices.

3.3. Comparison of causal mechanisms

The 500 hPa geopotential height anomalies were computed for the water years of 1956 and 2002. In 1956 (Fig. 5A), a trough appears over western Canada as well as over the East Coast. A broad ridge appears over the southwestern USA, which in association with the La Niña, kept any Pacific moisture well north of Arizona and New Mexico. In 2002 (Fig. 5B), the same end result occurred even though the center of the ridge was located over the East Coast. Nearly the entire continental United States had above average 500 hPa heights during the 2002 water year. The fact that 2 relatively different upper air patterns both led to very dry conditions in the southwestern USA shows that forecasting seasonal drought is a complex undertaking.

Recent research has shown that multi-year La Niña events are associated with persistent drought in the western USA (Cole et al. 2002) as well as in southern Europe, southern South America, and western Australia (Herweijer & Seager 2008). A single-year La Niña is generally associated with a 15 to 30% decrease in winter precipitation, but it has a negligible effect on the summer monsoon. In fact, the inverse relationship between winter precipitation and the summer monsoon means that La Niña winters are often followed by summers of above average precipitation (Gutzler & Preston 1997, Small 2001). Therefore, single-year La Niñas do not necessarily lead to drought conditions. Multi-year La Niñas, on the other hand, tend to cause multi-year droughts by strengthening the persistence of dry soil moisture anomalies that result from decreases in winter and spring precipitation in successive years. Evapotranspiration is reduced due to a lack of springtime soil moisture, which leads to a positive feedback mechanism that can lower the amount of summer rainfall from convective storms (Seager et al. 2003, 2005).

Based on our method of determining whether each water year was influenced by El Niño, La Niña, or neutral ENSO conditions, there have been 16 La Niña water years since 1950. This means that La Niña events occur roughly 30% of the time, or once every 3 yr. However, 9 of the 16 La Niña events occurred in 3 distinct clusters (1955–1957, 1974–1976, 1999–2001), all of which correspond to some of the driest periods dur-

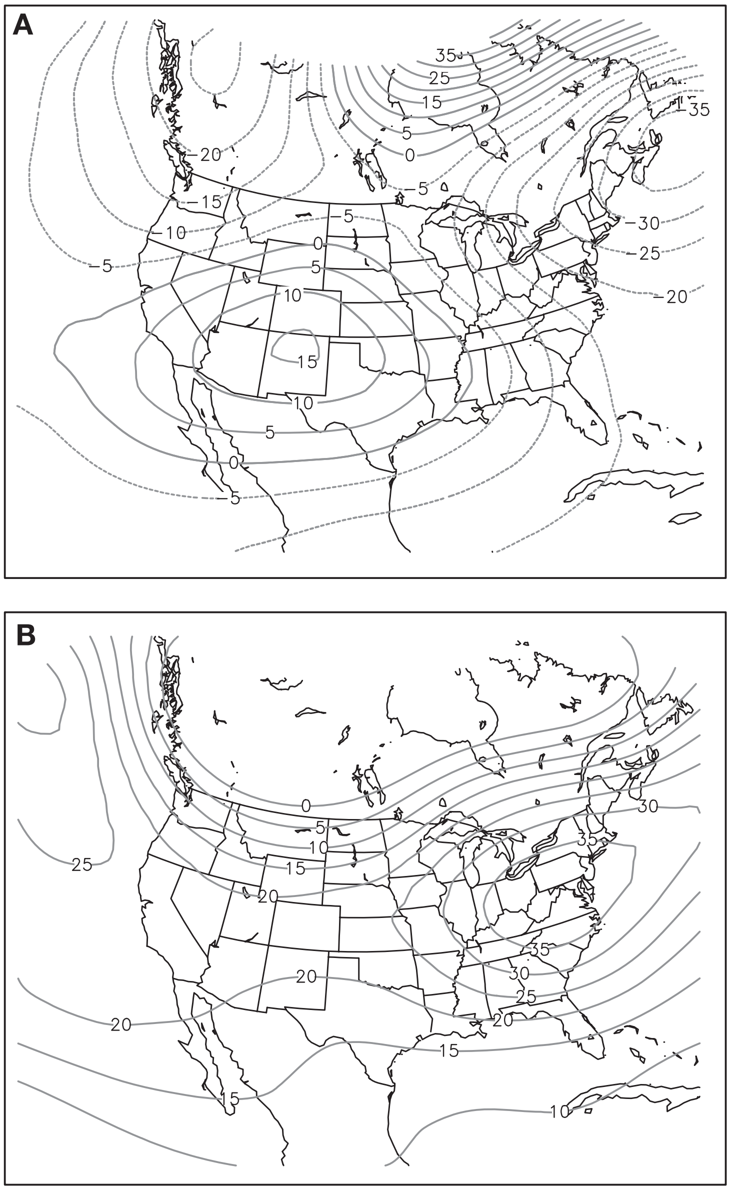

Fig. 5. The 500 hPa anomalies (geopotential meters, gpm) during the (A) 1956 and (B) 2002 water years

ing the last 60 yr. Closer inspection of the sign of the important teleconnections also revealed that all 3 multi-year La Niñas occurred during the cold phase of the PDO and during the positive phase of the EPO (Table 3). However, there were some differences. Two of the multi-year La Niñas (1955 to 1957 and 1999 to 2001) occurred during the warm phase of the AMO, which, when coinciding with the cold PDO, is also associated with drought in the western USA (McCabe et al. 2004). The 1955 to 1957 event includes the driest water year in the instrumental record (1956), while the 1999 to 2001 event precedes the fourth driest water year (2002). While 2002 did not occur during a La Niña, it did occur during neutral ENSO conditions that coincided with the cold phase of the PDO. Goodrich (2004, 2007) recently found that neutral ENSO/cold PDO years are as dry as La Niña/cold PDO years. Unlike the other 2 multi-year La Niñas, the 1974 to 1976 multi-year La Niña occurred during the cold phase of the AMO. Drought conditions were present over much of the western USA during the 1970s, but the impact on the southwestern USA was lessened by 1973, which was an anomalously wet water year. Generally, it appears that multi-year La Niñas, which are more likely to occur during the cold phase of the PDO, are strongly linked to the occurrence of multi-year droughts in the southwestern USA. This finding supports the work of many (Cole et al. 2002, Seager et al. 2003, 2005, Schubert et al. 2004, Herweijer et al. 2006) who found that persistent La Niña-like conditions in the tropical Pacific coupled with local soil–moisture feedbacks are responsible for many of the persistent droughts that have occurred around the world since 1850. Our research also supports the work of McCabe et al. (2004) who found that the warm phase of the AMO, when combined with the cold phase of PDO and La Niña, often result in dry winters in the western United States.

In contrast to multi-year La Niñas, multi-year El Niños have been relatively rare, at least during the last 60 yr (Table 3). There has never been an occurrence of 3 consecutive El Niños, although 3 occurred within a 4 yr span from 1991 to 1994. Not surprisingly, this was one of the wettest periods in the southwestern USA during the last century. Generally all of the teleconnections were of the opposite sign during this multi-year El Niño event compared to the 3 multi-year La Niña events (Table 3). The imbalance in the number of multi-year La Niñas versus multi-year El Niños means that multi-year droughts are more likely to occur than multi-year pluvials. This is another example of the challenges that water resource managers in the southwestern USA must face.

Table 3. Sign of the Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), Eastern Pacific Oscillation (EPO), and Standardized Precipitation Index (SPI) in the study region (dry: SPI < 0; wet: SPI > 0) during 3 multi-year La Niña events and 1 multi-year El Niño. The teleconnection indices are classified as cold (or negative) or warm (or positive), depending on whether the index values are less than or greater than zero, respectively

	ENSO	PDO	AMO	EPO	SPI
1955–1957	La Niña	Cold	Warm	Pos.	Dry
1974–1976	La Niña	Cold	Cold	Pos.	Dry
1999–2001	La Niña	Cold	Warm	Pos.	Dry
1991–1994	El Niño	Warm	Cold	Neg.	Wet

Fig. 6 shows the smoothed time series of 3 important teleconnections that impact moisture conditions in the southwestern USA. Both the PDO ($r = 0.45$, $p = < 0.001$) and ENSO ($r = 0.44$, $p = 0.001$) are significantly correlated with precipitation (e.g. 12 mo SPI) in the southwestern USA, while the AMO is not ($r = -0.18$, $p = 0.078$). It is notable that the multidecadal phase changes in the PDO (e.g. warm to cold or cold to warm) have closely matched the multidecadal changes in moisture conditions (e.g. wet to dry or dry to wet) during the past 50 yr. Correlations between PDO and the 12 mo SPI ($r = 0.64$, $p < 0.001$) increase greatly when the PDO and AMO are in opposing phases (cold PDO/warm AMO 1944 to 1963, warm PDO/cold AMO 1977 to 1994), but are not as robust ($r = 0.49$, $p = 0.005$) when the PDO and AMO are in the same phase (warm PDO/warm AMO 1926 to 1943, cold PDO/cold AMO 1964 to 1976). This modulation of the PDO–southwestern USA precipitation relationship by the AMO was discussed by McCabe et al. (2004), but they only focused on changes in drought frequency during various PDO/AMO phases rather than changes in the strength of the relationship (e.g. non-stationarity of the correlations).

It is notable that some of the driest periods during the past 100 yr occurred during cold PDO/warm AMO conditions, while some of the wettest periods occurred during warm PDO/cold AMO conditions. Periods of average wetness tend to occur when the PDO and AMO are in the same phase. Since the AMO is currently in the warm phase and it is expected to remain there for, at least, the next 10 to 20 yr, knowing the phase of the PDO could help water resource managers prepare for the coming decades. Unfortunately, the current phase of the PDO remains uncertain, and the PDO continues to exhibit greater than expected interannual variability. Therefore, it is not yet possible to determine whether moisture conditions in the southwestern USA will be drier than normal (cold PDO/warm AMO) or near normal (warm PDO/warm AMO) during the coming decades.

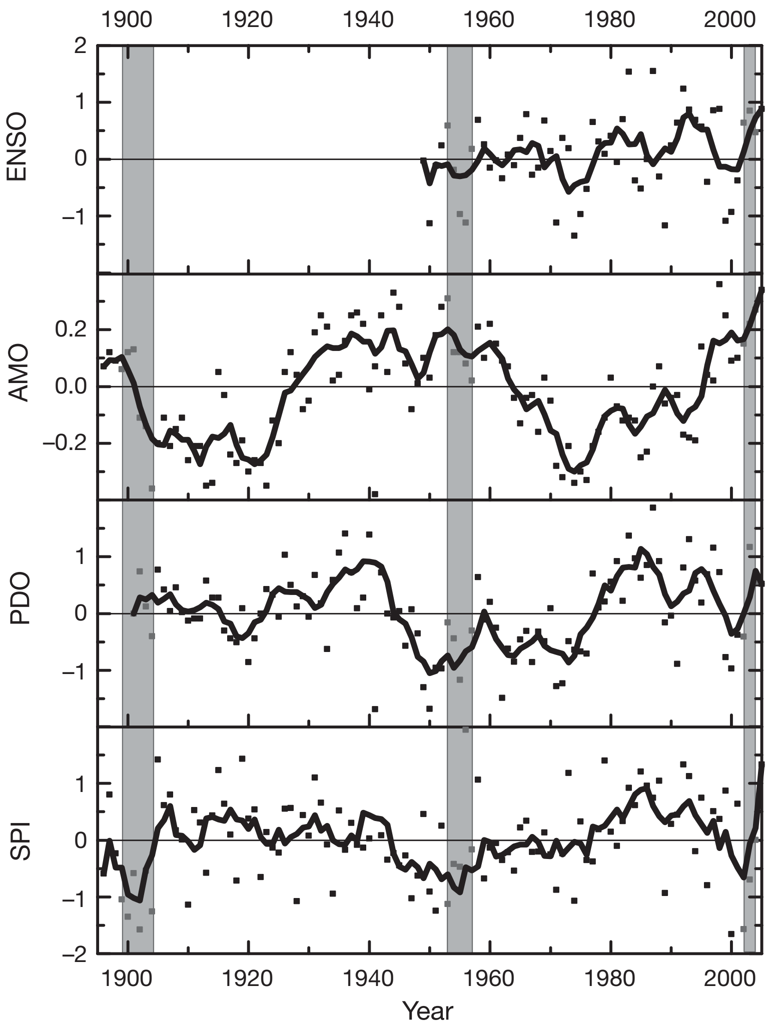

Fig. 6. Bivariate El Niño/Southern Oscillation (ENSO), Atlantic Multidecadal Oscillation (AMO), Pacific Decadal Oscillation (PDO), and 12 mo Standardized Precipitation Index (SPI) for southwestern USA (1896 to 2005). Squares: the mean annual values for each index; solid line: the 5 yr moving average; grey shaded regions: the 3 major droughts

4. CONCLUSIONS

The 1950s drought (1953 to 1957) and the recent drought (2002 to 2004) are 2 of the longest and most severe droughts to affect the southwestern USA, with the exception of the turn-of-the-century drought (1899 to 1905), since 1895. Both these droughts consisted of a series of dry years interspersed with very wet years, which mitigated the consequences of the dry years somewhat. The 1953 to 1957 drought was more severe and spatially extensive than the 2002 to 2004 drought. Although the 1953 to 1957 drought was centered over New Mexico, it was quite severe over much of the southwestern USA; the impact of the 2002 to 2004 drought was mostly felt in Arizona. The peak drought year during the 1950s drought (1956) and the recent drought (2002) rank as the driest and fourth driest water-years in the instrumental record, respectively.

Both of these droughts occurred during multi-year La Niña events and were associated with the cold phase of the PDO, the warm phase of the AMO, and the positive phase of the EPO. These conditions tend to produce anomalous atmospheric ridging over the southwestern USA, which prevents Pacific moisture from entering the study region. Therefore, both 1956 and 2002 were associated with increases in the number of DT days and decreases in the number of DM and MT days. These statistically significant changes in air mass frequencies were relatively consistent across the 3 locations and during the 2 drought events. Anomalously wet years tend to be associated with the opposite changes (e.g. increases in the number of DM and moist air mass days, and decreases in the number of DT days). It has also been shown that both the PDO and ENSO are correlated with precipitation in the southwestern USA and that the strength of the correlations is enhanced when the PDO and AMO are in opposing phases.

The results of this work suggest that the occurrence of major droughts in the southwestern USA is strongly influenced by low frequency oscillations in the global climate system, such as PDO and AMO, and by higher frequency oscillations, such as ENSO and EPO. The occurrence of prolonged droughts in the southwestern USA is associated with a cold PDO and warm AMO, conditions seen during both the 1950s and recent droughts. Given that the AMO and PDO are known to persist on decadal-to-multidecadal time scales it may be possible to use these relationships to forecast the occurrence of future drought events in the southwestern USA with long lead times. This information would be extremely valuable for water resource managers and state and federal emergency management agencies.

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