Distinguishing Pronounced Droughts in the Southwestern United States: Seasonality and Effects of Warmer Temperatures

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ABSTRACT

Higher temperatures increase the moisture-holding capacity of the atmosphere and can lead to greater atmospheric demand for evapotranspiration, especially during warmer seasons of the year. Increases in precipitation or atmospheric humidity ameliorate this enhanced demand, whereas decreases exacerbate it. In the southwestern United States (Southwest), this means the greatest changes in evapotranspirational demand resulting from higher temperatures could occur during the hot–dry foresummer and hot–wet monsoon. Here seasonal differences in surface climate observations are examined to determine how temperature and moisture conditions affected evapotranspirational demand during the pronounced Southwest droughts of the 1950s and 2000s, the latter likely influenced by warmer temperatures now attributed mostly to the buildup of greenhouse gases. In the hot–dry foresummer during the 2000s drought, much of the Southwest experienced significantly warmer temperatures that largely drove greater evapotranspirational demand. Lower atmospheric humidity at this time of year over parts of the region also allowed evapotranspirational demand to increase. Significantly warmer temperatures in the hot–wet monsoon during the more recent drought also primarily drove greater evapotranspirational demand, but only for parts of the region outside of the core North American monsoon area. Had atmospheric humidity during the more recent drought been as low as during the 1950s drought in the core North American monsoon area at this time of year, greater evapotranspirational demand during the 2000s drought could have been more spatially extensive. With projections of future climate indicating continued warming in the region, evapotranspirational demand during the hot–dry and hot–wet seasons possibly will be more severe in future droughts and result in more extreme conditions in the Southwest, a disproportionate amount negatively impacting society.

1. Introduction

a. *Climate in the southwestern United States*

Climate in the southwestern United States (hereafter Southwest) is highly seasonal. There are two distinct times during the year when precipitation typically is expected. From winter through early spring, westerly frontal systems bring both rain and snow, whereas from midsummer through early autumn, the North American monsoon (hereafter monsoon) and, to a lesser degree, dissipating tropical cyclones from the eastern Pacific Ocean supply rain (see review by Sheppard et al. 2002). Prominence of either of these peaks in the annual precipitation cycle is spatially variable, with a regional gradient from a winter-to-early-spring-dominated regime in the northwest to a regime dominated by the monsoon in the southeast. The period from late spring through early summer, often referred to as the foresummer, separates these two relatively wet seasons and is climatologically

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the hottest and driest part of the year. Drought in the Southwest thus depends on what modulates precipitation in two different seasons separated by the hot–dry foresummer.

b. Precipitation variability and drought in the Southwest

Drought is a normal part of climate in the Southwest. Over the past millennium, paleoclimate reconstructions indicate recurring periods of drought in the region (e.g., D'Arrigo and Jacoby 1991; Meko et al. 1995; review by Woodhouse and Overpeck 1998). These periods include severe multidecadal droughts, or ''megadroughts,'' such as the 1100s drought during medieval times that is considered the worst drought in the recent paleoclimate record (Cook et al. 2004; Meko et al. 2007). They also include the late-sixteenth-century drought, perceived to be the most severe drought of the past 500 years (Meko et al. 1995; Stahle et al. 2000). Southwest droughts also are conspicuous over the instrumental record of the past approximately 100 years. The most notable ones are the drought of the late 1890s and early 1900s, the drought of the 1950s, and the most recent, and possibly still ongoing, drought of the early 2000s (Swetnam and Betancourt 1998; Fye et al. 2003; Seager 2007; Quiring and Goodrich 2008). Several droughts analogous to the one during the 1950s, regarded as the worst of the twentieth century, likely occurred during the past 500 years, suggesting a recurrence interval of roughly 50 years for such conditions in the region (Fye et al. 2003; see also Hidalgo 2004). Societal impacts of droughts in the Southwest have been substantial and are reviewed in other publications (e.g., Schroeder 1968; Woodhouse and Overpeck 1998; Fye et al. 2003; Cook et al. 2007).

Spatiotemporal variability of sea surface temperatures (SSTs) and the consequent shifts in large-scale atmospheric circulation patterns considerably modulate natural drought variability in the Southwest. El Niño–Southern Oscillation (ENSO) in the tropical Pacific Ocean appears to dominate interannual variability of winter and early spring precipitation in the region, and precipitation tends to be below average during La Niña events (Ropelewski and Halpert 1987; Redmond and Koch 1991; Cole et al. 2002; Brown and Comrie 2004). Cool SST anomalies along the equator in the eastern and central Pacific Ocean (i.e., La Niña conditions) change the location of convection and atmospheric heating in this region. This change initiates teleconnection patterns, or Rossby wave trains, into the extratropics, weakens and moves poleward the subtropical jet stream, and creates an area of subsidence over the Southwest (Trenberth and Branstator 1992; Hoerling and Kumar 2003; Seager et al. 2003; Seager et al. 2005a).

Both the Pacific and Atlantic oceans appear to influence decadal-to-multidecadal (D2M) variability of winter and early spring precipitation in the region. Cool SST anomalies along the equator in the eastern and central Pacific Ocean and the coast of western North America, in conjunction with warm SST anomalies in the north-central Pacific Ocean, tend to promote below-average precipitation (Hidalgo 2004; McCabe et al. 2004). The ''cool phase'' of the Pacific decadal oscillation (PDO; Mantua et al. 1997) or ''La Niña–like'' conditions (see Seager 2007) typically refer to these SST anomalies. The cool phase of the PDO promotes drought in the Southwest similar to La Niña events as previously described, with additional atmospheric perturbations occurring over the northern Pacific Ocean (Harman 1991). Below-average precipitation also tends to occur in concert with warm North Atlantic SST anomalies (Enfield et al. 2001; Hidalgo 2004; McCabe et al. 2004), conditions often referred to as the ''warm phase'' of the Atlantic multidecadal oscillation (AMO; Enfield et al. 2001). Warm SST anomalies in the northern Atlantic Ocean appear to influence North Pacific climate variability through atmospheric perturbations via the tropics or mid- and high-latitude atmosphere, in turn weakening and moving poleward the subtropical jet stream (e.g., Dima and Lohmann 2007; Zhang and Delworth 2007).

Spatiotemporal variability of Pacific and Atlantic SSTs also may influence precipitation variability from midsummer through early autumn in the Southwest. Pacific SST anomalies associated with ENSO and the PDO tend to influence rainfall during this time of year in contrasting circumstances to that of winter and early spring precipitation. Onset of the monsoon tends to be later, and early seasonal precipitation tends to be lower in the region during El Niño events or the warm phase of the PDO (Harrington et al. 1992; Higgins et al. 1998, 1999; Higgins and Shi 2000; Castro et al. 2001, 2007). Warm SST anomalies along the equator in the eastern and central Pacific Ocean and the coast of western North America, in combination with cool SST anomalies in the north-central Pacific Ocean, produce teleconnection patterns that favor westerly upper-level winds that inhibit moisture transport into the Southwest and a weaker and more southwardly displaced monsoon ridge (Castro et al. 2001, 2007). Relationships between Pacific SSTs and summer precipitation tend to weaken during the middle and latter parts of the monsoon as the Pacific jet weakens, the monsoon ridge strengthens, and the Bermuda high extends westward. Pacific SSTs also may influence late summer and early autumn precipitation associated with dissipating tropical cyclones from the eastern Pacific Ocean, as a less favorable environment for cyclone development tends to happen during El Niño events or the warm phase of the PDO (Smith 1986; Reyes and Mejía-Trejo 1991; Englehart and Douglas 2001). North Atlantic SST anomalies associated with the AMO may affect precipitation variability from midsummer through early autumn in similar circumstances to that of winter and early spring precipitation. During the warm phase of the AMO, the western part of the Bermuda high tends to be weaker, and moisture transport across northern Mexico and into the Southwest tends to decrease (Sutton and Hodson 2005; Curtis 2007).

Destructive and constructive interference between interannual and D2M SST variability in the Pacific Ocean and between D2M variability in the Pacific and Atlantic Oceans can occur. For example, the tendency of La Niña events to result in below-average winter and early spring precipitation in the Southwest is less consistent during a warm phase of the PDO than it is during a cool phase (Gershunov and Barnett 1998; Gutzler et al. 2002). Pacific SSTs most coherently influence summer precipitation deficits in the region when El Niño events occur during the warm phase of the PDO (Castro et al. 2001; 2007). Also, the cool phase of the PDO and the warm phase of the AMO can enhance regional drought conditions (McCabe et al. 2004). The various effects of Pacific and Atlantic SST anomalies on Southwestern precipitation, together with the unknown causes of megadroughts and the roles of other influences on precipitation such as land surface conditions (e.g., Trenberth and Guillemot 1996; Seager et al. 2005b), make understanding and predicting droughts in the Southwest difficult.

c. *The 1950s and 2000s droughts in the Southwest*

Several aspects of SST variability and large-scale atmospheric circulation patterns were similar during the 1950s and 2000s droughts in the Southwest. La Niña events and the cool phase of the PDO likely influenced both droughts, as did the warm phase of the AMO (Fig. 1). Geopotential height anomalies from winter through early spring were positive during both periods over the region, indicating an area of subsidence (Fig. 2; see also Seager 2007; Quiring and Goodrich 2008). In June during both droughts, positive geopotential height anomalies also reflected La Niña events and the cool phase of the PDO, indicating less influence from the westerlies and a more northwardly displaced monsoon ridge.

Other aspects of SST variability and large-scale atmospheric circulation patterns notably contrasted during the 1950s and 2000s droughts. Warm SST anomalies in the Indian Ocean occurred during the 2000s drought instead of the cool SST anomalies that typically have coincided with La Niña–like conditions (Hoerling and Kumar 2003; Seager 2007). The anomalously warm SSTs in the Indian Ocean as well as the warmest SSTs in the western Pacific Ocean of the twentieth century were both part of a warming trend since the mid-twentieth century and likely contributed to persistent midlatitude drying throughout the Northern Hemisphere, including the Southwest. A weak El Niño event that occurred in 2002/03 did not result in above-average precipitation during winter and early spring, contrary to what has tended to happen in the Southwest when warm SST anomalies occur along the equator in the eastern and central Pacific Ocean (Ropelewski and Halpert 1987; Redmond and Koch 1991; Seager 2007). Influences other than ENSO, such as a northward shift in storm tracks at this time of year as indicated by high index values of the northern annual mode (Thompson and Wallace 1998; McAfee and Russell 2008), may have modulated precipitation variability in the region during these years of the 2000s drought.

The 1950s and 2000s droughts in the Southwest are conspicuous in surface climate records, with combinations of warm temperatures, low precipitation, and strongly negative values of the Palmer drought severity index (PDSI; Palmer 1965), a soil moisture proxy (Fig. 1). The continuously most negative PDSI values for the region took place during the 4-year periods 1953–56 for the 1950s drought and 2000–03 for the 2000s drought. Within the region during these years, low precipitation and strongly negative PDSI values varied spatiotemporally. The 1950s drought was focused mainly over Colorado and New Mexico, whereas the 2000s drought was centered more over the Southwest (see also Swetnam and Betancourt 1998; Fye et al. 2003; Hoerling and Eischeid 2007; Quiring and Goodrich 2008). The percent of normal seasonal precipitation in the region from winter through early spring was 74% during the 1950s drought and 86% during the 2000s drought (not shown). From midsummer through early autumn, 82% of normal seasonal precipitation fell during both droughts. Compared to the 1950s drought, relatively warmer annual temperature anomalies appear to have occurred during the 2000s drought, as did a relatively higher percent of normal precipitation and more strongly negative annual average PDSI values. Warmer temperatures during the 2000s drought, coupled with low precipitation, apparently resulted in greater soil moisture deficits than during the relatively cooler and drier 1950s drought (see also Easterling et al. 2007).

Both the 1950s and 2000s droughts induced significant vegetation mortality in biomes from deserts to forests (Neilson 1986; Allen and Breshears 1998; Swetnam and Betancourt 1998; Breshears et al. 2005; Gitlin et al. 2005; Mueller et al. 2005; Shaw et al. 2005; Miriti et al. 2007),

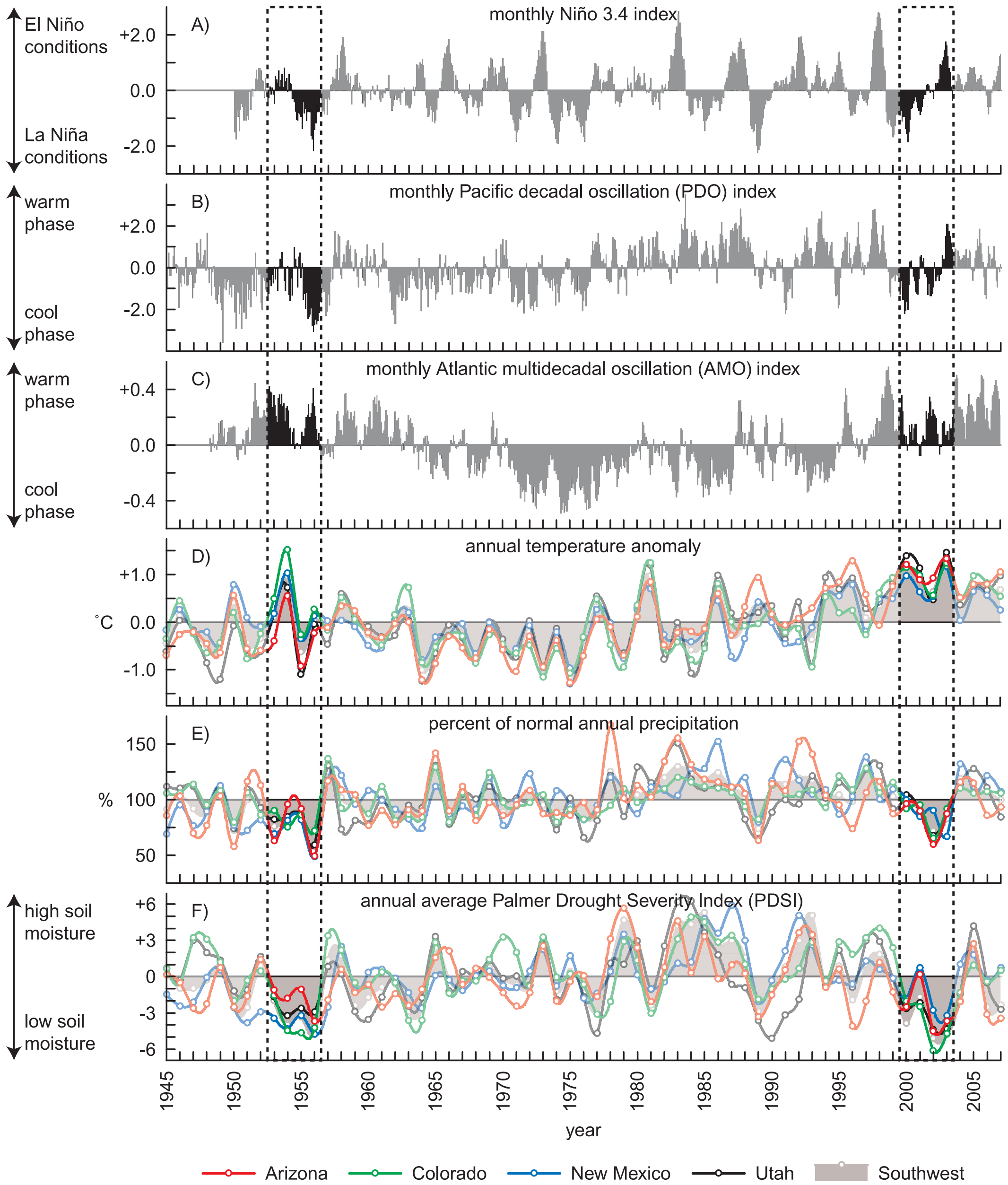

FIG. 1. Time series of monthly (a) Niño 3.4, (b) PDO, and (c) AMO indices along with (d) annual temperature anomalies, (e) percent of normal annual precipitation, and (f) annual average PDSI for Arizona, Colorado, New Mexico, Utah, and the Southwest from 1945 through 2007. Dashed rectangles highlight the 1950s (1953–56) and 2000s (2000–03) Southwest droughts. Annual temperature anomalies and percent of normal annual precipitation are relative to 1945–2007. The National Oceanic and Atmospheric Administration (NOAA) Climate Diagnostics Center (CDC) and Joint Institute for the Study of the Atmosphere and Ocean (JISAO) provided SST index data. NOAA National Climatic Data Center (NCDC) provided state and regional data.

suggesting that Southwest droughts also have the potential to affect surface climate via impacts on albedo, roughness, and latent and sensible heat fluxes. For example, the 2000s drought resulted in widespread death of piñon pine over 12 000 km^2 in the Southwest (Breshears et al. 2005). Despite more total precipitation during the years 2000–03 than 1953–56, observations indicated that piñon pine die-off during the 2000s drought was significantly greater in magnitude and extent than during the 1950s drought. Warmer temperatures during the 2000s drought, coupled with low precipitation, seemingly drove higher vegetation water stress, increased susceptibility to insect

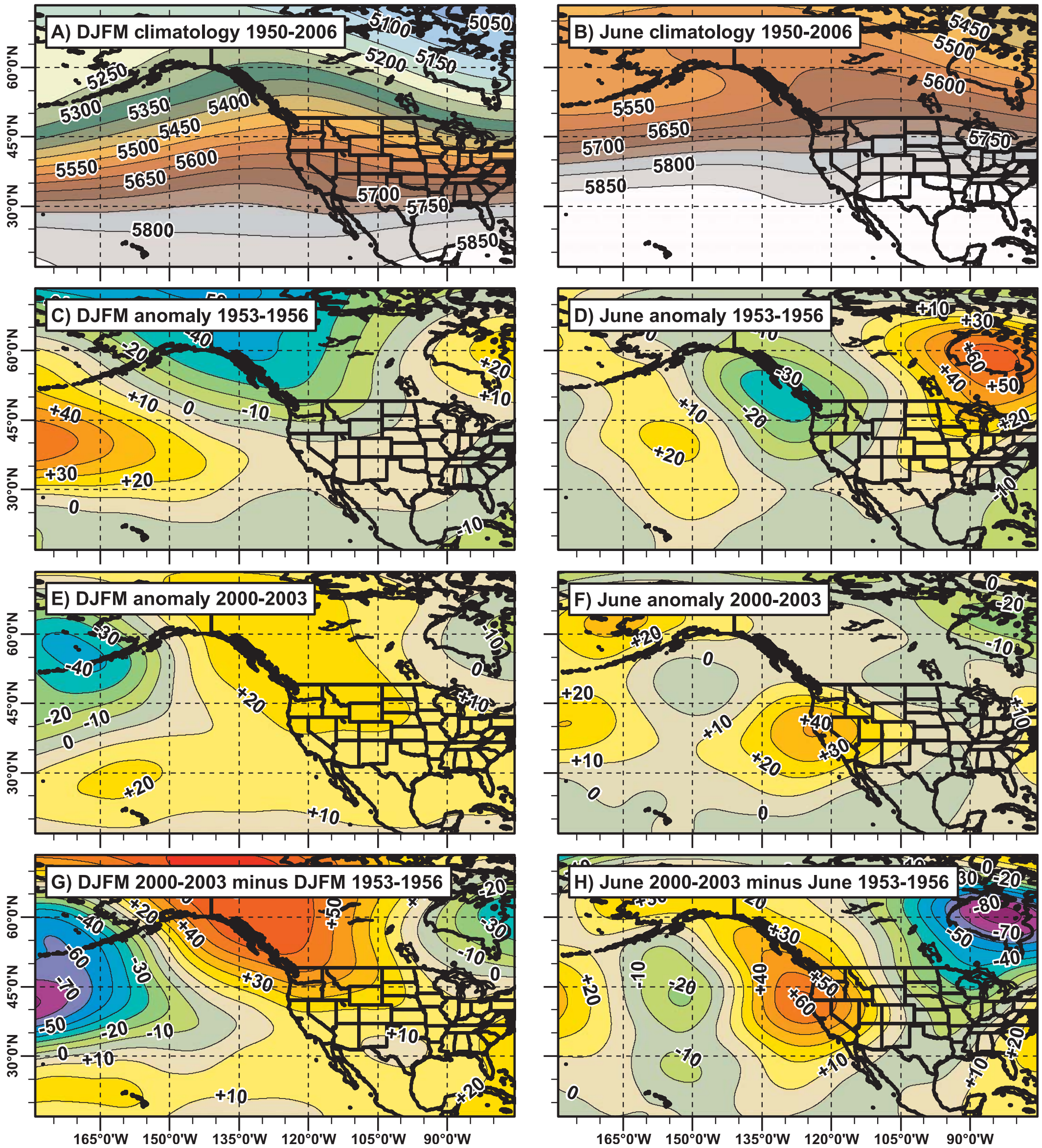

FIG. 2. The 500-mb geopotential height climatologies, anomalies during 1953–56 and 2000–03 and differences between 1953–56 and 2000–03 for (a),(c),(e), and (g) December–March and (b),(d),(f), and (h) June. Climatologies are relative to 1950–2006. Units are meters. NOAA/Office of Oceanic and Atmospheric Research/Earth System Research Laboratory (OAR/ESRL) Physical Sciences Division (PSD) provided National Centers for Environmental Prediction (NCEP) reanalysis data (Kalnay et al. 1996).

infestations, and more plant mortality than during the relatively cooler and drier 1950s drought.

d. Seasonality and effects of warmer temperatures during drought in the Southwest

Although it is not clear if anthropogenic climate change has affected precipitation variability in the Southwest, it likely influenced the 2000s drought in part through warmer temperatures. Global- to subcontinental-scale climate change detection and attribution studies demonstrate that trends in temperature means and extremes, such as decreasing frost days and increasing heat wave intensity, broke away from expected natural variability approximately in the mid-1980s (Hegerl et al. 2007; Meehl et al. 2007a; Barnett et al. 2008; Bonfils et al. 2008). Other regional observational evidence is consistent with such detection and attribution studies, displaying increases in surface temperatures across the Southwest in recent decades (Cayan et al. 2001; Easterling 2002; Weiss and Overpeck 2005; Trenberth et al. 2007).

The seasonality of temperature and precipitation differences between the 1950s and 2000s droughts in the Southwest is crucial in distinguishing these two dry periods. Higher temperatures increase the moisture-holding capacity of the atmosphere and can lead to greater atmospheric demand for evapotranspiration, especially during warmer seasons of the year. Increases in precipitation or atmospheric humidity ameliorate this enhanced demand, whereas decreases exacerbate it. In the Southwest, this means the greatest increases in evapotranspirational demand resulting from higher temperatures could occur during the hot–dry foresummer and hot–wet monsoon. Moisture deficits in winter and early spring can carry over into the hot–dry foresummer and exacerbate this enhanced demand. From midsummer through early autumn, moisture deficits can exacerbate this enhanced demand during the hot–wet monsoon. Our goal in this paper is to use surface climate observations during the pronounced Southwest droughts of the 1950s and 2000s to calculate seasonal differences in temperature and moisture conditions and determine how they affected evapotranspirational demand.

2. Methodology

We examined seasonal differences of surface climate observations during the 1950s and 2000s droughts in the Southwest using gridded observational data compiled by the Parameter-elevation Regressions on Independent Slopes Model (PRISM) Group at Oregon State University. PRISM data are meteorological station data interpolated to 4-km grid cells using a human expert and statistical knowledge-based system (Daly et al. 2002; http://www.prism.oregonstate.edu). We used PRISM monthly means of maximum temperature (Tmax, °C), minimum temperature (Tmin, °C), and dewpoint temperature (Tdmean, °C). We calculated 3-month standardized precipitation index values (SPI-3, unitless) using PRISM monthly precipitation amounts from December 1949 through January 2007 (McKee et al. 1993). We also calculated vapor pressure deficit (VPD, kPa), the difference between saturation and actual vapor pressure, using PRISM data and the formula

$$a\exp\left(\frac{b\,\mathrm{Tmean}}{\mathrm{Tmean}+c}\right)-a\exp\left(\frac{b\,\mathrm{Tdmean}}{\mathrm{Tdmean}+c}\right),$$

where $a = 0.611$ kPa, $b = 17.502$, $c = 240.97$°C, Tmean = monthly mean temperature in °C, and Tdmean = monthly mean dewpoint temperature in °C (Campbell and Norman 1998). Both Tdmean and VPD are measures of moisture condition in the atmosphere, with the latter being an estimate of the atmospheric demand for evapotranspiration. The spatial domain for our study was the Southwest region between 27° and 43°N and 117° and 100°W (Fig. 3). PRISM data only were available for domain areas within the United States, and thus our analysis only included the Southwest region of the United States, rather than extending into Mexico.

We defined the analysis periods for the 1950s and 2000s droughts in this study by the 4-year periods 1953–56 and 2000–03, respectively, after Breshears et al. (2005) (see also Fig. 1). We used monthly means of the variables Tmax, Tmin, Tdmean, and VPD from December 1952 to January 1957 and December 1999 to January 2004 to calculate 3-month seasonal values centered on each calendar month for both drought periods. For example, the seasonal January [i.e., December–February (DJF)] 1953 Tmax value was the average of Tmax monthly means from December 1952, January 1953, and February 1953. It was unnecessary to calculate seasonal values for SPI-3, as by definition it incorporates precipitation amounts over a 3-month period (McKee et al. 1993). Thus, for statistical tests described below, we used a seasonal value for each variable and month from January 1953 through December 1956 for the 1950s drought and from January 2000 through December 2003 for the 2000s drought.

We performed difference of means tests to determine local statistically significant differences (i.e., at an individual grid cell) between seasonal mean values of the 1950s and 2000s droughts for each variable and season. We regarded values of a particular variable and season in a drought period (e.g., Tmax values for DJF from the period 1953–56) as temporally independent for sample size calculation. We also considered whether or not results from one season were independent from results in other seasons for a particular variable. In general, the *e*-folding time through the domain indicated that results from seasons with nonoverlapping months could be viewed as independent. To address possible spatial autocorrelation in fields of joint difference of means tests, we carried out nonparametric field significance tests with a permutation randomization approach of 500 iterations (Livezey and Chen 1983; Wilks 2006). All tests were conducted at the 95% level.

3. Results

In this section, we present the results from seasonal difference of means and field significance tests for the five surface climate variables being analyzed during the 1950s and 2000s Southwest droughts: SPI-3, Tmax, Tmin, Tdmean, and VPD. Although we show figures for results of all seasons for each variable, we only describe locally significant results of seasons that are field

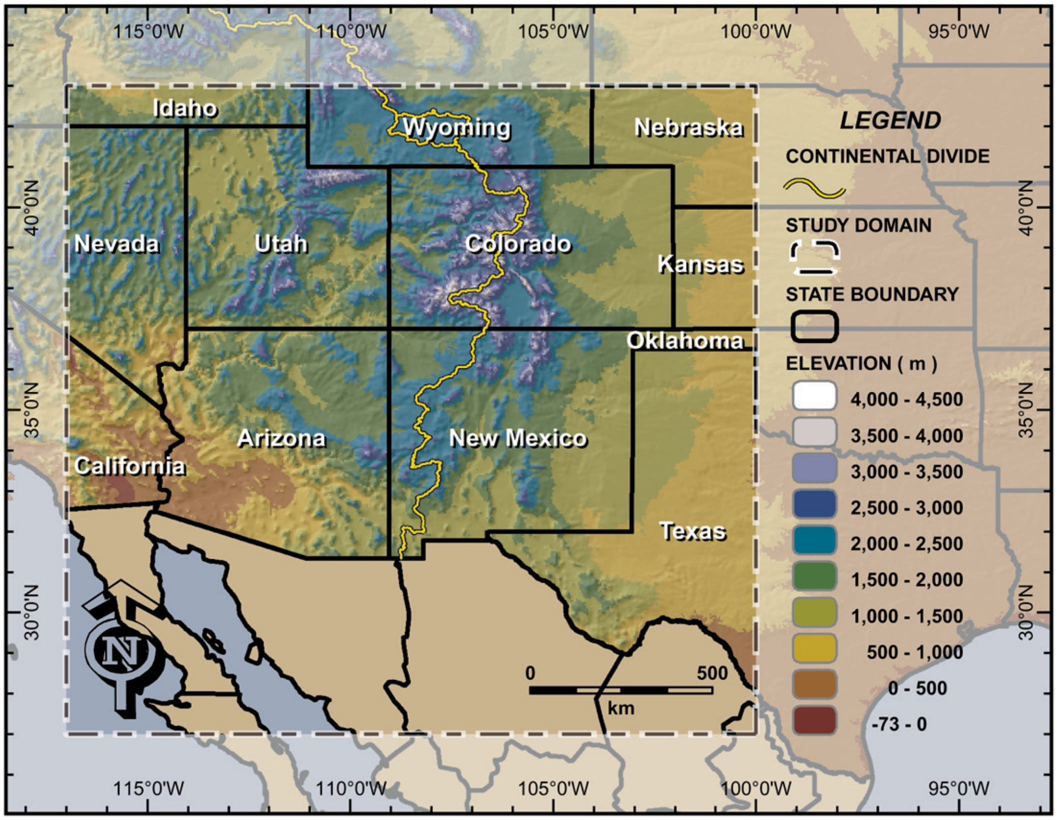

FIG. 3. Map of study domain. The PRISM Group at Oregon State University provided elevation data. PRISM data were only available for domain areas within the United States.

significant. We interpret the significant results in the following sections.

a. *SPI-3*

Seasonal SPI-3 during the 1950s and 2000s droughts in the Southwest shows significant differences only from midautumn through early winter and for early summer (Fig. 4). Significant positive differences from September–November (SON) through November–January (NDJ) mostly range from +1.0 to +2.0, indicating that the 2000s drought was wetter than the 1950s drought in these seasons, largely over Arizona and western New Mexico in SON and October–December (OND), and over most of New Mexico in NDJ. Significant negative differences are very few during SON and OND but increase across northern Arizona, southeastern Utah, and western Colorado in NDJ with values from −1.0 to −2.0, indicating that the 2000s drought was drier than the 1950s drought in these areas at this time of year. Significant negative differences with values from −1.0 to −2.0 also occur in May–July (MJJ), mainly over northern Arizona and adjacent areas of neighboring states. Significant positive differences are very few during this warm season.

b. *Tmax*

Seasonal Tmax for the 1950s and 2000s Southwest droughts shows significant differences only from early through late summer and demonstrates that maximum temperatures were warmer in the more recent drought at this time of year (Fig. 5). In MJJ and June–August (JJA), significant positive differences cover a large area of the region with most values from +2°C to +4°C. Areas displaying significant positive differences decrease in July–September (JAS), with values generally from +1°C to +3°C. Significant negative differences are very few during these warm seasons. Areas of significant differences largely are widespread west of a longitudinal margin through central Colorado and central New Mexico, most notably in MJJ and JJA.

c. *Tmin*

During the 1950s and 2000s droughts in the Southwest, significant differences of seasonal Tmin occur from midspring through early autumn (Fig. 6). Values of significant positive differences cover a large area of the region throughout these seasons and mostly range from +1°C to +4°C, showing that minimum temperatures

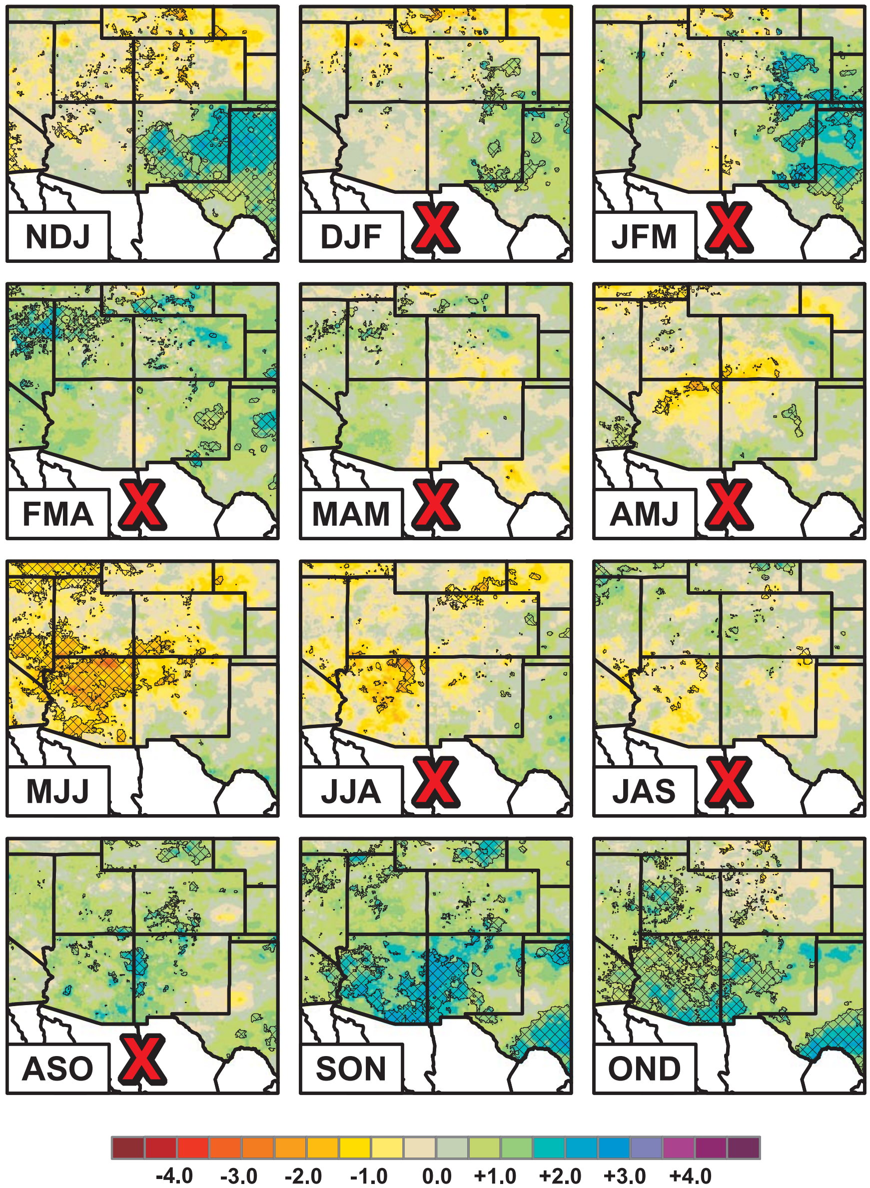

FIG. 4. Difference of means and field significance test results for seasonal SPI-3. Color gradation quantifies unitless differences between seasonal mean values of the 2000s and 1950s droughts (e.g., DJF SPI-3 $\text{mean}_{2000\text{–}2003}$ − DJF SPI-3 $\text{mean}_{1953\text{–}1956}$). Crosshatched areas are locally significant at the 95% level. Seasonal maps with a red X are not field significant at the 95% level. Positive (negative) values indicate wetter (drier) SPI-3 during the 2000s drought than the 1950s drought.

were warmer during the more recent drought. Significant negative differences are very few during these seasons. As with Tmax, areas of significant differences generally are widespread west of a longitudinal margin through central Colorado and central New Mexico.

d. Tdmean

Seasonal Tdmean during the 1950s and 2000s Southwest droughts shows significant differences only from late spring through late autumn (Fig. 7). Lower dewpoint temperatures predominate in the hot–dry foresummer whereas higher dewpoint temperatures predominate during and after the hot–wet monsoon in the more recent drought. From AMJ through JJA, significant negative differences with values from −1°C to −3°C are present around the four corners area and extreme southern New Mexico and western Texas. In contrast, significant positive differences with values +1°C to +4°C

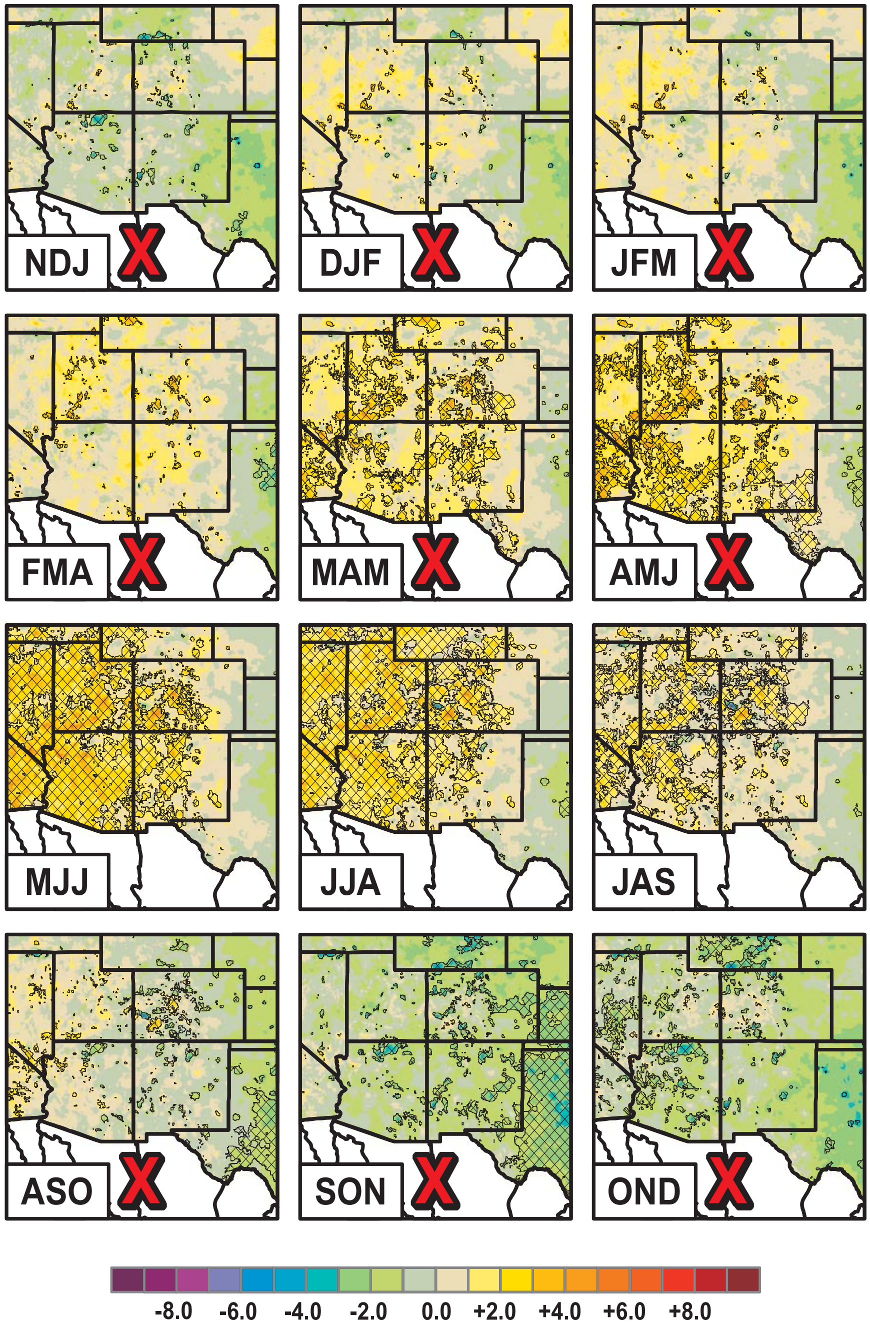

FIG. 5. As in Fig. 4, but for Tmax. Units are °C. Positive (negative) values indicate warmer (cooler) Tmax during the 2000s drought than the 1950s drought.

occur in central New Mexico at this time of year. Significant positive differences become more widespread from JAS through OND with values largely from +2°C to +6°C, occurring principally in Arizona and New Mexico. Significant negative differences are very few during these seasons. Spatial patterns of significant differences for seasonal Tdmean broadly resemble those of precipitation as measured by SPI-3.

e. VPD

As the difference between saturation and actual vapor pressure, VPD estimates atmospheric demand for evapotranspiration. Seasonal VPD of the 1950s and 2000s droughts in the Southwest shows significant differences only from midspring through late summer, in midautumn, and in early winter (Fig. 8). Significant positive differences

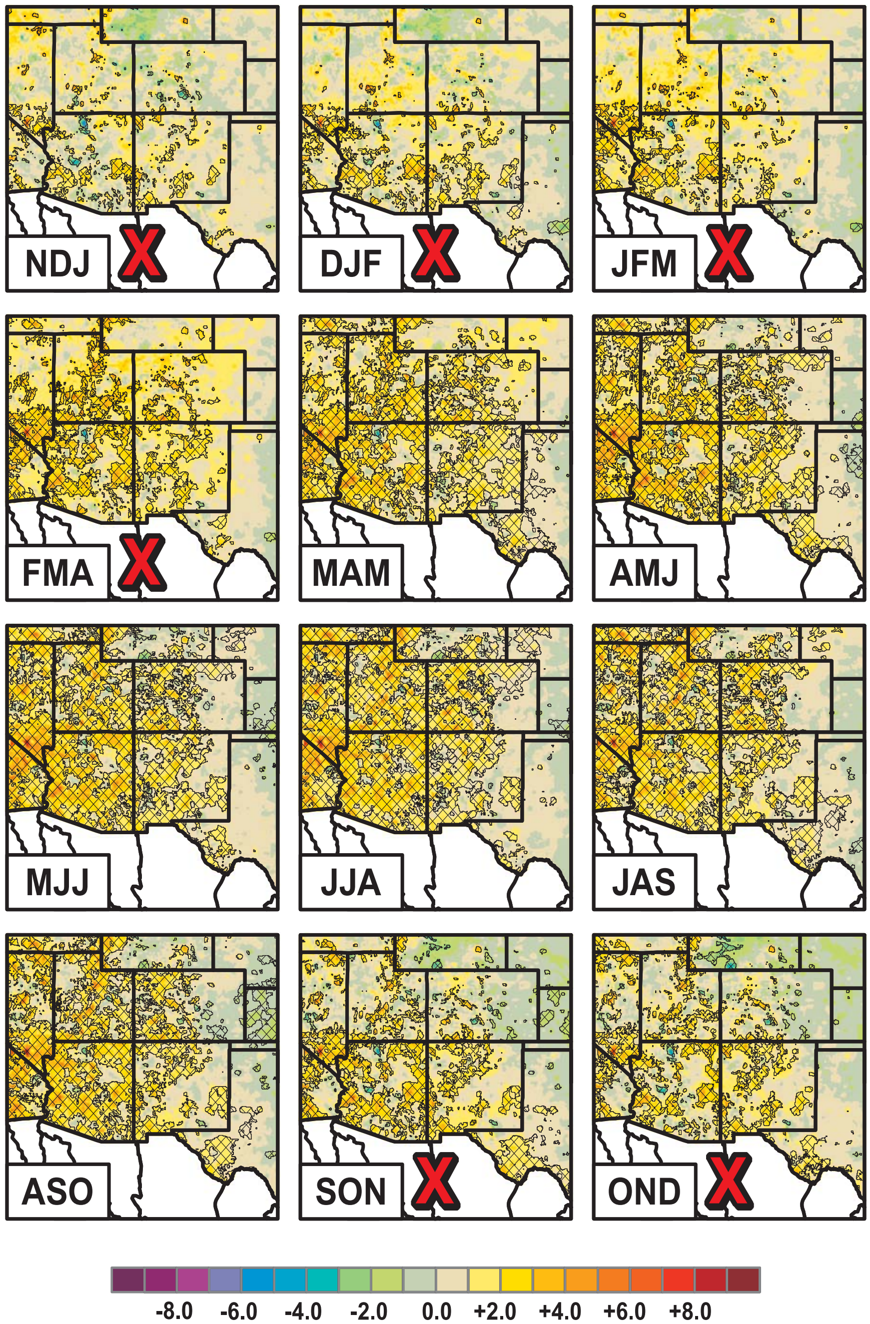

FIG. 6. As in Fig. 4, but for Tmin. Units are °C. Positive (negative) values indicate warmer (cooler) Tmin during the 2000s drought than the 1950s drought.

cover large areas from March–May (MAM) through JAS with most values from +0.15 to +0.75 kPa, indicating that greater evapotranspirational demand occurred in the more recent drought during the hot–dry foresummer and hot–wet monsoon. These areas generally are widespread west of a longitudinal margin through central Colorado and central New Mexico, similar to spatial patterns of significantly warmer maximum and minimum temperatures. Significant negative differences of VPD are very few during these seasons. In SON and NDJ, areas with significant negative differences are present, with values from −0.15 to −0.30 kPa, indicating less evapotranspirational demand during the 2000s drought than the 1950s drought at this time of year, most notably in southeastern Arizona and central New Mexico. Significant positive differences are very few during these seasons.

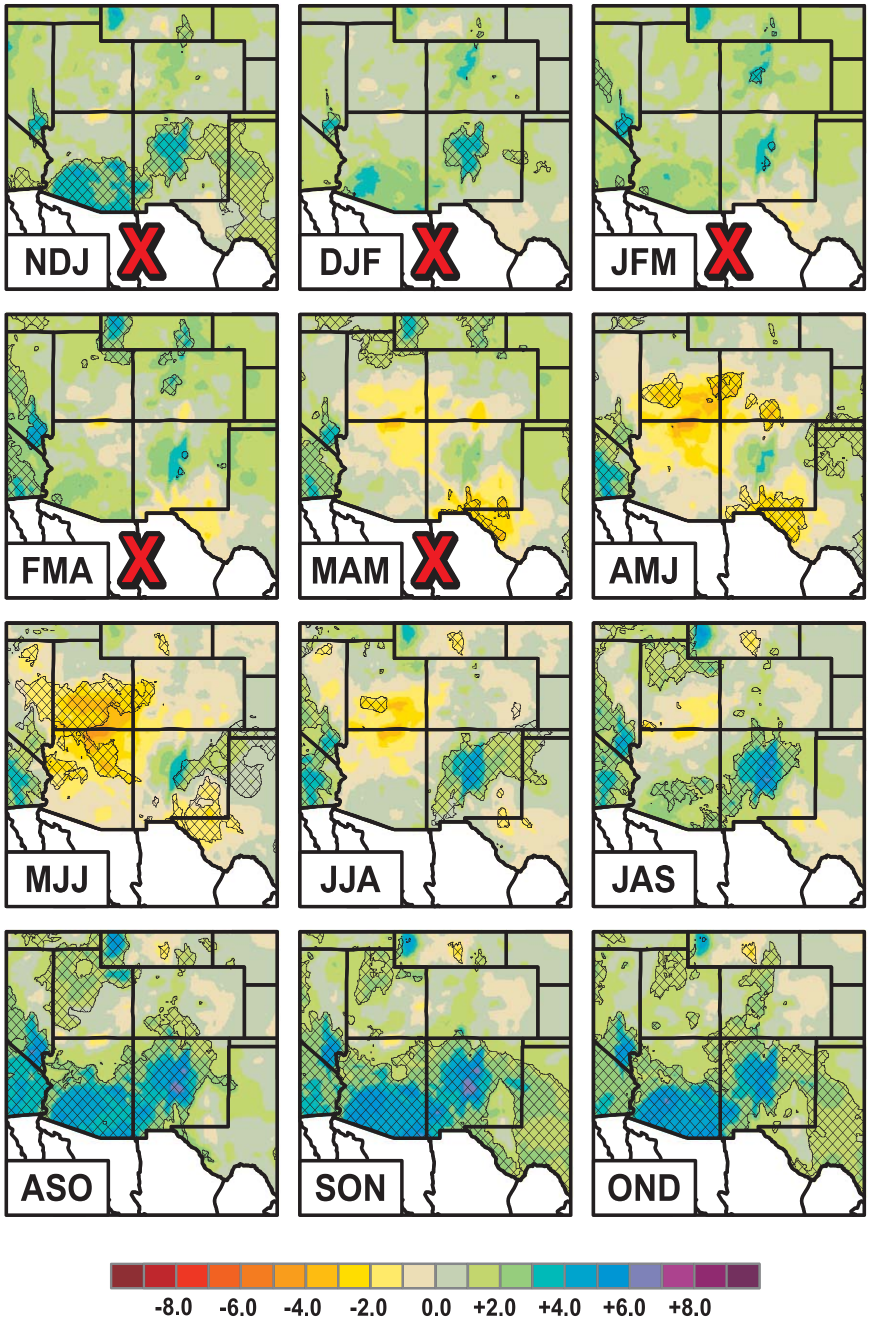

FIG. 7. As in Fig. 4, but for Tdmean. Units are °C. Positive (negative) values indicate higher (lower) Tdmean during the 2000s drought than the 1950s drought.

4. Discussion

Several significant differences in seasonal temperature and moisture conditions distinguish the 2000s drought from the 1950s drought. Precipitation during the 2000s drought was greater than the 1950s drought largely over Arizona and western New Mexico from mid- to late autumn and over most of New Mexico in early winter. It was less in early winter across northern Arizona, southeastern Utah, and western Colorado, as well as in early summer mostly over northern Arizona and adjacent areas of neighboring states. Maximum temperatures during the 2000s drought were warmer than the 1950s drought throughout summer in much of the region. Minimum temperatures associated with the 2000s drought were warmer than the 1950s drought from midspring

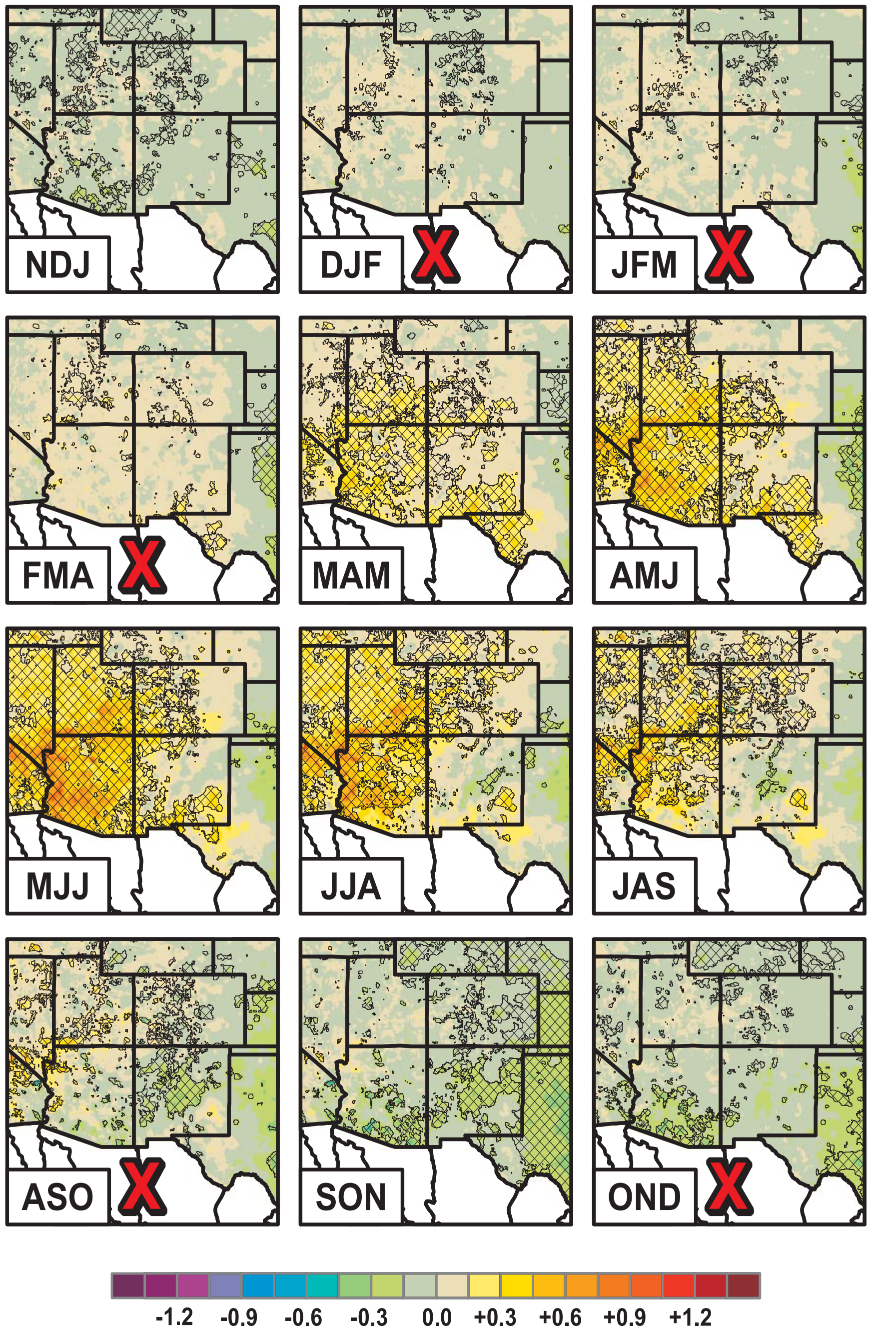

FIG. 8. As in Fig. 4, but for VPD. Units are kPa. Positive (negative) values indicate higher (lower) VPD during the 2000s drought than the 1950s drought.

through early autumn throughout much of the region as well. From late spring through midsummer during the 2000s drought, lower dewpoint temperatures than during the 1950s drought primarily over northern Arizona and southern Utah contrasted with areas of higher dewpoint temperatures in central New Mexico. Higher dewpoint temperatures during the more recent drought were widespread from late summer through late autumn, mainly in Arizona and New Mexico. Evapotranspirational demand during the 2000s drought from midspring through late summer was greater in many areas of the Southwest than during the 1950s drought. In midautumn and early winter during the 2000s drought, evapotranspirational demand was lower than during the 1950s drought, most notably in southern Arizona and central New Mexico. Apart from these significant differences, seasonal temperature and moisture conditions during the 1950s and 2000s droughts were similar.

The significant differences in seasonal precipitation illustrate how spatial patterns of snowfall and rainfall can vary within the region between pronounced Southwestern droughts. Our results agree with Breshears et al. (2005) and Quiring and Goodrich (2008) in that some aspects of the 1950s drought were significantly drier than the 2000s drought, specifically seasonal precipitation amounts in mid- and late autumn over Arizona and western New Mexico, and in early winter over most of New Mexico. Decreased influence of the monsoon in early September, dissipating tropical cyclones from the eastern Pacific Ocean in September and October, or westerly frontal systems from October through January may have caused the lower precipitation during the 1950s drought in these seasons (Smith 1986; Adams and Comrie 1997; Sheppard et al. 2002). Other aspects of precipitation in our results contrastingly show that the 2000s drought was significantly drier than the 1950s drought, in particular seasonal precipitation amounts in early winter across northern Arizona, southeastern Utah, and western Colorado and in early summer mostly over northern Arizona and adjacent areas of neighboring states. Decreased influence of westerly frontal systems from November through January as well as in May, or perhaps a weaker monsoon in July, may have promoted less precipitation during the 2000s drought in these seasons (Higgins and Shi 2000; Sheppard et al. 2002; Grantz et al. 2007).

Our results also are consistent with the Breshears et al. (2005) conclusions that the 2000s drought in the Southwest was significantly warmer than the 1950s drought, and that the warmer temperatures probably drove greater soil moisture deficits and higher plant mortality. In particular, maximum temperatures were warmer throughout summer, minimum temperatures were warmer from midspring through early autumn, and evapotranspirational demand was greater from midspring through late summer in much of the region during the more recent drought. Greater positive anomalies of 500-mb heights in June during the 2000s drought (Figs. 2d,f,h) partly reflect these warmer conditions. Warmer temperatures increase the saturation vapor pressure of the atmosphere and, without a corresponding increase in actual vapor pressure from higher atmospheric moisture (i.e., dewpoint temperatures), drive higher vapor pressure deficits. Lower dewpoint temperatures during the more recent drought from late spring through midsummer around the four corners area and extreme southern New Mexico and western Texas increased evapotranspirational demand in addition to that resulting from warmer temperatures. Higher dewpoint temperatures during the 2000s drought in the core area of the monsoon in the United States (Comrie and Glenn 1998), specifically in central New Mexico during summer and southeastern Arizona in late summer, compensated the warmer temperatures enough to maintain evapotranspirational demand similar to what it was during the relatively cooler and drier 1950s drought.

Through our analysis we determined how seasonal differences in temperature and moisture conditions affected evapotranspirational demand during the pronounced Southwestern droughts of the 1950s and 2000s. In the hot–dry foresummer during the 2000s drought, much of the Southwest experienced significantly warmer temperatures that largely drove greater evapotranspirational demand. Lower atmospheric moisture at this time of year over parts of the region also allowed evapotranspirational demand to increase during the more recent drought. Significantly warmer temperatures in the hot–wet monsoon during the 2000s drought primarily drove greater evapotranspirational demand as well, but only for parts of the region outside of the core monsoon area. Had atmospheric moisture during the more recent drought been as low as during the 1950s drought in the core monsoon area at this time of year, greater evapotranspirational demand during the 2000s drought could have been more spatially extensive.

5. Implications and conclusions

The hot–dry foresummer and hot–wet monsoon are times during the year when climate has important societal implications in the Southwest. Climatologically hot and dry conditions from late spring through early summer influence the annual peak in urban water demand, air quality with respect to ozone and particulate matter levels, incidence of valley fever, and intensity of the wildfire season (see review by Ray et al. 2007). Climatologically hot and wet conditions from midsummer through early autumn influence populations of mosquito species known to be vectors for dengue fever and West Nile virus, incidence of valley fever, decline of the wildfire season, and ranching operations. Drought can negatively affect many of these seasonal circumstances. For example, below-average precipitation in winter and early spring can worsen air quality during the hot–dry foresummer. From midsummer through early autumn, drought can allow the wildfire season to continue further into the normally hot–wet monsoon. With projections of future climate indicating continued warming in the region (Christensen et al. 2007; Meehl et al. 2007b), evapotranspirational demand during the hot–dry and hot–wet seasons possibly will be more severe in future droughts and result in more extreme conditions in the

Southwest, with a disproportionate amount negatively impacting society.

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