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# The climate of the US Southwest

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ABSTRACT: This paper summarizes the current state of knowledge of the climate of southwest USA (the 'Southwest'). Low annual precipitation, clear skies, and year-round warm climate over much of the Southwest are due in large part to a quasi-permanent subtropical high-pressure ridge over the region. However, the Southwest is located between the mid-latitude and subtropical atmospheric circulation regimes, and this positioning relative to shifts in these regimes is the fundamental reason for the region's climatic variability. Furthermore, the Southwest's complex topography and its geographical proximity to the Pacific Ocean, the Gulf of California, and the Gulf of Mexico also contribute to this region's high climatic variability. El Niño, which is an increase in sea-surface temperature of the eastern equatorial Pacific Ocean with an associated shift of the active center of atmospheric convection from the western to the central equatorial Pacific, has a well-developed teleconnection with the Southwest, usually resulting in wet winters. La Niña, the opposite oceanic case of El Niño usually results in dry winters for the Southwest. Another important oceanic influence on winter climate of the Southwest is a feature called the Pacific Decadal Oscillation (PDO), which has been defined as temporal variation in sea-surface temperatures for most of the Northern Pacific Ocean. The effects of ENSO and PDO can amplify each other, resulting in increased annual variability in precipitation over the Southwest. The major feature that sets the climate of the Southwest apart from the rest of the United States is the North American monsoon, which in the US is most noticeable in Arizona and New Mexico. Up to 50 % of the annual rainfall of Arizona and New Mexico occurs as monsoonal storms from July through September. Instrumental measurement of temperature and precipitation in the Southwest dates back to the middle to late 1800s. From that record, average annual rainfall of Arizona is 322 mm (12.7″), while that of New Mexico is 340 mm (13.4″), and mean annual temperature of New Mexico is cooler (12°C [53°F]) than Arizona (17°C [62°F]). As instrumental meteorological records extend back only about 100 to 120 yr throughout the Southwest, they are of limited utility for studying climate phenomena of long time frames. Hence, there is a need to extend the measured meteorological record further back in time using so-called 'natural archive' paleoclimate records. Tree-ring data, which provide annual resolution, range throughout the Southwest, extend back in time for up to 1000 yr or more in various forests of the Southwest, and integrate well the influences of both temperature and precipitation, are useful for this assessment of climate of the Southwest. Tree growth of mid-elevation forests typically responds to moisture availability during the growing season, and a commonly used climate variable in paleo-precipitation studies is the Palmer Drought Severity Index (PDSI), which is a single variable derived from variation in precipitation and temperature. June–August PDSI strongly represents precipitation and, to a lesser extent, temperature of the year prior to the growing season (prior September through current August). The maximum intra-ring density of higher elevation trees can yield a useful record of summer temperature variation. The combined paleo-modern climate record has at least 3 occurrences of multi-decadal variation (50 to 80 yr) of alternating dry (below average PDSI) to wet (above average PDSI). The amplitude of this variation has increased since the 1700s. The most obvious feature of the temperature record is its current increase to an extent unprecedented in the last 400 yr. Because this warming trend is outside the variation of the natural archives, it is possible that anthropogenic impacts, such as increased atmospheric concentrations of greenhouse trace gases, are playing a role in climate of the Southwest. Accordingly, this pattern merits further research in search of its cause or combination of causes.

KEY WORDS: Southwest · Climate · El Niño-Southern Oscillation (ENSO) · Monsoon · Palmer Drought Severity Index (PDSI) · Summer temperature · Dendrochronology · Tree rings

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## 1. INTRODUCTION

Dry and hot! For many people, these 2 words sum up the climate of the southwestern United States, but the climate of the Southwest is much more complex than that. While low deserts of the Southwest experience searing heat and desiccating winds in the early summer, its forested mountains and plateaus endure biting cold and drifting snow in the heart of winter. Climate variability is the norm within this region as temperature and precipitation fluctuate on time scales ranging from seasons to centuries. The Southwest may be drenched by torrential monsoon thunderstorms in July and August, occasionally accompanied by flash flooding (Maddox et al. 1979), and it can be warm under fair skies from fall to spring. Periods of droughts are also not uncommon in the Southwest. Indeed, severe regional floods or droughts have affected both indigenous and modern civilizations on time scales ranging from single growing seasons to multiple years, even decades.

For this paper, the core region of the Southwest is defined as the states of Arizona and New Mexico. When necessary, we extend and contract the boundaries of this core area, emphasizing, for example, atmospheric circulation over northern Mexico, western North America, and neighboring parts of the Pacific Ocean, as well as climatic signals seen in the Upper Colorado River Basin (UCRB) of Utah, Colorado, and Wyoming. The climate of the UCRB is important to the Southwest because the rivers of the basin serve as a supply of water to Arizona and New Mexico.

### 1.1. Key questions

What are the basic characteristics of the climate of the Southwest? What are the atmospheric features that control southwestern climate? How has climate changed over time? In this review we address these and related questions to account for the current state of knowledge of natural climate variability of the Southwest. Specifically: What is the understanding of the climate variability of the Southwest on seasonal to interdecadal time scales and what are the sources of this variability? With respect to extremes and/or periodic and quasi-periodic features, what are the major patterns or types of variability evident from the instrumental record and natural archives such as tree rings? How typical has the instrumental period (i.e. the 20th century) been in the context of earlier patterns from natural archives? What challenges might the patterns of the instrumental and natural archive records pose to the understanding of the sources of climatic variability in the region?

### 1.2. Organization

This paper was written as part of the Climate Assessment (CLIMAS) project for the Southwest, a Regional Integrated Assessment (RISA) project of the University of Arizona funded by the National Oceanic and Atmospheric Association (NOAA). In addition to answering the questions above, our goal was to make this climate knowledge useful to regional stakeholders of climate information as well as other researchers. Therefore, this paper was purposely written to be accessible to non-climatologists, covering major points but omitting overly technical terminology and concepts. Following this introduction, the instrumental climate observation network of the Southwest and the climate patterns that are evident from that network are described briefly. Then, principal atmospheric processes controlling Southwest climate during winter and summer are outlined. Then, historic and paleoclimatic variability in moisture and temperature is evaluated. The availability and extraction of natural climate records from tree rings are examined in Appendix 1 for those readers not familiar with dendroclimatology.

## 2. INSTRUMENTAL CLIMATE OBSERVATION NETWORK

Instrumental measurement of temperature and precipitation in the Southwest dates back to the middle to late 1800s. Weather stations were not initially located uniformly throughout all portions of Arizona and New Mexico, nor are they evenly spaced today. Factors such as site location, density of distribution, types of equipment, and observer bias all affect the precision, accuracy, and utility of the resulting climate data.

### 2.1. National weather service and co-operative stations

The National Climatic Data Center (NCDC) archives climatic data from a number of sources, including first-order National Weather Service (NWS) stations, co-operative stations, and other specialty automated stations. First-order stations are generally at airports and collect a large array of surface and upper-air variables, including hourly observations of temperature, precipitation, dewpoint, pressure, and wind speed and direction. In the late 1990s, the first-order stations switched to automated measurements.

The co-operative station network is operated by volunteer observers who report daily temperature and precipitation data to the NWS. Many co-operative stations list official observers as members of a federal agency, such as the US Weather Bureau, Geological

Service, Forest Service, or Bureau of Indian Affairs. Railroad companies, radio stations, mining corporations, and public schools are also listed. The Federal Aviation Agency, various fire departments, and even a Tucson-based natural history museum have carried out weather observations. The majority of the official observers have been private citizens (Sellers & Hill 1974).

Automated stations, many at high elevation, monitor precipitation and feed results directly into NWS offices. These automated stations are funded at the county level, and thus the coverage and total number of stations vary by county (John R. Glueck, NWS Tucson, pers. comm., 1998). Automated stations notwithstanding, high-elevation and sparsely populated areas are generally underrepresented in the overall record. For example, tribal and public lands, constituting a sizable portion of the total land area of the Southwest, are underrepresented (Merideth et al. 1998).

The NWS operates 5 first-order weather stations in Arizona, but hundreds of other co-operative stations regularly record temperature and precipitation (Fig. 1). Arizona's weather record keeping began in 1865 in Prescott and grew to 30 stations by 1900. Similarly, the NWS operates 3 first-order stations in New Mexico as well as one in El Paso, Texas, but again there are hundreds of co-operative stations throughout the state (Fig. 1). Weather record keeping began in New Mexico in 1850, with initial records being kept by Army personnel in Albuquerque, Laguna, Las Vegas, Santa Fe, and Socorro. By 1900, New Mexico had 44 weather stations. Fifty years later, there were more than 350 weather stations operating in New Mexico. Since then the total number has decreased, due in part to the movement of observers from rural areas to cities (Tuan et al. 1973).

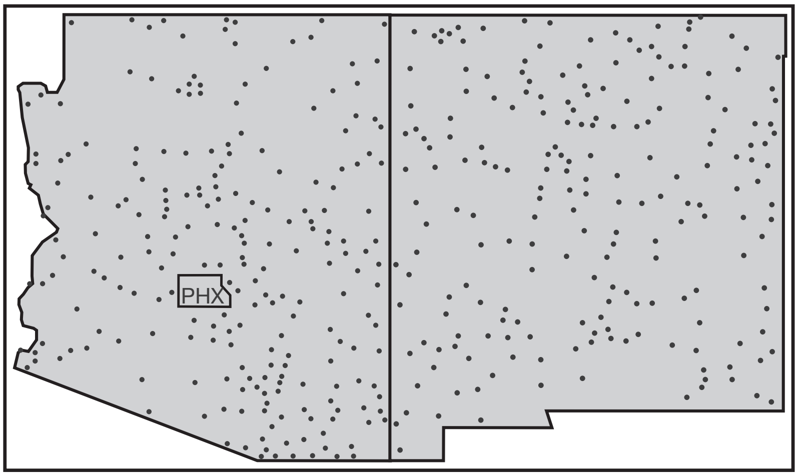

Fig. 1. Arizona and New Mexico cooperative weather stations. Many sites exist within Phoenix (the polygon PHX). Adapted from NCDC-NOAA website: http://lwf.ncdc.noaa.gov/oa/ncdc.html

### 2.2. Climate divisions

One method used in reporting climate data relies on dividing states into climate divisions. A climate division is defined as a region within a state that is reasonably homogenous with respect to climatic and hydrologic characteristics (Karl & Knight 1985). Climate divisions of the Southwest and the UCRB generally follow patterns of mean annual precipitation, though this pattern is less obvious for some divisions of Arizona (Fig. 2). Individual climate divisions can be hundreds of kilometers wide and represent weather stations that vary substantially in elevation. Arizona, for example, has a land area of 294 000 km$^2$ (113 500 mile$^2$) that ranges in elevation from 42 m (137 ft) to 3850 m (12 600 ft) above sea level, all of which is divided into just 7 climate divisions. New Mexico has even more land area (314 000 km$^2$ [121 300 mile$^2$]) and both a higher average elevation (1737 m [5700 ft]) and a higher maximum elevation (>4000 m [13 000 ft]), all of which is divided into just 8 climate divisions. Both the horizontal and vertical spatial differences within a climate division are important to note, as it is the combination of readings from disparate stations that makes up the reported averages for the individual climate divisions.

## 3. MODERN CLIMATE PATTERNS IN THE SOUTHWEST

### 3.1. Precipitation

Mean annual rainfall measurements across climatic divisions of the Southwest and the UCRB range from 127 mm (5″) to about 500 mm (20″) (Figs. 2 & 3). A more realistic account of snow accumulation in the high mountains would probably result in higher precipitation totals for the UCRB (Daly et al. 1994). Average annual rainfalls for Arizona (322 mm [12.7″]) and New Mexico (340 mm [13.4″]) are not significantly different. At the regional scale, orography influences the amount of precipitation received, especially in the UCRB. For example, the Sierra Nevada intercept winter rainfall, while the southern Rocky Mountains and the southern edge of the Colorado Plateau both intercept and promote convectional precipitation from the summer monsoon flow (Whitlock & Bartlein 1993). Mean annual precipitation increases with higher elevation due to orographic processes.

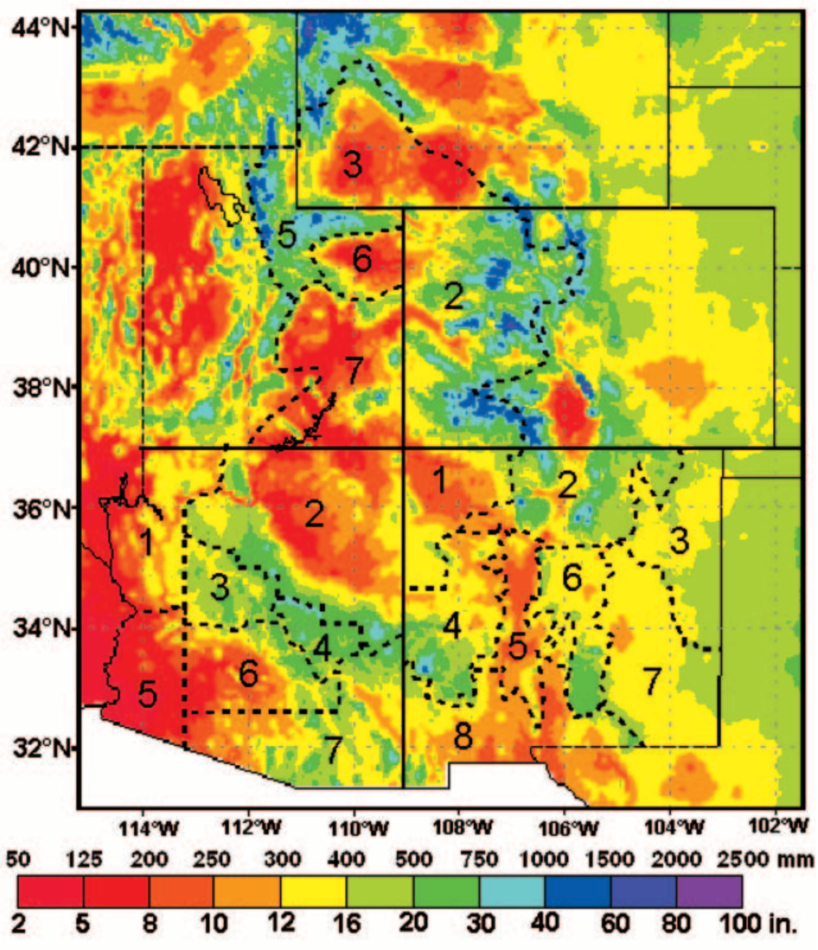

Fig. 2. Southwest Upper Colorado River Basin (UCRB) precipitation and divisions. Dashed-line boundaries delineate climate divisions as defined by NOAA, with divisions identified by number within each state. Colors represent mean annual precipitation across the Southwest and the UCRB. Adapted from Western Regional Climate Center Website: www.wrcc.dri.edu

At the monthly scale, precipitation over the UCRB is relatively evenly distributed through the year (Fig. 3) (Whitlock & Bartlein 1993). In sharp contrast to that even distribution, precipitation patterns in Arizona and New Mexico have a primary maximum in summer (typically from July through September), which provides up to half of the total annual rainfall. A secondary maximum in winter (typically from November through March) provides an average of 30 % of the annual rainfall (Barry & Chorley 1998). Areas with a summer precipitation peak usually experience an arid fore-summer prior to the onset of summer rains and a relatively dry autumn, which is especially notable in Arizona (Bryson & Lowry 1955, Reitan 1957, Carleton 1985, Adams & Comrie 1997). Although the winter precipitation peak is generally smaller than that of summer, winter precipitation is still considered to be hydrologically important, because much of the summer rainfall evaporates before it infiltrates into the ground and because winter rain falls primarily as snow at higher elevations (Bryson & Hare 1974). Summer precipitation may aid stakeholders with large non-irrigated land holdings, but spring runoff from melting snow from high elevation provides water for reservoirs.

### 3.2. Temperature

Temperature across the region displays the typical seasonal cycle with a maximum in mid-summer and a minimum in mid-winter. Mean annual temperature decreases with higher elevation due to adiabatic cooling (Fig. 4).

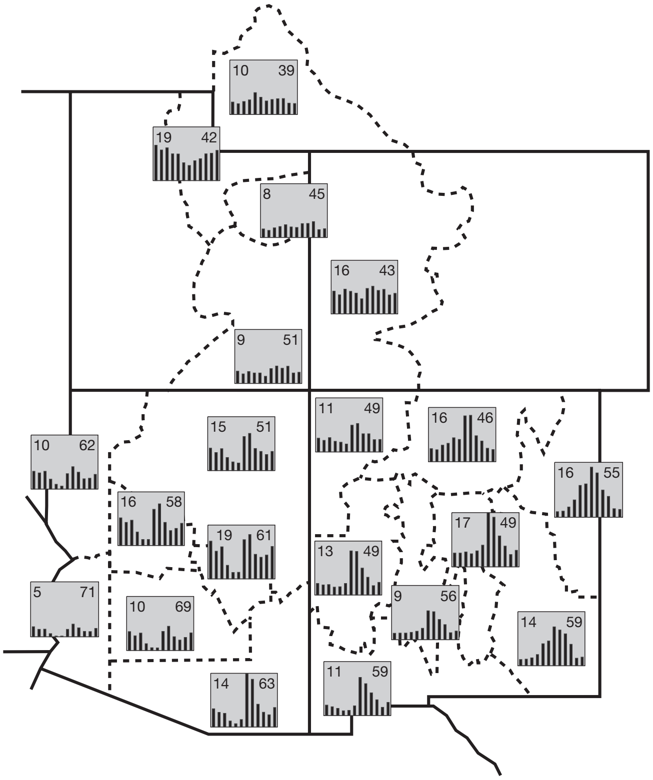

Fig. 3. Southwest UCRB precipitation climographs. For each divisional climograph, $y$-axis scales range from 0 to 3″ (76 mm) of precipitation and $x$-axis scales are months from January through December. Number in upper-left corner is mean annual precipitation (″) and number in upper-right corner is mean annual temperature (°F)

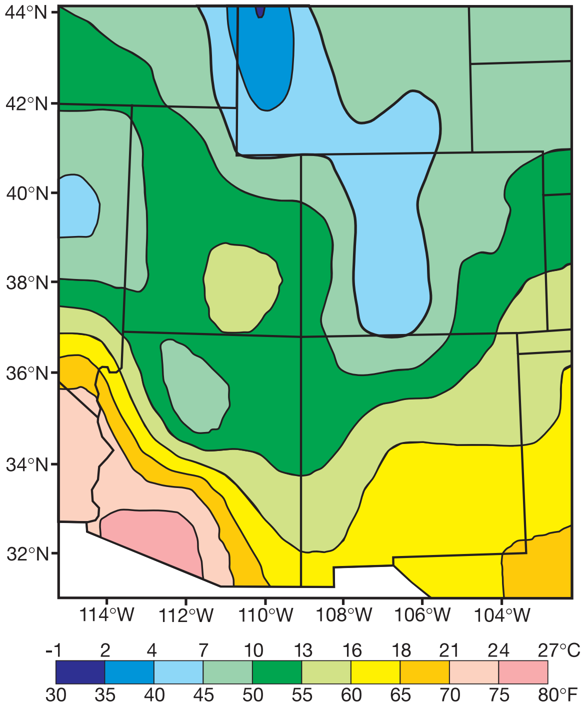

Fig. 4. Mean annual temperature across the Southwest and UCRB

The mean annual temperature of the Southwest (14°C [57°F]) is higher than that of the UCRB (7°C [44°F]), and within the Southwest, New Mexico (12°C [53°F]) is cooler than Arizona (17°C [62°F]). Across Arizona and New Mexico, daily average temperatures range from winter lows of −7°C (20°F) at high elevations to summer highs of 27°C (80°F) to 35°C (95°F) at low elevations (Tuan et al. 1973, Sellers & Hill 1974).

## 4. ATMOSPHERIC CONTROLS ON SOUTHWEST CLIMATE

The Southwest regional climate is influenced by features of both the mid-latitude and subtropical atmospheric circulation regimes. This positioning relative to shifts in these regimes is the fundamental reason for the region's climatic variability. The low annual precipitation, clear skies, and year-round warm climate over much of the Southwest are due in large part to a combination of the North Pacific Anticyclone during winter and the Bermuda High during summer. Climate variation within the region also results from overall physiographic and topographic relief, rainshadow effects from mountain ranges, and from proximity to

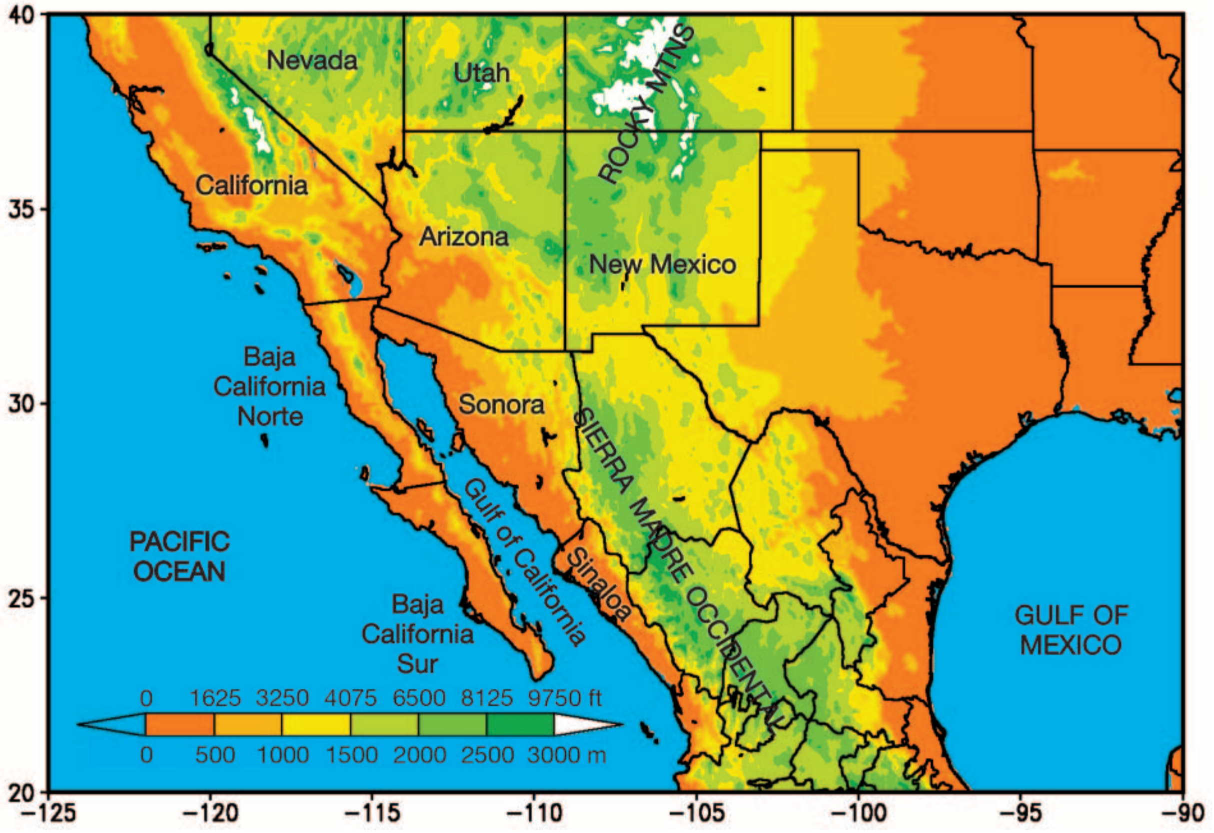

Fig. 5. Southwest digital elevation map (from Comrie & Glenn 1998)

the moisture sources of the Gulf of Mexico, the Gulf of California, and the eastern Pacific Ocean (Fig. 5). Regional aridity is associated with large differences between sensible heat flux (measurable heating of air by the land surface) and latent heat flux (energy expended to evaporate water), that is, most of the incoming solar insolation goes into heating the land surface instead of evaporating soil moisture (Scott 1991). This results in high rates of evapo-transpiration and high temperatures, especially throughout the desert Southwest.

### 4.1. Winter climate features and processes

The Southwest lies south of the usual winter westerly storm tracks, which typically enter North America over the states of Washington and Oregon, well north of the low-latitude tropical flow of air across Mexico (Fig. 6). Cold fronts associated with these westerly storms usually result in high winds and cloudy skies—instead of substantial rainfall—over the Southwest. When winter precipitation occurs in the Southwest during normal years, it comes from the occasional cyclonic storms that attain very large size (i.e. a diameter of a few thousand kilometers) and/or follow more southerly tracks that enter North America over California (Sellers & Hill 1974, Woodhouse 1997). Winter precipitation is typically widespread, with soaking rains at lower elevations and snowfall in mountainous areas (Trewartha 1981), and low to moderate in intensity but may persist for several days (Barry & Chorley 1998).

When the typical high-pressure ridge is displaced westward and a low-pressure trough forms over the western US (Fig. 6), storms enter the continent south of San Francisco. Several such storms may pass in succession and provide the Southwest with relatively large amounts of moisture (Sellers & Hill 1974). There is a tendency for a quasi-stationary trough to form off the California coast during periods when the Pacific high-pressure ridge becomes extremely well developed. Individual winter storms that move from the trough inland over the Southwest are capable of producing intense precipitation. Such storms occur about once every 6 yr (Sellers & Hill 1974). Heavy winter rains in Arizona often coincide with unusually dry periods in the states of Oregon and Washington because of the equatorward shift of the flow pattern. Large-scale atmospheric circulation patterns that result in wet Januarys in Arizona also result in record low amounts of precipitation for Washington. Of particular note is January 1949, when 'Seattle ... was drier than Yuma' (Sellers & Hill 1974).

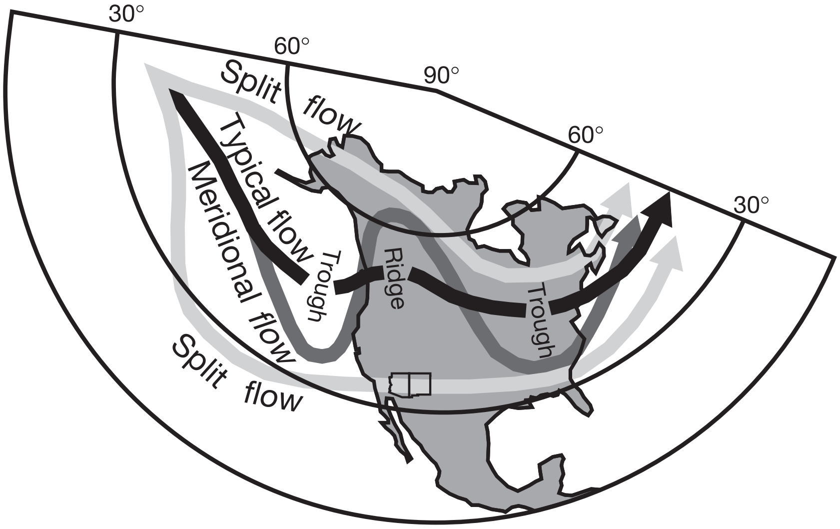

Fig. 6. Winter flow patterns drawn from circulation patterns at the 700 mb geopotential height, which relates well to the climate over North America (Jorgensen et al. 1967)

#### 4.1.1. Winter climate variability related to the Pacific/North American pattern

One mode of atmospheric variability during North American winters is represented by the Pacific/North American (PNA) pattern (Simmons et al. 1983, Leathers & Palecki 1992), which results in a meridional (highly sinuous) flow (Fig. 6). Strong PNA patterns can be linked to above-average precipitation in the Southwest (Redmond & Koch 1991), depending on the east-west position of the trough-ridge pattern. Conversely, the reverse PNA pattern results in a zonal (non-sinuous) flow and below-average precipitation in the Southwest. The PNA pattern can also exist in a modified form, during which the centers of activity are displaced to the east (Keables 1992). The modified PNA pattern is associated with an increase in precipitation in the Southwest due to a combination of heightened southwesterly flow originating in the tropical Pacific and a southward shift of the westerly storm tracks (Woodhouse 1997).

#### 4.1.2. Winter climate variability related to southwestern troughing

Southwest winter climate variability is also affected by several circulation patterns related to a phenomenon known as southwestern troughing, where the meridional flow is essentially displaced westward (Sellers & Hill 1974). In Southwestern troughing, a strong low-pressure trough is positioned over the Southwest with concurrent high-pressure ridges found over the Gulf of Alaska and the Great Lakes (Woodhouse 1997). During southwestern troughing, the winter circumpolar vortex expands and displaces Pacific storm tracks southward, allowing them to absorb more moisture while in their formative stages. In southern Arizona, over 60 % of January precipitation totals are attributed to southwestern troughing, though the total percentage of precipitation related to southwestern troughing is lower in eastern New Mexico (Burnett 1994).

#### 4.1.3. Winter climate variability related to El Niño-Southern Oscillation (ENSO)

In the most basic sense, El Niño is an increase in sea-surface temperature of the eastern equatorial Pacific Ocean with an associated shift of the active center of atmospheric convection from the western to the central equatorial Pacific (i.e. the atmospheric component called the Southern Oscillation) (National Oceanic and Atmospheric Administration 1999: website on El Niño and La Niña; available at www.websites.noaa.gov/guide/sciences/atmo/elnino.html). La Niña, in contrast, is a decrease in sea-surface temperature of the eastern equatorial Pacific Ocean with no shifting of the active center of atmospheric convection from the western equatorial Pacific. The combined El Niño-Southern Oscillation phenomenon (ENSO) has a period of variation of approximately 2 to 10 yr, with an average interval of 3 to 4 yr between El Niño events (Barry & Chorley 1998). The influence of ENSO on the climate system accounts for a large source of annual variability in the troposphere (Diaz & Kiladis 1992), typically resulting in a nearly global shift in precipitation patterns (J. Hill 1998: El Niño and La Niña: what's the difference? NOAA, Washington, DC; available at www.elnino.noaa.gov/lanina.html). One result of this atmospheric perturbation is a 'tropospheric wave-train' that moves out from the equator to regions of higher latitude, affecting the subtropical jet, and associated moisture transport (Horel & Wallace 1981).

The PNA pattern that affects the climate of the Southwest may be a manifestation of this wave-train (Wallace & Gutzler 1981, Yarnal & Diaz 1986). Many studies (general circulation models, theoretical, and observational) support the link between ENSO and the PNA pattern, singling out the Northern Hemisphere winter as the season in which this teleconnection becomes well developed (van Loon & Madden 1981, van Loon & Rogers 1981, Chen 1982, Webster 1982, Shukla & Wallace 1983, Blackmon et al. 1984, Yarnal & Diaz 1986, Dettinger et al. 1998). In particular, during El Niño events the westerly flow shifts southward, becoming more meridional or even splitting into 2 branches (Fig. 6). Storms that travel the southern branch may tap into moisture of lower latitudes over the eastern Pacific Ocean, resulting in an increase in low-intensity winter precipitation in the Southwest (Douglas & Englehart 1981, Cayan & Peterson 1989). Thus, Southwest winters are relatively cool and wet during El Niño events (Kiladis & Diaz 1989, Douglas & Englehart 1981), and southwestern deserts of the Colorado River basin often experience winter flooding as a result of El Niño events (Hirschboeck 1988, Webb & Betancourt 1992).

Conversely, the dominant anomaly pattern during La Niña events is the reverse PNA pattern (i.e. the typical flow situation) (Fig. 6). Thus, La Niña events typically result in warmer and drier winter conditions in the Southwest (Kiladis & Diaz 1989). With respect to temperature, a strong positive correlation exists between the ENSO-type circulation and maximum winter temperature in southwestern New Mexico and southeastern Arizona (Woodhouse 1997).

Recent observations suggest that El Niño events have been occurring more often in recent decades than before, especially during the 1990s. El Niño events have outnumbered La Niña events by a ratio of 2:1 since the late 1970s, whereas they occurred approximately equally before (Trenberth 1997). This trend is evident in time series of the Southern Oscillation Index, which is the normalized sea-level pressure difference between Tahiti (central Pacific Ocean) and Darwin, Australia (western Pacific Ocean), and which quantifies El Niño (negative index) versus La Niña (positive index) events (Fig. 7). There also may be a link between trends in global warming and the

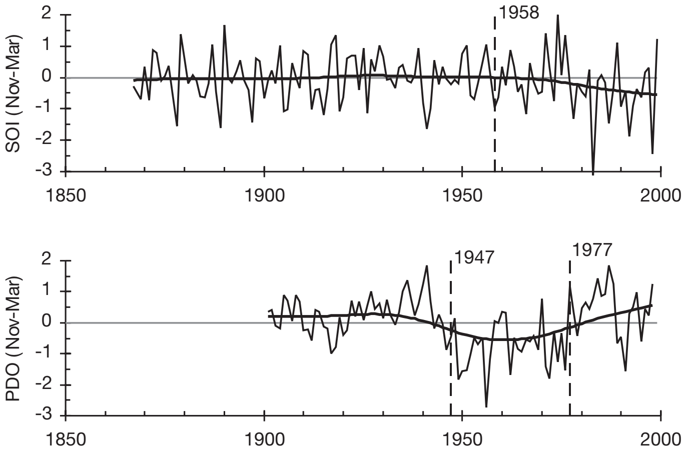

Fig. 7. Southern Oscillation Index (SOI) and Pacific Decadal Oscillation (PDO). Smooth lines show multi-decadal (50–80 yr) variation. For SOI, negative values indicate El Niño, while positive values indicate La Niña. For PDO, positive values indicate warm northern Pacific sea-surface temperatures, while negative values indicate cool temperatures

increase in number and intensity of El Niño events (Trenberth & Hoar 1997).

#### 4.1.4. Winter climate variability related to Pacific Decadal Oscillation

Another important oceanic influence on winter climate of the Southwest is a feature called the Pacific Decadal Oscillation (PDO). An index for the PDO has been developed from the temporal changes in the dominant pattern of Northern Pacific Ocean sea surface temperatures (Mantua et al. 1997, Zhang et al. 1997). This index is positive when northeastern Pacific Ocean temperatures are warm, coincident with cooler temperatures in the central and western North Pacific. Although the PDO is compiled at the monthly scale, its important climate signature is its ocean-atmosphere covariability during winter (November through March) at the multi-decadal timescale (50–80 yr) (Fig. 7). Shifts in the PDO have been identified for 1925, 1947, and 1977 (Gershunov & Barnett 1998). The strongest atmospheric manifestation of the PDO corresponds with unusually low sea-level pressure over the northern Pacific Ocean during strong positive phases of PDO (warm water) and vice versa (Gershunov & Barnett 1998). Because of this, the PDO is positively correlated with winter precipitation throughout western North America (Mantua et al. 1997). Additionally, PDO and ENSO climate patterns are related spatially and temporally (Mantua et al. 1997). The effects of ENSO are enhanced synergistically during constructive phases of the PDO (i.e. El Niño is stronger during positive phases of the PDO and La Niña is stronger during negative phases of the PDO) (Gershunov & Barnett 1998). Conversely, effects of ENSO are dampened during destructive phases of the PDO (i.e. El Niño is weaker during negative phases of the PDO and La Niña is weaker during positive phases of the PDO).

#### 4.1.5. Winter precipitation in mountainous regions

Localized orographic factors augment or diminish the non-orographic precipitation resulting from widespread intense cyclonic storms (Jorgensen et al. 1967). In high-elevation portions of the Colorado Plateau in Arizona and New Mexico, more than 75% of winter precipitation falls as snow, with annual totals ranging from 2.4 to 3.3 m (96 to 132″). During extremely cold and wet periods, over 2.5 m (100″) can fall in a single month. Southwest mountain ranges with elevations above 2100 m (7000 ft) typically receive as much as 1.5 m (60″) of snow annually. High deserts (e.g. southeastern Arizona) record between 25 and 150 mm (1 and 6″) of snow annually. Low deserts (e.g. southwestern Arizona) rarely receive snow, and the snow that they do receive typically melts soon after settling (Sellers & Hill 1974).

### 4.2. Summer climate features and processes

The major feature that sets the climate of the Southwest apart from the rest of the US is the North American monsoon, which is noticeable mostly in Mexico and up into Arizona and New Mexico (Douglas et al. 1993, Adams & Comrie 1997). By definition, a monsoon is a distinctive seasonal change in wind direction of at least 120° (Ramage 1971), including mid-tropospheric winds (Bryson & Lowry 1955). This definition applies to the North American monsoon (Tang & Reiter 1984), although this and other monsoons are more commonly associated with the seasonal rains brought by the wind reversals. The effect of the monsoon extends over much of the western US and northwestern Mexico, and it is an important feature of summer season atmospheric circulation over the continent (Higgins et al. 1997, 1998, 1999). Physiography of the western US and northwestern Mexico is characterized by large upland areas bordered by lowlands, and the monsoon system is aided by the seasonally warm land surfaces in both the uplands and the lowlands in combination with atmospheric moisture supplied by the nearby maritime sources (V.L. Mitchell 1976, Trewartha 1981, Carleton 1985, Adams & Comrie 1997).

Onset of the monsoon is related to the retreat of the westerlies and simultaneous advance of the subtropical high-pressure ridge over the region. In addition, a thermal low-pressure area forms over the Lower Colorado River Basin (Adams & Comrie 1997). Onset of the North American monsoon usually occurs in June over Mexico and by the end of the first week of July over the US Southwest (Fig. 8) (Higgins et al. 1997, 1998, 1999). Monsoon onset occurs later with higher latitude (Carleton 1985), and northern Arizona, for example, may see monsoon onset dates that are closer to the middle of July.

Many of the important controlling dynamics of the monsoon occur at the mesoscale (i.e. at a finer spatial resolution than conventional weather measurements), making day-to-day forecasting of the monsoon quite difficult. Examples of these dynamics include the fluxes of low-level atmospheric moisture westward over the Sierra Madre Occidental and northward up the Gulf of California. The interaction of mesoscale and synoptic-scale dynamics creates a complex regional circulation with extremely high seasonal and multi-year variability, limiting the predictability of monsoonal rainfall.

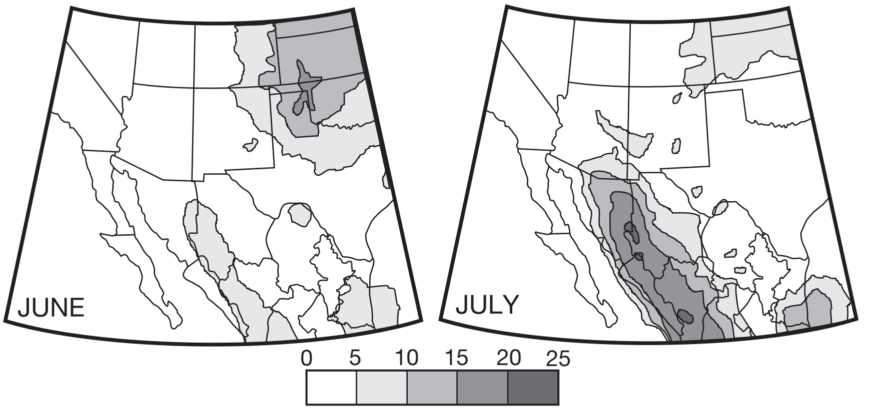

Fig. 8. June-July monsoon onset. Scale is frequency (% of total hours) of cloud-top temperatures below –38°F (–39°C), indicating depth of convection (Adams & Comrie 1997)

### 4.2.1. North American monsoon moisture sources

There has been a great deal of debate surrounding the moisture source regions of the North American monsoon. For many years, the Gulf of Mexico was viewed as the sole source of water-vapor advection (Bryson & Lowry 1955). Currently, however, the literature suggests that it is a combination of low-level moisture advection from the Gulf of California and the eastern tropical Pacific Ocean as well as mid-level moisture from the Gulf of Mexico (Adams & Comrie 1997, Higgins et al. 1997, 1998, 1999, Wright et al. 2001). For areas west of the continental divide, the primary source appears to be the Gulf of California and the eastern tropical Pacific Ocean, while the Gulf of Mexico may contribute some upper level moisture that interacts with low-level moisture from the Gulf of California. The means by which atmospheric moisture is transported northward through the Gulf of California are described as 'gulf surges' (Hales 1972, Brenner 1974). At the northern end of the Gulf of California, a mean northward flow exists that includes a low-level flow during the months of July and August (Badan-Dangon et al. 1991, Douglas 1995). This results from pressure gradients that are created in the lower troposphere as the thermal equilibrium between the Gulf of California and the tropical Pacific Ocean is disrupted due to the development of a cloudy, rainy air mass near the mouth of the Gulf (Fig. 9) (Adams & Comrie 1997).

### 4.2.2. Diurnal variability of precipitation

During the North American monsoon season, the Southwest experiences strong diurnal variability in cloud cover, which is linked to diurnal cycles of surface heating and convection (Sellers & Hill 1974, Tang & Reiter 1984, Carleton 1985). Precipitation variation is due in part to shifts in the surface layer circulation, specifically the change from daytime cyclonic circulation to nighttime anticyclonic circulation (Tang & Reiter 1984). Precipitation waxes in the evening hours and wanes during morning hours, a pattern that follows the strong influence of thermal heating (Sellers & Hill 1974). Numerous studies have shown that diurnal variability in convective activity and precipitation is strongly dependent upon geographic location (McDonald 1956, Ackerman 1959, Hales 1972, 1977, Brenner 1974, Reiter & Tang 1984, Balling & Brazel 1987, Maddox et al. 1991, 1995, Watson et al. 1994). For example, convective activity peaks in the early afternoon over the Colorado Plateau, in the early evening over southern Arizona and the Sonoran Highlands, and in the late evening and/or nighttime in the low desert areas of southern and central Arizona as well as northwestern Mexico and its coastal lowlands. This pattern occurs in part when mid-level cold air derived from afternoon thunderstorms over mountain areas is advected to lower desert areas during evenings (Hales 1977).

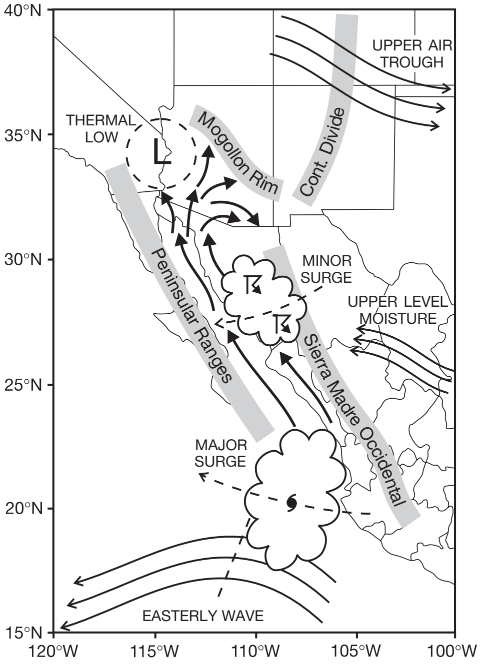

Fig. 9. Conceptual model of monsoonal gulf surge. Moisture from the eastern Pacific is advected northward and combines with upper-level Gulf of Mexico moisture moving through the core monsoon area to Arizona and New Mexico. Adapted from Adams & Comrie (1997)

#### 4.2.3. Intraseasonal variability: bursts and breaks

In general, months within a year are typically coherent in being mostly above average in above-average years or mostly below average in below-average years (Higgins et al. 1999). Consequently, years with early onset of the monsoon typically result in above-average total monsoonal rainfall and vice versa (Higgins et al. 1999). However, the monsoon season in the Southwest is noted for having considerable intraseasonal variability in the form of periods of heavy thunderstorm activity ('bursts') versus drier periods ('breaks') (Hales 1972, Brenner 1974). Total cloud cover variation of as much as 40% may be observed within a few days time, reflecting latitudinal changes in anticyclonic activity in association with subtropical ridging over the Southwest (Carleton 1986, Carleton et al. 1990). Atmospheric instability over the Southwest (i.e. extensive convective cloudiness and precipitation) results from a combination of intense surface heating and high topographic relief. Conversely, a decrease in convective precipitation results from the intensification and northward shift of the subtropical ridge, as this leads to the formation of a high-pressure center over southern Arizona and a concurrent enhancement of subsidence over the Southwest (Carleton 1986).

#### 4.2.4. Interannual and decadal variability

Duration and intensity of the North American monsoon and the associated summer rainfall vary on interannual and decadal time scales (Schmidli 1969, Revelle & Delinger 1981, Carleton et al. 1990). Much of this variability is associated with the summer season expansion of the Bermuda subtropical ridge and an intensification of the surface low in southwestern Arizona (Bryson & Lowry 1955, Green & Sellers 1964). Wet summers in Arizona are associated with a northward shift of the subtropical ridge, while a southward shift of the subtropical ridge is linked to dry summers (Carleton et al. 1990, Comrie & Glenn 1998). Summers in which the subtropical ridge exhibits extreme northward displacement used to be preceded by positive departures in sea-surface temperatures throughout the central and eastern equatorial Pacific and along the coast of Baja California, with concurrent negative departures in the central North Pacific. The reverse was true during summers in which the subtropical ridge is shifted to the south (Carleton et al. 1990). However, this pattern did not occur during the 1990s.

A particular distinction has been defined between certain anomalously wet and dry summers (Carleton 1987). For example, though the 1950s was a noted period of drought generally, its summers experienced anomalously frequent wet 'burst' events as the subtropical ridge was displaced to the north. Conversely, summers of the 1970s experienced anomalously frequent 'break' events and were drier by comparison to the 1950s. During the 1970s, the mean latitude of the subtropical ridge shifted to the south and changed the persistence of wet and dry anticyclonic patterns. That trend lasted into the early 1980s, when the anticyclonic wet 'burst' patterns became more frequent.

#### 4.2.5. ENSO effects on the Southwest monsoon

There have been contradictory results from research on the relationship between ENSO and total summer precipitation, which might be partly due to variable definitions used to identify the timing of El Niño or La Niña events. On one hand, Arizona and New Mexico have been shown to receive significantly higher monsoon precipitation in July during El Niño years than during La Niña years (Harrington et al. 1992). On the other hand, El Niño is thought to reduce the number of monsoonal storms that affect Arizona (Webb & Betancourt 1992). In another study, La Niña events have been associated with below-average monsoon rainfall in Arizona and New Mexico, but El Niño events have resulted in normal rainfall (Higgins et al. 1999). Thus, as of now there is no clear relationship between ENSO and total summer precipitation (Andrade & Sellers 1988, Adams & Comrie 1997).

#### 4.2.6. Tropical cyclones

In late summer and early fall, widespread and intense rainfall may occur in the Southwest because of northeastward penetration of tropical cyclones (Webb & Betancourt 1992, Adams & Comrie 1997) (Fig. 9). Notably, in 1951 a cyclone-induced storm brought 310 mm (12″) of rain in just 5 d to central Arizona, with major flood damage occurring along the Salt and Gila Rivers (Sellers & Hill 1974). Increased frequency of El Niño events since 1960 (Fig. 7) has coincided with the tendency of tropical cyclones in the Eastern North Pacific Ocean to move into the Southwest (Webb & Betancourt 1992).

## 5. CLIMATE VARIATION IN THE SOUTHWEST

### 5.1. Extreme short-term climatic events

Single-day record high rainfall totals in the Southwest are 290 mm (11.4″) on September 4, 1970, in east central Arizona and 287 mm (11.3″) on May 18, 1955, in north central New Mexico (National Climatic Data Center 2001: website on extreme weather and climate events; available at www.ncdc.noaa.gov/ol/climate/severeweather/extremes.html). Record high annual rainfall totals are 1496 mm (58.9″) during 1978 in east central Arizona and 1588 mm (62.5″) for 1941 in southeastern New Mexico. Record low annual rainfall totals are 2 mm (0.07″) for 1956 in west central Arizona and 25 mm (1.0″) during 1910 in southwestern New Mexico.

Prolonged droughts (below-average rainfall) and wet periods (above-average rainfall) are common in the instrumental record of the Southwest. For example, no less than 13 episodes of drought and 10 episodes with above-average precipitation are reported for southeastern Arizona for 1866–1961 (Cooke & Reeves 1976). Flooding events that resulted in the destruction of dams, irrigation channels, and crop-producing fields (and that may be linked to ENSO) appear in the record as far back as the 1880s (Nabhan 1994).

As for short-term fluctuations in moisture availability, the notable 1950s drought, which reached its extreme from 1954 to 1956 with a 3 yr average Palmer Drought Severity Index (PDSI) of below –3.0, was one of the worst 3 yr long periods of below-average moisture availability since 1700 (Fig. 10) (Meko & Graybill 1995). Other notable 3 yr long droughts were centered on 1847 and 1729, but the 1950s drought was probably more severe because it was embedded in a longer period of severely dry conditions (Meko et al. 1993, Swetnam & Betancourt 1998). Conversely, exceptional 3 yr periods of above-average moisture availability were centered on 1907, 1868, 1839, 1793, and 1726, with a frequency of 1 to 2 notable events per century (Stockton & Meko 1975). Furthermore, the greatest amplitude of interannual switching from wet to dry occurred from 1747 to 1748, possibly indicating an extreme El Niño followed by a severe La Niña (Swetnam & Betancourt 1998).

Record high temperatures in the Southwest are 53°C (128°F) on June 29, 1994, in west central Arizona and 50°C (122°F) on June 27, 1994, in southeastern New Mexico (National Climatic Data Center 2001). Record low temperatures are –40°C (–40°F) on January 7, 1971, in east central Arizona and –45°C (–50°F) on February 1, 1951, in northwestern New Mexico.

As for short-term fluctuations in temperature, the coolest 3 yr long temperature events of the 20th century (1906–1908 and 1964–1966) were exceeded by 1 reconstructed cool event, 1725–1727 (Fig. 11). The 1800s had 2 notable cool years, 1835 and 1866. Likewise, the warmest event of the 20th century (1934) was exceeded by 1 reconstructed warm event in 1651 and equaled by others in 1865 and 1881.

### 5.2. Long-term climate variations

For those readers not familiar with general principles of paleoclimatology, with the historical and technical details of dendroclimatology, or with the specific dendrochronological reconstructions of climate of the Southwest, please refer to Appendix 1 for a discussion on natural records of climate. Otherwise, the following discussion of past moisture availability is based on prior research by Cook et al. (1999), while the discussion of past temperature variation is based on prior research by Briffa et al. (1992).

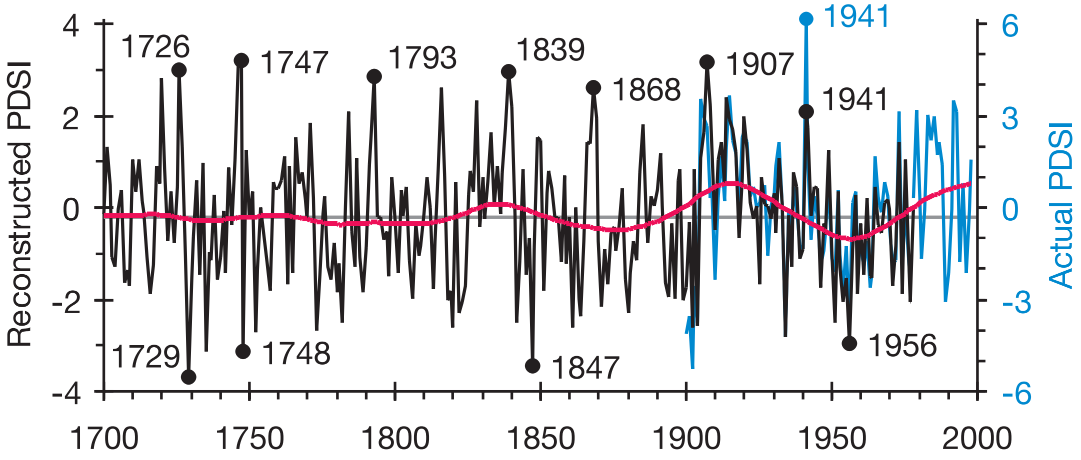

Fig. 10. Southwest Palmer Drought Severity Index (PDSI). Tree-ring-reconstructed PDSI (black) since 1700 with actual PDSI (blue). During the period of overlap (1900–1978), the 2 series correlate strongly but have different ranges (note the different *y*-axis scales). The reconstructed series shows multi-decadal (50–80 yr) variation (red), which has been increasing in amplitude with time since the late 18th century

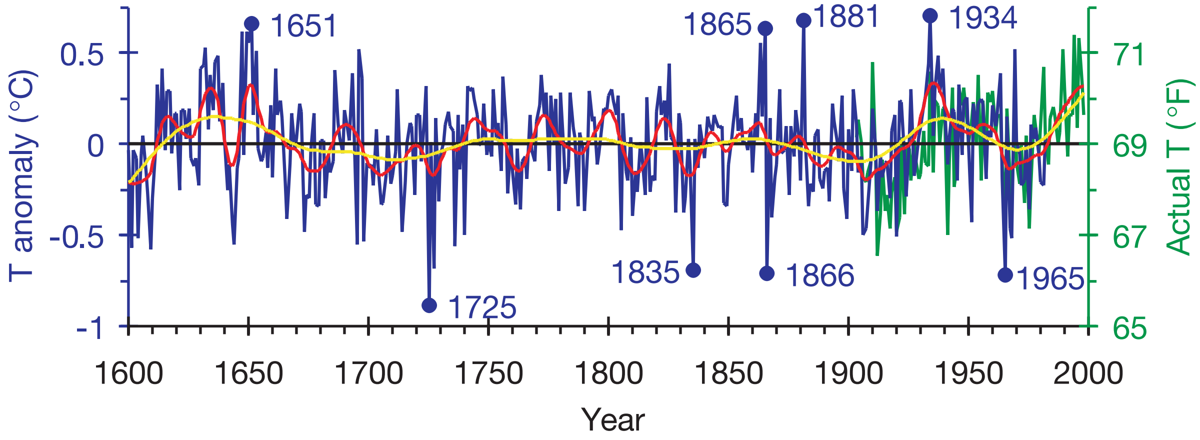

Fig. 11. Southwest temperature. Tree-ring reconstructed temperature (blue) and actual temperature (green). During the period of overlap (1900–1980), the 2 series correlate strongly. Red line shows 20 yr period variation, and yellow line shows multi-decadal (50–80 yr) variation

### 5.2.1. Southwest summer PDSI (moisture availability) since AD 1700

During the 20th century, the Southwest experienced wet years in the early part of the century (1905–1930), a mid-century dry period (1942–1964), and warm, wet winters and erratic summers since 1976 (Fig. 10), as has been shown by others (e.g. Swetnam & Betancourt 1998). The 20 yr long wet period of the early 20th century appears to be unprecedented in the paleoclimatic reconstruction of PDSI back to 1700. This early 20th century wet period has been noted in much past dendrochronological research of the paleoclimate of the Southwest (Stockton & Meko 1975, Meko & Graybill 1995, Smith & Stockton 1981). There was a similarly long period of above-average PDSI in the past, from 1820–1840, but its departure from the mean PDSI value was not as high as that of 1905–1925.

The rate of decline from above- to below-average moisture availability since 1925 also appears to be unprecedented in the paleoclimatic reconstruction of PDSI (Fig. 10), and this feature has also been noted in past dendrochronological research of paleoclimate of the Southwest (Woodhouse & Meko 1997). Again, there were other declines in moisture availability in the past, but their rates of decline were less than that of the decline beginning in 1925. The period 1930–1960, when zonal flow was common and PDSI values were consistently below average, appears to be climatically distinct from periods before 1930 or after 1960, when meridional flow and frontal storms were more common (Webb & Betancourt 1992). Other long periods of generally below-average moisture availability occurred from 1850 to 1905 as well as from 1770 to 1825. Other reconstructions back to AD 1000 show a very long period of drought for most of the 1500s, which appears to have been the longest drought of the millennium (D'Arrigo & Jacoby 1991).

Several tree-ring chronologies from the Southwest show an unprecedented trend of increasing tree growth beginning in the mid-1970s. This recent growth release may be a response to mild, wet winters and springs associated with El Niño events (Swetnam & Betancourt 1998) as well as to the prevalence of the warm phase of the PDO that began in 1977 (Fig. 7).

If the current period since 1980 is considered as one of above-average PDSI, which appears to be justified from the modern climate record (Fig. 10), then the combined paleo-modern climate record has at least 3 occurrences of a multi-decadal variation of alternating below- to above-average PDSI, a climate feature that has been noted in past dendrochronological research of paleoclimate of the Southwest (D'Arrigo & Jacoby 1991, Sheppard 1998). In general, low-frequency variability characterizes the climate changes over the North Pacific and North America from the late 19th century onward (Fig. 7). This variability is likely to be an internal oscillation in the coupled atmosphere-ocean system, although it could be modulated by solar radiation heating in the present century (Minobe 1997).

This 50–80 yr feature is curiously absent in the early part of the reconstruction since 1700 (Fig. 10), though it is strong before 1700 in other reconstructions back to AD 1000 (e.g. D'Arrigo & Jacoby 1991). Other dendrochronological research has noted that droughts were relatively rare in the Southwest prior to 1800 (Meko & Graybill 1995). Thus, the amplitude of this variation seems to have increased since the 1700s (Fritts 1991, Dettinger et al. 1998). Possible natural climatic forcing factors include solar variation (Cook et al. 1997, Shindell et al. 1999), ocean-atmosphere dynamics (J. M. Mitchell Jr 1976), and explosive volcanism (Kelly & Sear 1984). Solar variation is known to oscillate at a multi-decadal period, the so-called Gleissberg 88 yr cycle (Garcia & Mouradian 1998). This variation is observed in radiocarbon variation of tree rings (Suess 1992), but whether or not the Gleissberg cycle of solar variation causes climate changes that are substantial enough to affect radial tree growth is yet to be clearly shown.

Another technique for viewing the variability of past climate is to calculate a time series of standard deviations centered on some period of time, for example, 21 yr (Grissino-Mayer 1995). The 21 yr moving standard deviation of PDSI shows that the Southwest has experienced relatively low inter-annual variability in climate for much of the 20th century (Fig. 12). A period of high inter-annual variation occurred from 1895 to 1915, corresponding to the large shift from dry conditions of the late 1800s to the very wet period beginning in 1905. The Southwest experienced similarly high inter-annual climate variability in the early 1700s. Conversely, the early 1800s was a period of relatively stable moisture availability through time. Indeed, the period 1794–1815 is remarkable for its lack of reconstructed PDSI values greater than +2 or less than −2 (Fig. 10) (Swetnam & Betancourt 1998).

### 5.2.2. Southwest versus UCRB PDSI

When looking at the separate subregions of the Southwest (Arizona & New Mexico) versus the UCRB, the high- and low-frequency patterns of variation are similar (Fig. 13). For most of the record since 1700, PDSI values of the UCRB have been slightly higher than those of the Southwest, as indicated by the low-frequency lines. This is to be expected because temperatures of the Southwest are higher than those of the UCRB. However, this pattern curiously changed in the last 20 yr, with the trend in PDSI for the Southwest going higher than that of the UCRB. This may indicate a recent change in the relative importance of winter versus summer precipitation in the Southwest, and it merits further investigation.

### 5.2.3. Southwest summer temperature since 1600

The paleo-temperature reconstruction for the Southwest has significant periods of variation at 80 and 20 yr (Briffa et al. 1992) (Fig. 11). The 1920s and 1930s stand out as unusually warm and have been noted as a dominant feature of the temperature record across the western US (Bradley et al. 1982). The 20 yr period variation has its highest peak of the entire reconstruction centered on 1935, but 2 closely analogous warm periods were centered on 1635 and 1650. The cool period centered on 1907 was exceeded only by that of the beginning of the reconstruction (i.e. the early 1600s).

A similar cool-warm-cool pattern occurred in the 17th century, but it was conspicuously reduced for most of the 18th and 19th centuries, which has also been noted for all of western North America (Fritts 1991). The most obvious feature of the low-frequency variation is the current increase in temperature to an extent unprecedented in the last 400 yr (Fig. 11). This feature has been noted even at the hemispherical and global scales (Mann et al. 1998, 1999), and this regional pattern of warming merits further research into

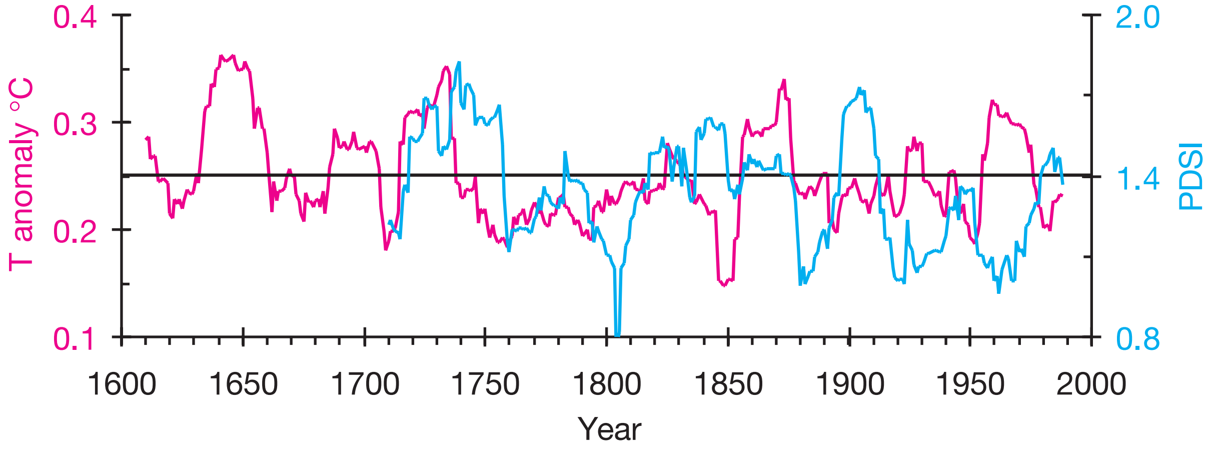

Fig. 12. Temporal variance. 21 yr running standard deviations of Southwest PDSI (blue line) and temperature (red line)

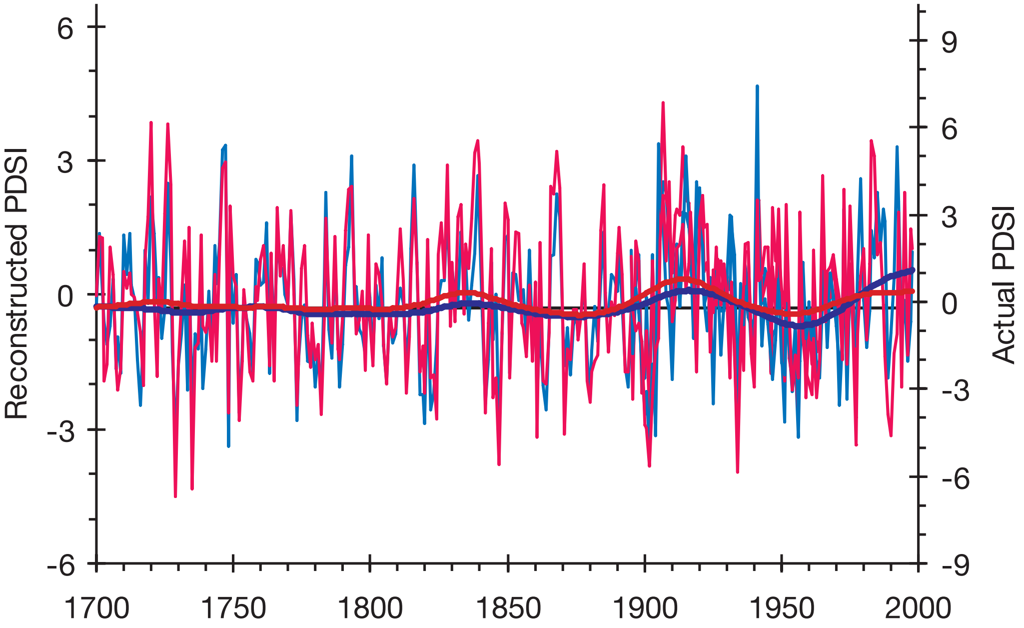

Fig. 13. Reconstructed Southwest (blue) vs. UCRB (red) PDSI. Smoothed lines track the multi-decadal (50–80 yr) variation of each series. Scaling of actual PDSI, which is wider than reconstructed PDSI, is shown on the secondary y-axis

its cause or combination of causes (Tol & de Vos 1993). Future research should include the extent to which anthropogenic impacts, such as increased atmospheric concentrations of greenhouse trace gases (Rind & Overpeck 1993), are playing a role in climate of the Southwest.

As with PDSI, temporal variability of temperature has been generally low during the 20th century relative to the entire period of the reconstruction since 1600 (Fig. 12). The current period of a high temporal variability since 1955 has been equaled or exceeded 3 times in the past: 1633–1661, 1715–1737, and 1856–1877.

## 6. CONCLUSIONS

This paper, written in a non-technical style, in order to be accessible to non-climatologists, as part of the Climate Assessment project of the Southwest, has covered the major points of the climate of the Southwest with emphasis on its modern features as well as its long-term past variation. The Southwest climate may be characterized as semi-arid and warm. An important feature of precipitation over most of Arizona and New Mexico is that it has 2 modes of occurrence during the year: summer (July through September) and winter (November through April). Temperature ranges widely on both the daily and seasonal scales. The winter climate of the Southwest is affected primarily by what happens with westerly storm tracks originating over the Pacific Ocean. When those tracks shift over the region, the Southwest can receive widespread precipitation. Otherwise, the Southwest is relatively dry. The ENSO phenomenon plays a role in winter precipitation, with El Niño events typically resulting in wet winters and La Niña events resulting in drier winters.

The North American monsoon brings summer moisture to most of Arizona and New Mexico. Moisture from a combination of oceanic sources typically moves into the Southwest by July, and convective storms occur when local conditions cause air masses to ascend. Variation in summer rainfall exists at daily and intraseasonal scales and across various spatial scales.

Past precipitation of the Southwest has varied sharply at timescales ranging from annual to multidecadal (50–80 yr). With respect to annual variation, the instrumental record of summer PDSI appears to be typical when compared to that the past 300 yr. However, the recent multi-decadal pattern of PDSI shows strong amplitude. Interannual and decadal precipitation variability plays major societal and ecological roles in western North America (Dettinger et al. 1998), for example, in areas such as ranching, farming, tourism, urban water management, and regional power production within the Southwest. Thus, understanding the cause of this low-frequency variation could be critical in the future for possibly projecting variation in water resources used by various stakeholders of the Southwest.

Past temperature of the Southwest has also varied from year to year and on decadal scales. Of particular interest is the recent upward trend of temperatures during the instrumental period, perhaps to a point outside the range of variation of past temperature as reconstructed from tree rings. Other research suggests that the late 20th century is ‘unusually’ warm generally, with 1990, 1995, 1997, and 1998 noted as the warmest years since the beginning of instrumentally recorded climate data and potentially the warmest since AD 1000 (Mann et al. 1999). This clearly calls for improved understanding of the causes of such temperature variation.

*Acknowledgements.* We drew much from a small set of earlier authors whose work specifically described the climate of the Southwest as well as from a broader group of papers that addressed regionally relevant findings by season or process. We formally acknowledge the groundbreaking work of these researchers. We also thank Henry Diaz, Art Douglas, and Nate Mantua for providing useful comments on earlier drafts of this review. This project was funded with support from National Oceanic and Atmospheric Administration.

## **Appendix 1.** Natural records of climate

### General paleoclimatology

As instrumental meteorological records extend back only about 100–120 yr throughout the Southwest, they are of limited utility for studying climate phenomena at the century or longer time frame. Long-term climate phenomena, such as extended periods of drought or abundant rainfall as well as extended periods of time with unusually high or low interannual variation, simply have not occurred enough times in only the last century for their temporal frequency to be reliably estimated (Cook et al. 1996). Likewise, it is also inappropriate to estimate the frequency of short-term (down to a single year) extreme climate events based on only 100+ yr of recorded meteorological data.

Hence, there is a need to extend the measured meteorological record further back in time using so-called ‘natural archive’ paleoclimate records. In general, many different types of natural archives exist for studying paleoclimate, and many of those types exist in the Southwest. However, each type of natural paleoclimate archive has a peculiar combination of attributes that make it more or less useful for understanding climate throughout the last few hundred to 1000 yr. That is, some natural paleoclimate archives are more useful than others with respect to this review of paleoclimate of the Southwest. Tree-ring data, which provide annual resolution, range throughout the Southwest, extend back in time for up to 1000 yr or more in various places of the Southwest, and integrate well the influences of both temperature and precipitation, are useful for this assessment of climate of the Southwest.

### Dendroclimatology

The formal scientific discipline of studying tree-ring variation, called dendrochronology, was founded in the Southwest in the early 20th century. The astronomer Andrew Ellicott Douglass had been in Arizona since the 1890s selecting a suitable site for a new observatory (Webb 1983). With his traits of excellent observational skills and a creative and open mind, Douglass noted from various cut pine stumps around Flagstaff that they all had essentially the same temporal pattern of wide or narrow rings, and he correctly surmised that some spatially large environmental factor—climate—caused that synchronous growth variation (Bannister 1965). Astronomer Douglass was personally interested in solar output variation and its effect on the Earth's climate (Bannister 1965), so he quickly speculated that a serious study of tree-ring variation might ultimately yield useful information about past climate variation and, by extension, past solar variation. Thus dendrochronology began in the Southwest, and after nearly 100 yr of tree-ring research by Douglass and many successors, a dense network of long and well-replicated tree-ring chronologies exists in the US Southwest (Fig. A1). It is with this type of natural archive that we will provide a longer context and perspective with which to better evaluate modern climate variation later in this assessment of the climate of the Southwest.

### Development of tree-ring data for paleoclimatology

The most basic unit of sampling in dendrochronology is the individual tree, which, in temperate regions, typically grows 1 layer of new wood tissue (a tree ring) each year. Throughout its life, a tree creates a series of rings that vary from one another in appearance as a result of annual climate variation and possibly other factors. To observe annual rings of a tree, dendrochronologists collect an increment core that extends along a radius from the tree's pith to its bark. To best sample ring growth, at least 2 replicate increment cores are collected from a tree, usually from opposite sides of the tree.

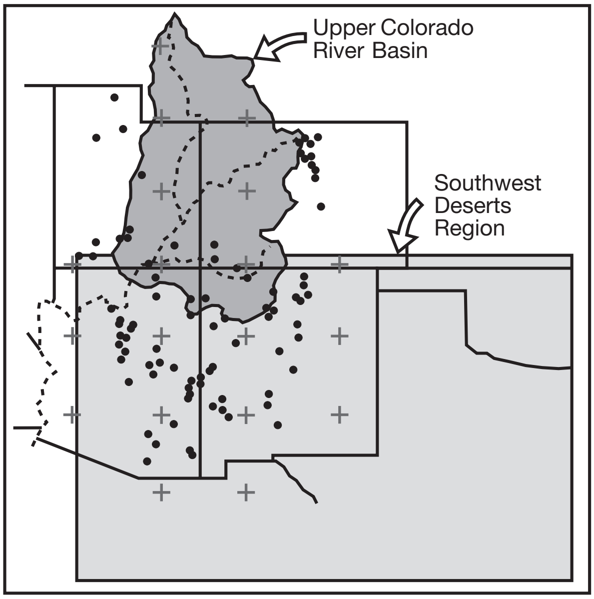

Fig. A1. Southwest-UCRB site map. For the purposes of this assessment of climate of the Southwest, the region of interest includes Arizona, New Mexico, and the UCRB. Dots indicate tree-ring sites, showing an extensive network throughout the Four-Corners states. Crosses indicate grid points of the PDSI reconstruction of Cook et al. (1996). The Southwest Deserts region of temperature reconstruction by Briffa et al. (1992) is also shown

## Appendix 1 (continued)

Although the individual tree may be considered the sampling unit in dendrochronology, sampling just 1 tree is not sufficient for representing tree-ring variation of a sampling site (i.e. an ecologically homogeneous stand of trees). Instead, typically at least 20 trees are sampled from within a forest stand that may range in area from 0.5 to 5 ha (1 to 12 acres) or larger. For paleoclimatology, trees are chosen for sampling not by random selection but rather with the conscious intent of maximizing the uniformity of microsite conditions such as slope angle and aspect and soil type as well as of tree characteristics such as age and absence of past injuries.

After several steps of preserving and processing tree-ring samples (Phipps 1985, Swetnam et al. 1985), the rings of each sample are dated to the exact year of formation with a technique of pattern matching called cross-dating (Douglass 1941). In cross-dating, temporal patterns of relatively wide and narrow rings are matched across samples and then the actual year date of formation may be assigned to each ring.

After crossdating, all dated rings are measured, typically for ring width (Fig. A2), which often relates strongly to moisture availability, (e.g. precipitation in semi-arid regions). Precipitation-ring width relationships are especially notable in the Southwest, where narrow rings indicate drought years and wide rings moist years (Schulman 1956). Ring width is measured quickly using a computer-linked linear encoding device along with a microscope (Robinson & Evans 1980). Additionally, other ring-growth features such as intra-ring wood density are often measured. Summer temperature-ring density relationships are notable in trees growing in mesic, cool environments where dense late-woods indicate warm years and less dense late-woods indicate cool years (Parker & Henock 1971). Intra-ring wood density is measured directly using X-ray densitometry (Schweingruber 1990) or indirectly using image analysis (Sheppard et al. 1996). Regardless of the ring-growth variable, measurement series are subsequently routinely checked for possible dating and measurement errors (Holmes 1983).

After ring series are measured and the quality of measurements is confirmed, a 2-step process of data standardization is done. First, the series-length trend of each sample's measurement series is removed from each series. This trend is often best expressed as a negative exponential curve, which is logical biologically because the radial growth of a tree must decrease as the tree itself becomes bigger through time if the total volume of wood produced each year stays constant (Fritts 1976). The trend is removed by dividing the measured value by the estimated curve value for each year. This step results in a time series of dimensionless indices with a mean value of 1.0. The detrending preserves low-frequency growth departures from the mean line of up to one-half the series length (Cook et al. 1995).

The second step of standardization is to average all index series together into a single chronology that, like the individual index series, has a mean value of 1.0. After standardization, tree-ring chronologies typically contain temporal persistence, or autocorrelation, where the value at any time *t* is statistically related to values of years immediately prior to *t*. This persistence is partly biological in origin and is site and species specific (Fritts 1976). Therefore, autocorrelation may be removed from a site chronology by fitting a low-order autoregressive model. This may be done when the autocorrelation of tree growth is greater than or different from that seen in the meteorological variable of interest. The resultant residual chronology represents ring-growth variation through time for the particular site from where the samples were collected. This entire process has been repeated at literally hundreds of sites throughout the Southwest (Fig. A1). Consequently, an extensive network of tree-ring chronologies exists with which to reconstruct climate for this entire geographical region (Fritts 1965, 1991, Fritts et al. 1979, Dettinger et al. 1998).

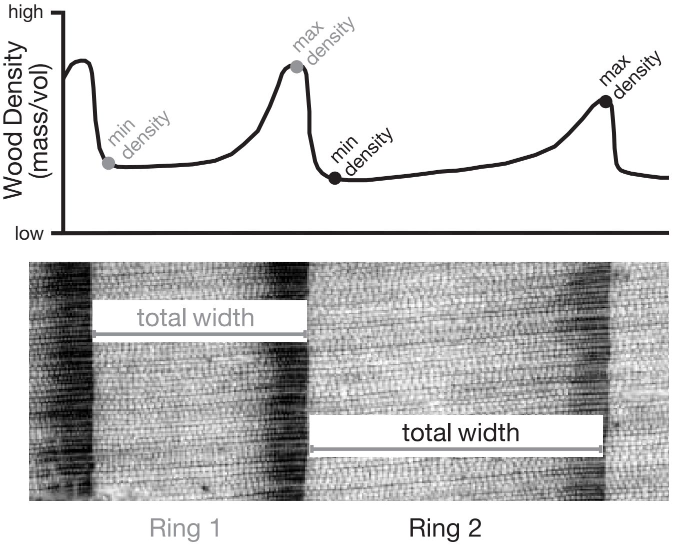

Fig. A2. Tree rings. Ring 1 is narrow compared to Ring 2; in the Southwest, ring-width variation typically corresponds to annual variation in moisture availability. The wood density scan above the image shows that the maximum densities, which associate with the dark late-wood bands of each ring, also vary, with Ring 1 having a higher density than Ring 2. In many cool, mesic tree-ring sites, variation of maximum late-wood density corresponds to annual variation in growing-season temperature

### Tree growth and precipitation/PDSI

Tree growth typically responds to moisture availability during the growing season, which generally occurs from late spring through early autumn for much of the Southwest (Fritts 1976). In general, moisture-ring width growth relationships are positive (i.e. above-average moisture increases ring width) (Fig. A2). A commonly used climate variable in paleoprecipitation studies is the Palmer Drought Severity Index (PDSI), which is a single variable that is derived from the variation in precipitation and temperature and considers various site environmental factors such as soil type (Palmer 1965). As such, the PDSI may be considered as a measure of moisture availability to trees. Given that summer is the critical season with respect to moisture availability for tree growth, the June–August PDSI is an intuitively reasonable climate variable for dendrochronological reconstruction. However, a given month's PDSI re-

**Appendix 1** (continued)

flects the moisture conditions of several preceding months in addition to that of the given month (Stockton & Meko 1975, Katz & Skaggs 1981) such that the summer PDSI reflects the precipitation of winter months (synoptic-scale winter climatology) as well as of summer months (mesoscale monsoonal summer climatology). In this review of climate of the Southwest, the June–August PDSI strongly represents the precipitation and, to a lesser extent, temperature of the year prior to the growing season (prior September through current August) (Fig. A3).

### Dendroclimatic modeling: moisture availability

The summer PDSI was reconstructed throughout North America by transforming irregularly spaced data into a regular grid pattern (Cook et al. 1999). In the case of the PDSI, each grid box covers 2° of latitude and 3° of longitude (Fig. A1). Individual meteorological station records were interpolated to the grid points using an inverse-distance weighting factor for weather stations within 150 km of each grid point. The shared variance between individual station records and their corresponding grid point interpolation is reasonably high throughout much of the Southwest, though the correlations are weaker in mountainous regions such as the Colorado Rocky Mountains. Just as with the tree-ring chronologies, the PDSI contains unwanted serial persistence and that autocorrelation was modeled out of the gridded climate data. Data from all grid points corresponding to the Southwest and the UCRB were merged into a single time series of the PDSI for the Southwest.

To dendrochronologically reconstruct the PDSI, a so-called point-by-point regression technique was used whereby each grid point of the interpolated PDSI was sequentially analyzed with selected tree-ring chronologies from the dendrochronological network. A necessary task prior to actually fitting a regression model for any point was selecting the appropriate tree-ring chronologies for that point. This task was accomplished using a 4-step process designed to maximize the number of tree-ring chronologies while minimizing the distance between the included tree-ring sites and the grid points. First, all chronologies within a 450 km radius of the grid point were selected; if that number of sites did not equal or exceed 5, then the search radius was expanded until at least 5 sites were selected. Second, the selected tree-ring series were pre-screened to have a consistent and strong correlation with summer PDSI of the grid point. Third, those chronologies that passed the pre-screening were reduced to a few statistically orthogonal series using principal components analysis (Fritts 1991). Finally, a best-subset regression approach optimized the climate-tree growth model for the grid point by maximizing the explained variance of PDSI by the chosen predictors while minimizing the number of predictors used in the model. These grid point reconstructions are available at http://www.ngdc.noaa.gov/paleo/drought.html.

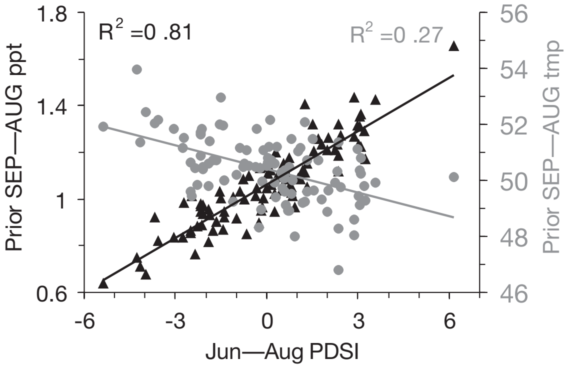

Fig. A3. PDSI related to annual precipitation and temperature. Triangles indicate precipitation, while circles indicate temperature

The average series of the reconstructed PDSI of the grid points of the Southwest correlates very highly (r = +0.83) with the average series of the actual PDSI values from 20 meteorological stations located within the Four-Corner states (Fig. 10). In general, the 2 series clearly share a high degree of annual variation, though the amplitude of the reconstructed PDSI variation is only about two-thirds that of the actual series, and extremely wet years, such as 1941, are underestimated. Tree-ring chronologies behave essentially as 'integrating rain gauges' (Stahle & Cleaveland 1992), and therefore the long-term reconstruction of the PDSI of the Southwest merits close scrutiny as a perspective of past precipitation with which to evaluate current and possible future patterns (Dettinger et al. 1998). In particular, it is reasonable to expect ENSO events to be positively correlated with tree-ring widths from moisture-sensitive conifers in the Southwest (Michaelsen 1989).

### Dendroclimatic modeling: temperature

Tree growth also typically responds to temperature during the growing season. Temperature-ring density growth relationships are positive (e.g. above-average temperature increases the maximum cell density). A commonly used climate variable in paleo-temperature studies is the average of monthly temperatures for the growing season. The exact timing of the growing season may vary across tree sites, even within the Southwest, but in the case reported here the temperature season of April through September was analyzed by Briffa et al. (1992).

As in the PDSI analysis, the networks of temperature and maximum cell density series were first transformed into 2 sets of principal components prior to dendroclimatic analysis (Briffa et al. 1992). Regression equations were calculated to model temperature using weighted combinations of significant principal components of tree-ring data. Selected grid point series were then averaged into coherent regions, the most appropriate of which for this assessment of climate of the Southwest is 'Southwest Deserts' (Fig. A1).

In the case of summer temperature reconstructed by Briffa et al. (1992), each grid box covers 5° of latitude and 10° of longitude (Briffa et al. 1992). As with the PDSI, individual meteorological station records were interpolated to the grid points using an inverse-distance weighting factor for weather stations within each grid box. The temperature series were converted into mean monthly anomalies from the mean of the period 1951–1970. The series of reconstructed temperature of the Southwest Desert region correlates highly (r = +0.54) with the average series of actual temperature departures (Fig. 11)

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