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ABSTRACT

This paper summarizes the current state of knowledge concerning the climate of the Southwest. Low annual precipitation, clear skies, and year-round warm weather 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. 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 major feature that sets 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 in.] while that of New Mexico is 340 mm [13.4 in.], 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 100-120 years throughout the Southwest, they are of limited utility for studying climate phenomena at the multi-decadal to century or longer 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 years 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 three occurrences of a multi-decadal variation of alternating dry (below average PDSI) to wet (above average PDSI). The amplitude of this multi-decadal variation seems to have increased since the 1700s. Should this pattern persist into the future, then perhaps the American Southwest will next enter an extended dry period. The most obvious feature of the temperature record is its current increase to an extent unprecedented in the last four hundred years. Because this warming trend is outside the variation of the natural archives, it is possible that anthropogenic impacts are playing a role in climate of the Southwest. Accordingly, this pattern merits further research in search of its cause or combination of causes.

Keywords: Southwest, climate, El Niño-Southern Oscillation (ENSO), monsoon, Palmer Drought Severity Index (PDSI), summer temperature, dendrochronology, tree rings

INTRODUCTION

Dry and hot! For many people, these two words sum up the climate of the southwestern United States, but 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. The Southwest may be drenched by torrential monsoon thunderstorms in July and August, yet it can warm gently under fair skies from fall to spring. Periods of droughts, which may be punctuated by extreme flooding events, are not uncommon in the Southwest. Climate variability is the norm within this region as temperature and precipitation fluctuate on time scales ranging from seasons to centuries.

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. 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.

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 speak to 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 inter-decadal 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 prehistoric 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?

This paper was written as part of the Climate Assessment project for the Southwest, an Integrated Regional Assessment program of the University of Arizona. In addition to answering the questions of above, our goal was to make this climate knowledge useful to regional stakeholders of climate information as well as other researchers. 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. Southwest precipitation is especially variable, with regional floods or droughts severe enough to affect both indigenous and modern civilizations on time scales ranging from single growing seasons to multiple years, even decades.

Organization

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. Next, the availability and extraction of natural climate records from tree rings are examined. Then, historic and paleoclimatic variability in moisture and temperature is evaluated.

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.

National Weather Service and Co-Operative Stations

The National Weather Service (NWS) operates three stations in Arizona: Flagstaff, Phoenix, and Tucson. Additionally, over 240 co-operative stations regularly gather and report temperature and precipitation data (Figure 1). Automated stations, many at high elevation, monitor levels of 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, personal communication, 1998). Automated stations notwithstanding, high-elevation areas are generally underrepresented in the overall record. Arizona's tribal lands, which constitute a sizable portion of the total land area of the state, are also underrepresented (Merideth et al. 1998).

The NWS operates two stations for New Mexico: Albuquerque, New Mexico, and El Paso, Texas. New Mexico also has over 200 co-operative stations throughout the state (Figure 1). Record keeping began in New Mexico in 1850, with weather records being kept by Army personnel

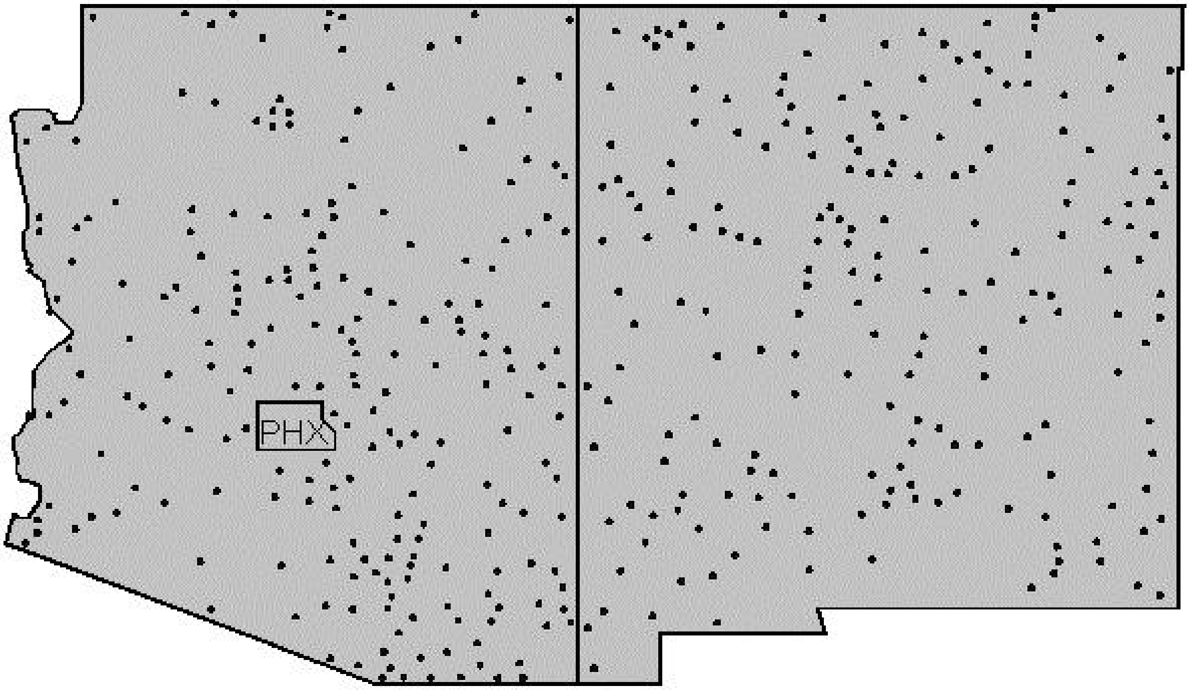

Figure 1. Arizona and New Mexico Cooperative Weather Stations. Many sites exist within Phoenix (the polygon PHX). Adapted from NCDC-NOAA web site.

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). Sparsest coverage is in the northwestern corner and in New Mexico's uplands. In most cases, upland stations (>2100 m [7000 ft] elevation) also have shorter periods of record keeping.

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 official observers have been private citizens. Individuals, like "Miss M. Shoemaker" or the father and son team of A. and J. A. Hord, dominate the list (Sellers and Hill 1974).

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" (US Department of Commerce, National Oceanic and Atmospheric Administration, no date). 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 (Figure 2). Individual climate divisions can be hundreds of kilometers wide and represent weather stations that vary in elevation by thousands of meters. Arizona, for example, has a land area of 294,000 sq. km. (113,500 sq. mi.) 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 seven climate divisions. New Mexico has even more land area (314,000 sq. km. [121,300 sq. mi.]) 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 eight 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.

SOUTHWEST CLIMATE PATTERNS

Precipitation

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

At the monthly scale, precipitation over the UCRB is relatively evenly distributed through the year (Figure 3) (Whitlock and Bartlein 1993). In sharp contrast to that even distribution, precipitation patterns in Arizona and New Mexico have primary maxima in summer (typically from

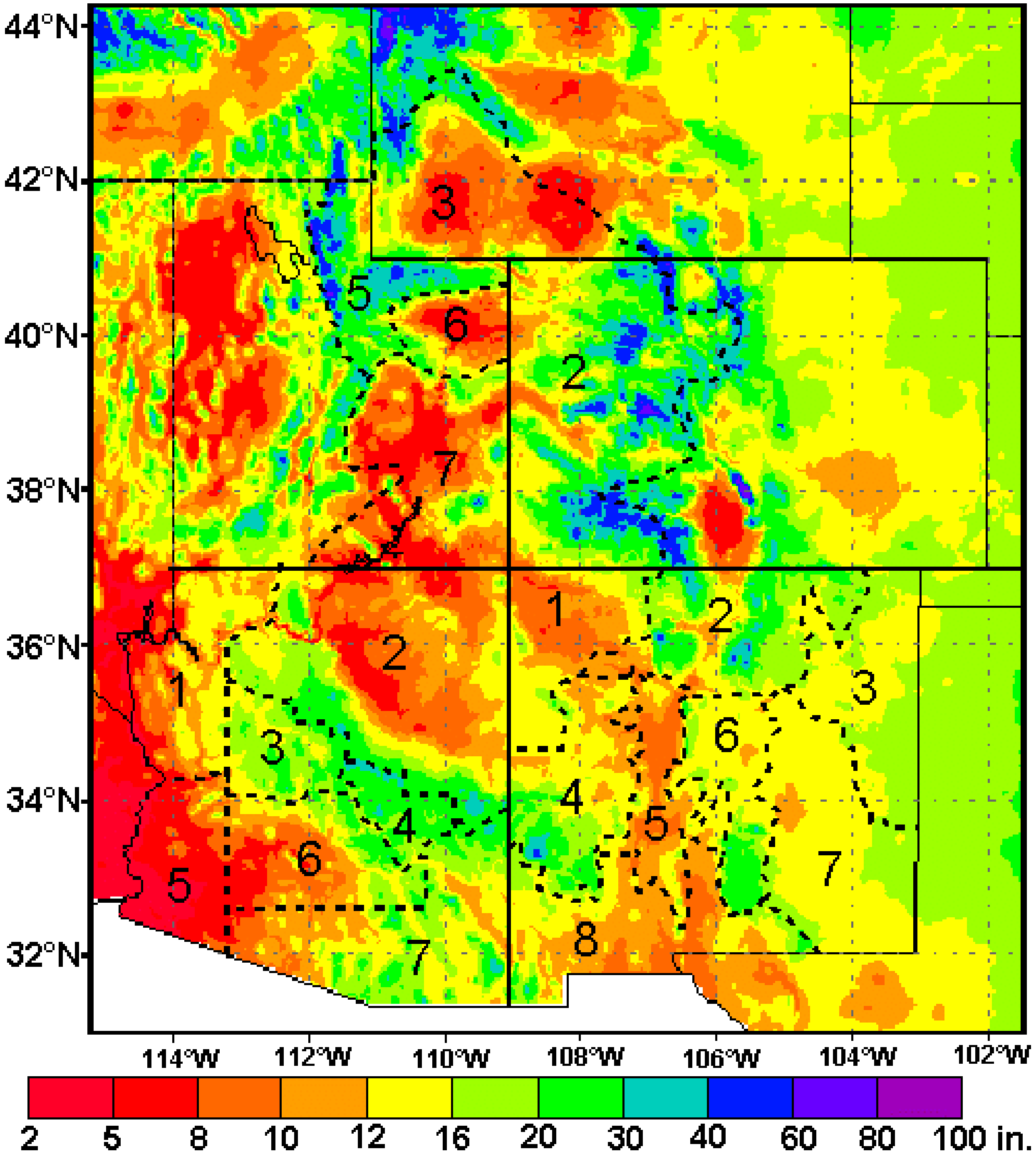

Figure 2. Southwest-Upper Colorado River Basin Precipitation and Divisions. Dashed-line boundaries delineate climate divisions as defined by National Oceanic and Atmospheric Administration, with divisions identified by number within each state. Colors represent mean annual precipitation (in.) across the Southwest and the Upper Colorado River Basin. Adapted from WRCC web site.

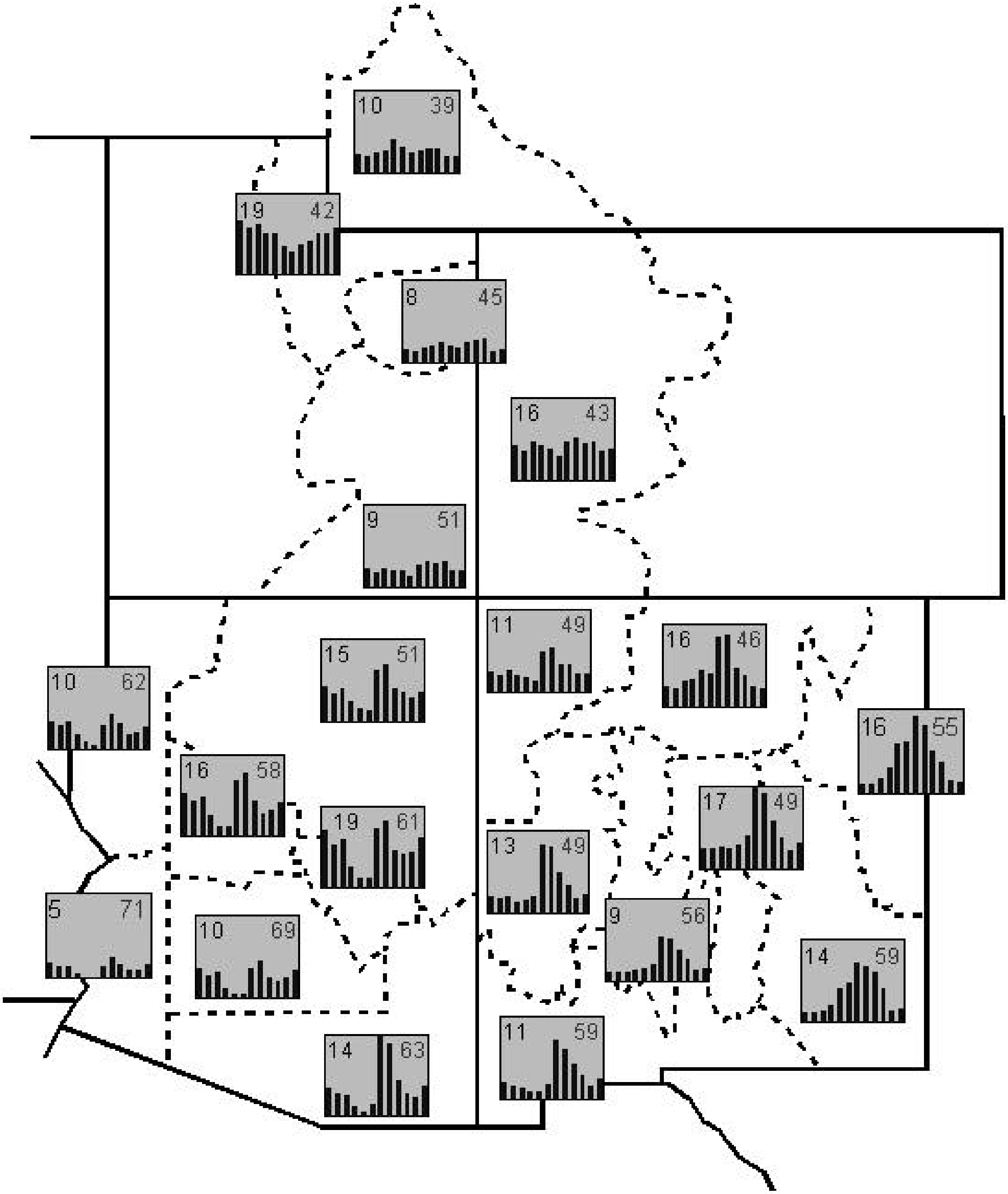

Figure 3. Southwest-Upper Colorado River Basin Climographs. For each divisional climograph, y-axis scales range from 0 to 3 in. of precipitation and x-axis scales are months from January through December. Number in upper-left corner is mean annual precipitation (in.) and number in upper-right corner is mean annual temperature (°F).

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 thirty percent of the annual rainfall (Barry and Chorley 1998). Areas with a summer precipitation peak usually experience an arid foresummer prior to the onset of summer rains and a relatively dry autumn, which is especially notable in Arizona (Bryson and Lowry 1955; Reitan 1957; Carleton 1985; Adams and 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 summer rainfall evaporates before infiltrating into the ground and because it falls primarily as snow at higher elevations. Summer precipitation may aid stakeholders with large non-irrigated land holdings, but spring runoff from melting snow from high elevation provides water for reservoirs.

Temperature

Temperature across the region displays the typical seasonal cycle with a maximum in midsummer and a minimum in midwinter. Mean annual temperature decreases with higher elevation due to adiabatic cooling (Figure 4). 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 and Hill 1974). The highest temperature ever reported in Arizona was 53°C (127°F) (Sellers and Hill 1974) while the lowest recorded temperature noted in New Mexico was -46°C (-50°F) (Tuan et al. 1973).

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 weather over much of the Southwest are due in large part to a quasi-permanent subtropical high-pressure ridge over the region. Climate variation within the region also results from overall physiography and topographic relief and from proximity to the moisture sources of the Gulf of Mexico, the Gulf of California, and the eastern Pacific Ocean (Figure 5). Additionally, high temperatures, high rates of evapotranspiration, and rainshadow effects of mountain ranges all contribute to regional aridity (Scott 1991).

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/Oregon, well north of the low latitude tropical flow of air across Mexico (Figure 6). These typical westerly storms 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 sizes (i.e., a diameter of a few thousand kilometers) and/or follow more southerly tracks that enter North America over California (Sellers and Hill 1974; Woodhouse 1997). Winter precipitation is typically widespread, with soaking rains at lower elevations and snowfall in mountainous areas (Trewartha 1981), and is low to moderate in intensity but may persist for several days (Barry and Chorley 1998).

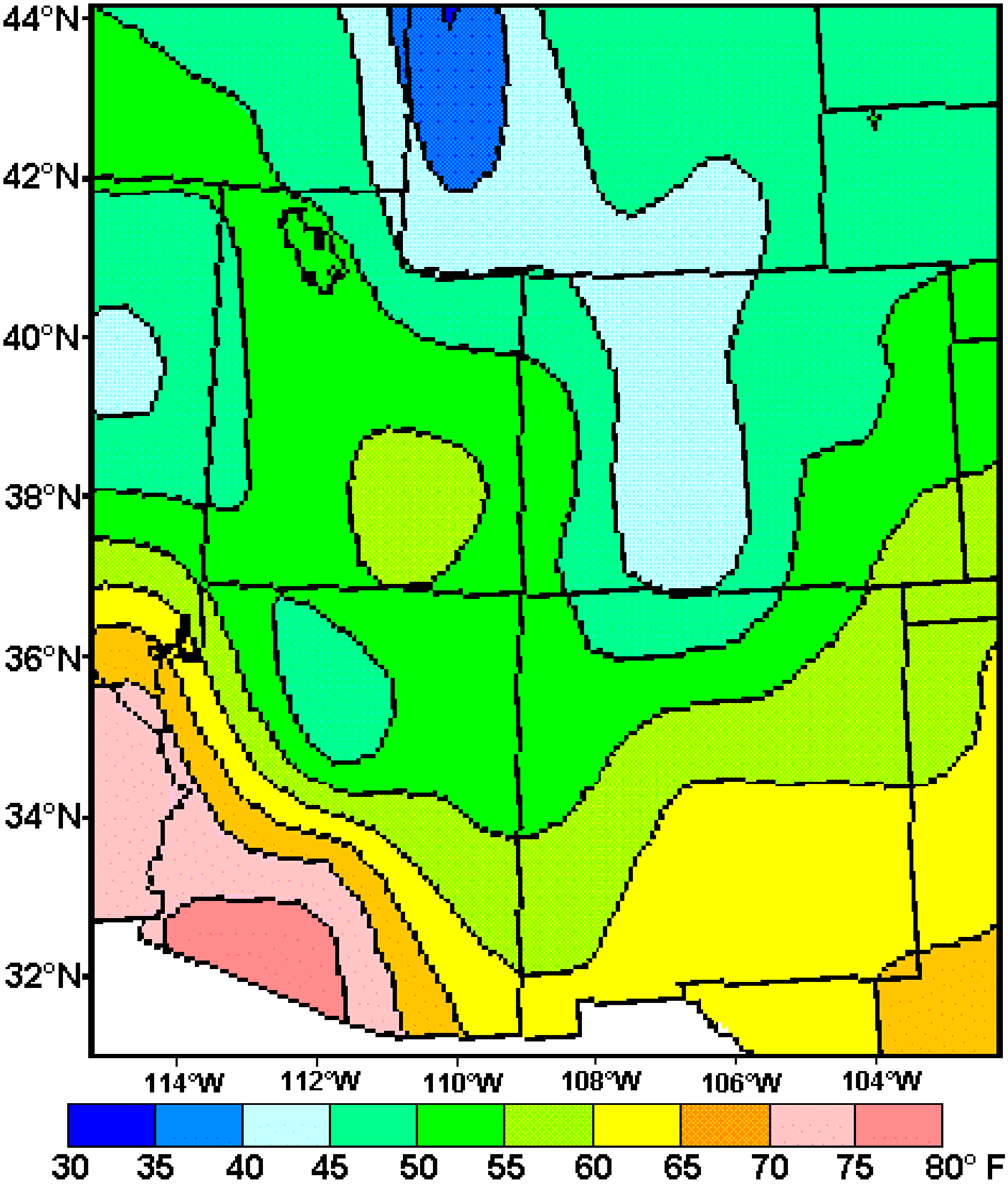

Figure 4. Southwest-Upper Colorado River Basin Temperature. Mean annual temperature (°F) across the Southwest and Upper Colorado River Basin.

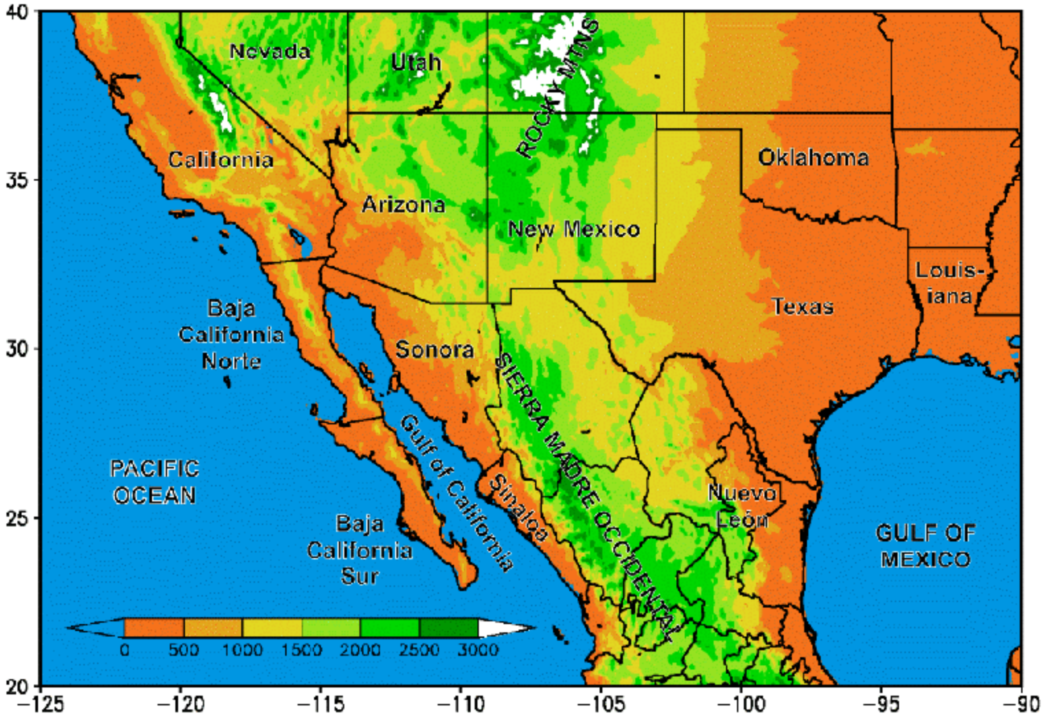

Figure 5. Southwest Digital Elevation Map. Scale is in m. From Comrie and Glenn (1998).

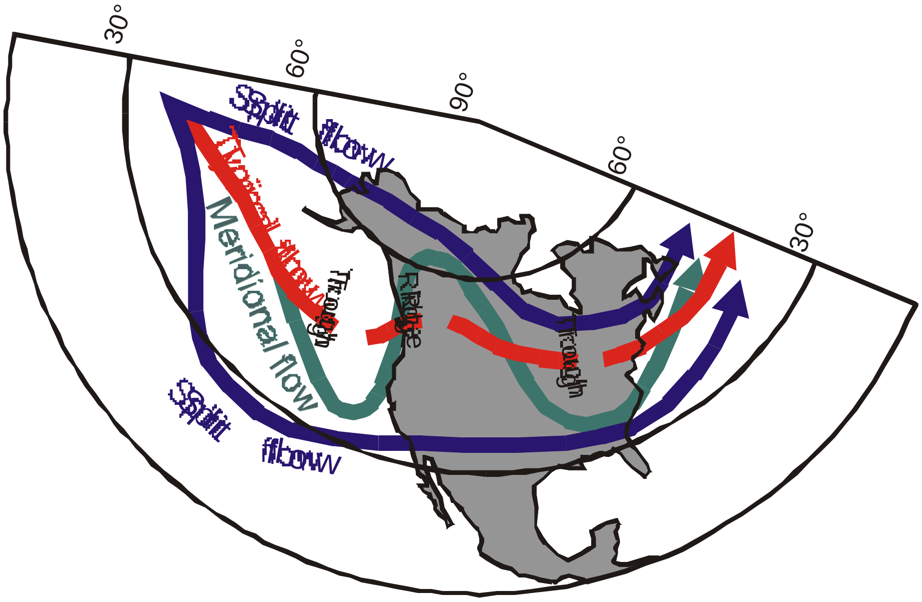

Figure 6. Winter Flow Patterns. These patterns are drawn from circulation patterns at the 700 mb geopotential height, which relates well to actual weather over North America (Jorgensen et al. 1967).

When the typical high-pressure ridge is displaced westward and a low-pressure trough forms over the western US (Figure 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 and 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 six years (Sellers and 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 was January of 1949, when "... Seattle ... was drier than Yuma" (Sellers and Hill 1974).

Winter Climate Variability Related to 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 and Palecki 1992), which results in a meridional (highly sinuous) flow (Figure 6). Strong PNA patterns can be linked to above average precipitation in the Southwest (Redmond and Koch 1991), depending on the east-west position of the high pressure ridge. 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 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).

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 and Hill 1974). In Southwestern troughing, which is only weakly related to PNA, 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 sixty percent 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).

Winter Climate Variability Related to El Niño-Southern Oscillation (ENSO)

In the most basic sense, El Niño events produce 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) (NOAA 1999). La Niña events, in contrast, produce 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 approximately two to ten years, with an average interval of three to four years between El Niño events (Barry and Chorley 1998). The influence of ENSO on the global climate system comprises the most global source of annual variability in the troposphere (Diaz and Kiladis 1992). Strong El Niño and La Niña events typically result in a nearly global shift in precipitation patterns (Hill 1998). One result of this atmospheric perturbation is a "tropospheric wave-train" that moves out from the equator to regions of higher latitude (Horel and Wallace 1981).

The PNA pattern that affects climate of the Southwest may be a manifestation of this wave-train (Wallace and Gutzler 1981; Yarnal and 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 and Madden 1981; van Loon and Rogers 1981; Chen 1982; Webster 1982; Blackmon et al. 1984; Shukla and Wallace 1983; Yarnal and Diaz 1986; Dettinger et al. 1998). In particular, during warm ENSO events (El Niño), westerly flow shifts southward by zonal flow displacing southward or becoming more meridional or by splitting into two branches (Figure 6). Storms that travel the southern branch may tap into moisture vapor of lower latitudes over the eastern Pacific Ocean, resulting in an increase in low-intensity (< 5 mm/hour) winter precipitation in the Southwest (Douglas and Englehart 1981; Cayan and Peterson 1989). Thus, Southwest winters are relatively cool and wet during El Niño events (Kiladis and Diaz 1989; Douglas, A.V., and Englehart 1981), and southwestern deserts often experience winter flooding as a result of El Niño events (Webb, R.H., and Betancourt 1992).

Conversely, the dominant anomaly pattern during cold ENSO events (La Niña) is the reverse PNA pattern (i.e., the typical flow situation) (Figure 6). Thus, La Niña events typically result in warmer and drier winter conditions in the Southwest (Kiladis and 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. El Niño events have outnumbered La Niña events by a ratio of two to one since the late 1970s, whereas they used to occur 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 (Figure 7). There also may be a link between trends in global warming and the increase in number and intensity of El Niño events (Trenberth and Hoar 1997).

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 (Figure 7). PDO shifts have been identified for 1925, 1947, and 1977 (Gershunov and 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 and Barnett 1998). Because of this, the PDO is positively cor-

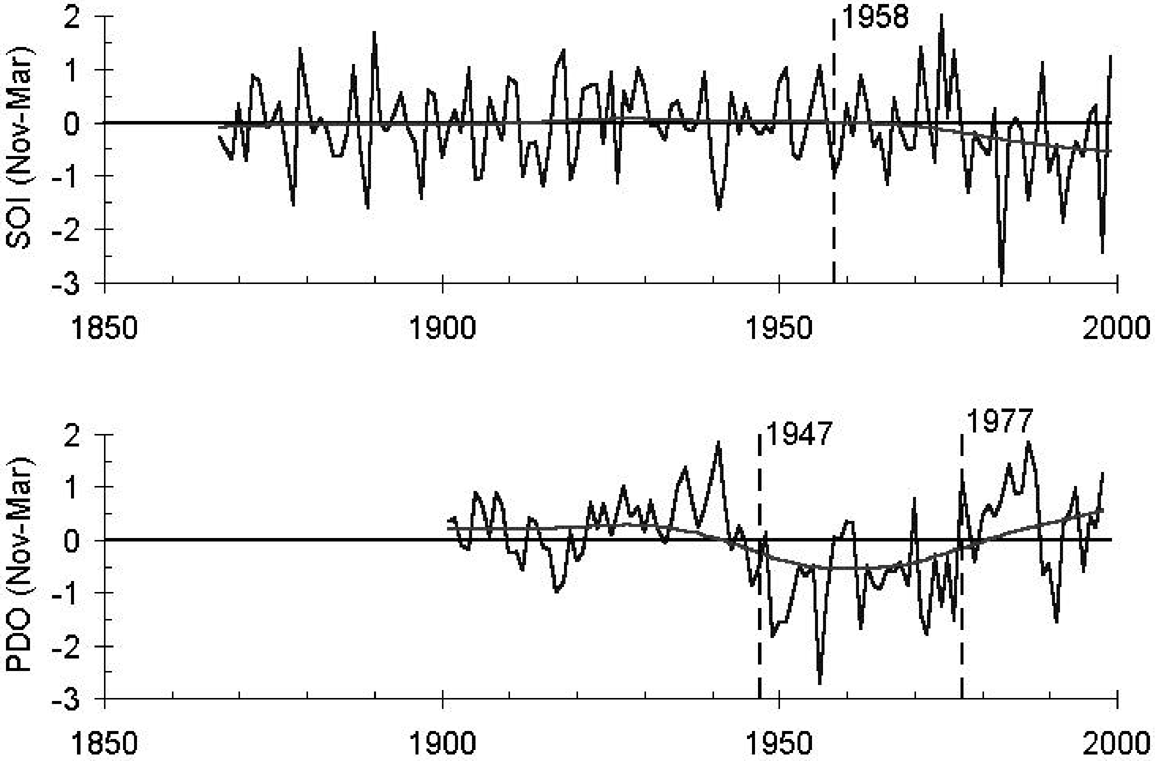

Figure 7. Southern Oscillation Index (SOI) and Pacific Decadal Oscillation (PDO). Smooth lines show multi-decadal variation. For SOI, negative values indicate El Niño while positive values indicate La Niña. For PDO, positive values indicate warm northern Pacific sea surface temperatures while negative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

related 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 Pacific Decadal Oscillation (i.e., El Niño is stronger during positive phases of PDO and La Niña is stronger during negative phases of PDO) (Gershunov and Barnett 1998). Conversely, effects of ENSO are dampened during destructive phases of the Pacific Decadal Oscillation (i.e., El Niño is weaker during negative phases of PDO and La Niña is weaker during positive phases of PDO).

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 percent of winter precipitation falls as snow, with annual totals ranging from 2.4 to 3.3 m (96 to 132 in.). During extremely cold and wet periods, over 2.5 m (100 in.) can fall in a single month. Other Southwest mountain ranges with elevations above 2100 m (7000 ft) typically receive as much as 1.5 m (60 in.) of snow annually. Precipitation in the high mountain areas accumulates as seasonal snowpack (Redmond and Koch 1991). High deserts (e.g., southeastern Arizona) record between 25 mm and 150 mm (1 and 6 in.) 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 and Hill 1974).

Summary Climate Features and Processes

The major feature that sets climate of the Southwest apart from the rest of the United States is the North American monsoon, which is noticeable mostly in Mexico and up into Arizona and New Mexico (Douglas, M.W., et al. 1993; Adams and Comrie 1997). By definition, a monsoon is a distinctive seasonal change in wind direction of at least 120 degrees. This definition applies to the North American monsoon (Tang and Reiter 1984), although this and other monsoons are more commonly associated with the seasonal rains they bring. 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). Western US and northwestern Mexico are characterized by large upland areas in the interior of both countries, the lowlands of the lower Colorado River basin, its neighboring low desert areas, and the coastal lowlands of Sonora and Sinaloa in Mexico. The formation of the monsoon system is aided by the seasonally warm land surfaces in both the lowlands and the elevated areas, in combination with atmospheric moisture supplied by the nearby maritime sources (Mitchell, V.L., 1976; Trewartha 1981; Carleton 1985; Adams and 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 (Figure 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. The 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 and Comrie 1997). Many of the important controlling dynamics of the monsoon occur at the mesoscale (i.e., at a finer spatial resolution than conventional weather

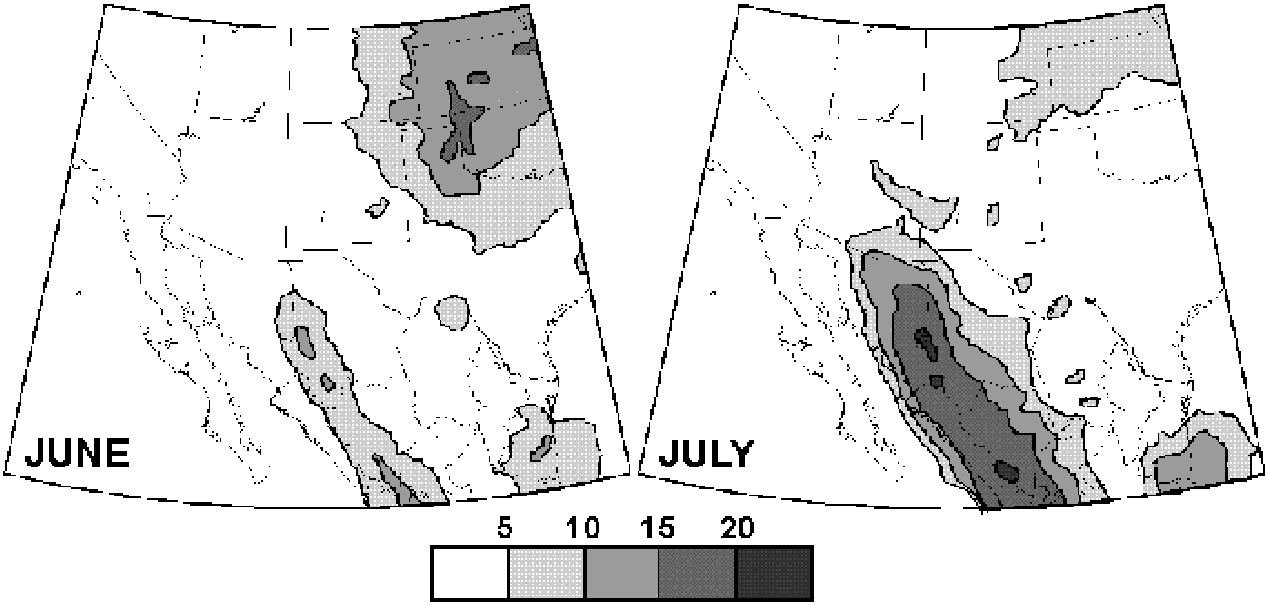

Figure 8. June-July Monsoon Onset. Scale is frequency (% of total hours) of cloud-top temperatures below -38°F, indicating depth of convection (Adams and Comrie 1997).

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.

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 and Lowry 1955). Currently, however, the literature suggests that it is a combination of moisture advection from the Gulf of California, the eastern tropical Pacific Ocean, and the Gulf of Mexico (Adams and Comrie 1997; Higgins et al. 1997, 1998, 1999). 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, M.W., 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 (Adams and Comrie 1997) (Figure 9).

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 and Hill 1974; Tang and 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 and Reiter 1984). Precipitation waxes in the evening hours and wanes during morning hours, a pattern that follows the strong influence of thermal heating (Sellers and 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 and Tang 1984; Balling and Brazel 1987; Maddox et al. 1991; Watson et al. 1994; Maddox et al. 1995). For example, convective activity peaks in early afternoon over the Colorado Plateau, in early evening over southern Arizona and the Sonoran Highlands, and in late evening and/or nighttime in the low desert areas of southern and central Arizona as well as northwestern Mexico and its coastal lowlands.

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). 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 forty percent

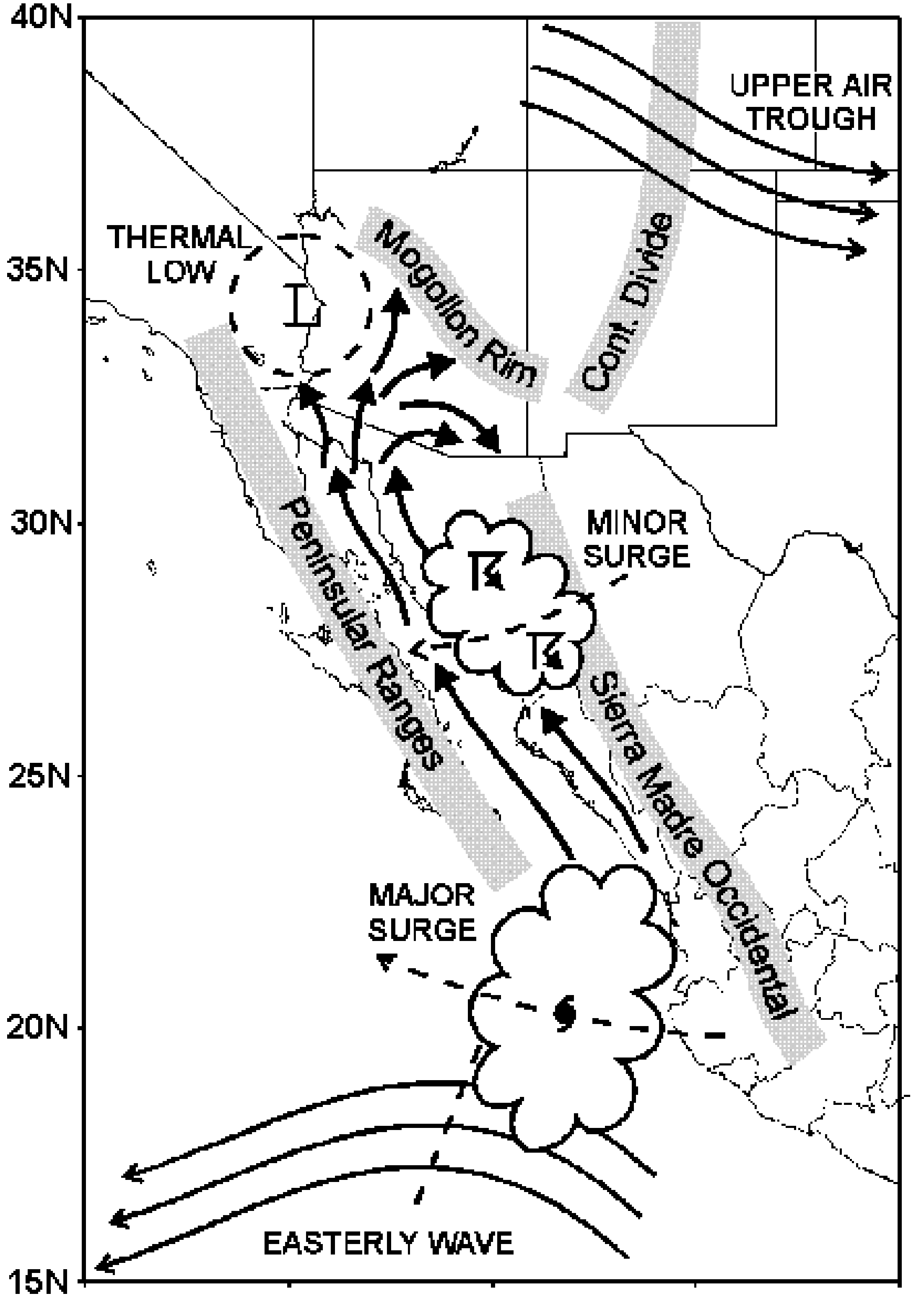

Figure 9. Conceptual Model of Monsoonal Gulf Surge. Moisture from eastern Pacific advectively moves northward through monsoon area to Arizona and new Mexico. Adapted from Adams and Comrie (1997).

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).

Interannual and Decadal Variability

Duration and intensity of the North American monsoon and the associated summer rainfall varies on interannual and decadal time scales (Schmidili 1969; Revelle and 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 and Lowry 1955; Green and 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 and 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. In general, years with early onset of the monsoon typically result in above-average total monsoonal rainfall and vice versa (Higgins et al. 1999).

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.

ENSO Effects on the Southwest Monsoon

There have been contradictory results from research on the relationship between ENSO and total summer precipitation. 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, R.H., and Betancourt 1992). In another study, La Niña events have been associated with below-average monsoon rainfall in Arizona and New Mexico, but El Niño 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 and Sellers 1988; Adams and Comrie 1997).

Tropical Hurricanes

In late summer and early fall, widespread and intense rainfall may occur in the Southwest because of northeastward penetration of tropical cyclones (Webb, R.H., and Betancourt 1992; Adams and Comrie 1997) (Figure 9). For example, in 1998 some late summer rain in Arizona was attributed to tropical storms. In 1951, a hurricane-induced storm brought 310 mm (12 in.) of rain in just five days to central Arizona, with major flood damage occurring along the Salt and Gila Rivers (Sellers and Hill 1974). Increased frequency of El Niño events since 1960 (Figure 7) has enhanced the tendency of tropical cyclones in the Eastern North Pacific Ocean to move into the Southwest (Webb, R.H., and Betancourt 1992).

NATURAL RECORDS OF CLIMATE

General Paleoclimatology

As instrumental meteorological records extend back only about 100-120 years throughout the Southwest, they are of limited utility for studying climate phenomena at the multi-decadal to century or longer time frame. Long-term climate phenomena, such as extended periods of drought or abundant rainfall as well as extended periods of weather with unusually high or low inter-annual 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 single year) extreme climate events based on only 100+ years 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 years. 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 years 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, G.E., 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 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 years of tree-ring research by Douglass and many successors, a dense network of long and well replicated tree-ring chronologies exists in the American Southwest (Figure 10). 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 climate of the Southwest.

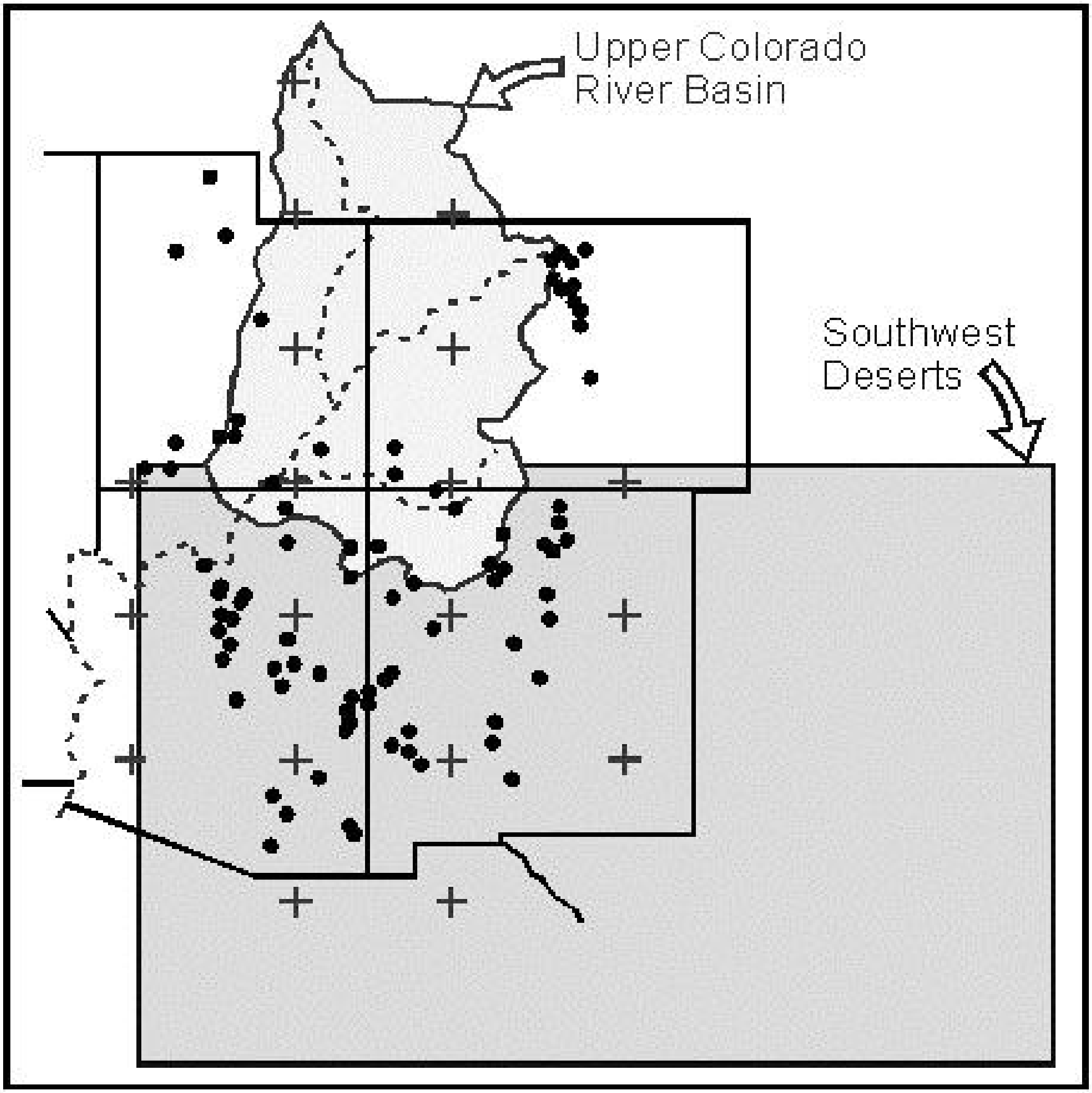

Figure 10. Southwest-Upper Colorado River Basin Site Map. For the purposes of this assessment of climate of the Southwest, the region of interest includes Arizona, New Mexico, and the Upper Colorado River Basin. Dots indicate tree-ring sites, showing an extensive network throughout the Four-Corners states. Crosses indicate grid points of the PDSI reconstruction of Cook et al. (1996). The Southwest Deserts box is the region of temperature reconstruction by Briffa et al. (1992).

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 one 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 two replicate increment cores are collected from a tree, usually from opposite sides of the tree.

Although the individual tree may be considered the sampling unit in dendrochronology, sampling just one 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 hectares 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 (Swetnam et al. 1985; Phipps 1985), the rings of each sample are dated to the exact year of formation with a technique of pattern matching called crossdating (Douglass 1941). In crossdating, 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 (Figure 11), which often relates strongly to moisture availability, (i.e., precipitation in semi-arid regions). Precipitation-ring width relationships are especially notable in the Southwest where narrow rings indicate drought years and wide rings indicate moist years (Schulman 1956). Ring width is measured quickly using a computer-linked linear encoding device along with a microscope (Robinson and 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 latewoods indicate warm years and less dense latewoods indicate cool years (Parker and 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 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 gets 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, autocorrela-

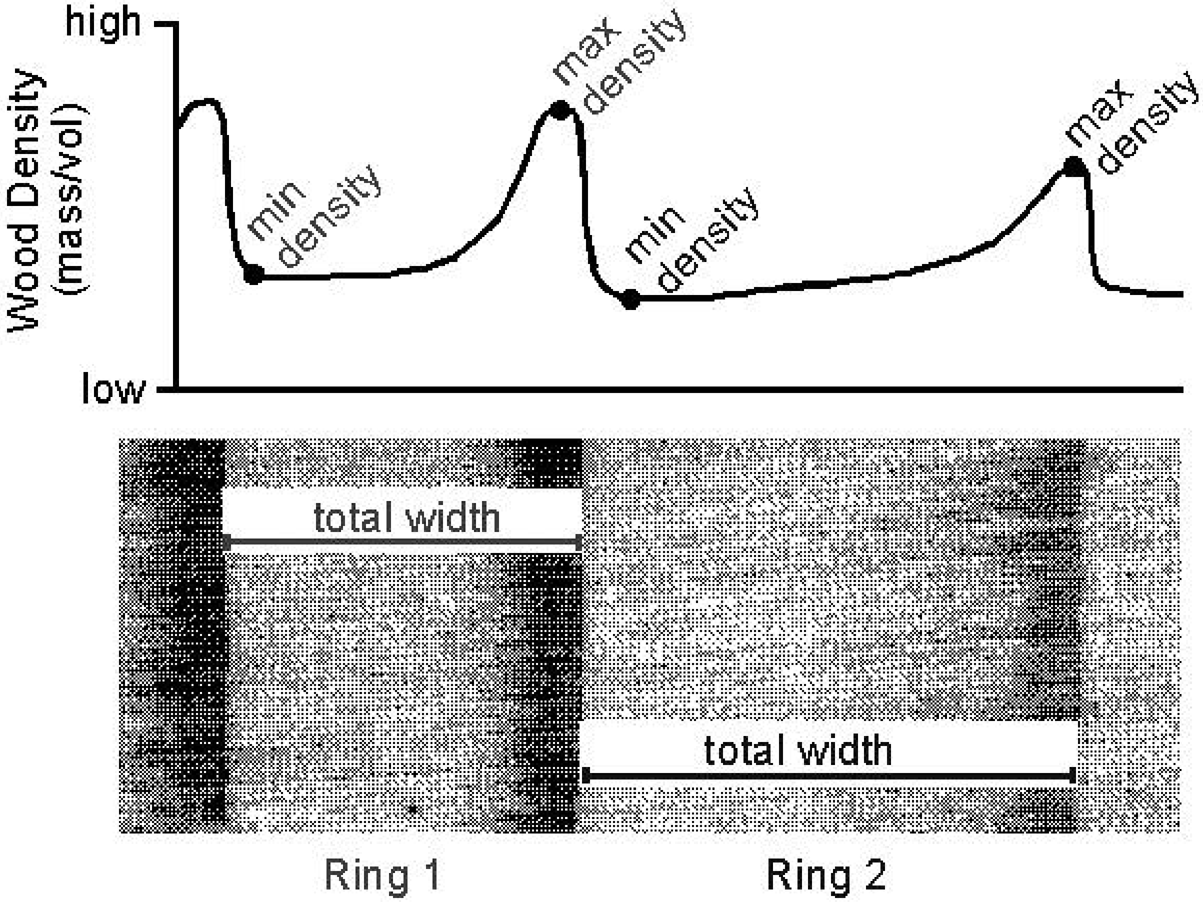

Figure 11. Tree Rings. The image shows two full tree rings, one of which is narrow (Ring 1) compared to the other (Ring 2). In the Southwest, ring-width variation typically corresponds to annual variation in moisture availability. The wood density scan above the image shows that the maximum densities, which associate with the dark latewood 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 latewood density corresponds to annual variation in growing-season temperature.

tion 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 (Figure 10). Consequently, an extensive network of tree-ring chronologies exists with which to reconstruct climate for this entire geographical region (Fritts 1965; Fritts et al. 1979; Fritts 1991; Dettinger et al. 1998).

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) (Figure 11). A commonly used climate variable in paleo-precipitation studies is Palmer Drought Severity Index (PDSI), which is a single variable that is derived from variation in precipitation and temperature and considers various site environmental factors such as soil type (Palmer 1965). As such, 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, June-August PDSI is an intuitively reasonable climate variable for dendrochronological reconstruction. However, a given month's PDSI reflects moisture conditions of several preceding months in addition to that of the given month (Stockton and Meko 1975; Katz and Skaggs 1981) such that summer PDSI reflects 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, 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) (Figure 12).

Dendroclimatic Modeling: Moisture Availability

This section is a summary of analytical methods used by Cook et al. (1996) to reconctruct summer PDSI throughout North America. Because weather stations are not evenly distributed spatially, the information that they contain has been transformed mathematically into a regular grid pattern. In the case of PDSI, each grid box covers 2° of latitude and 3° of longitude (Figure 10). 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 relatively

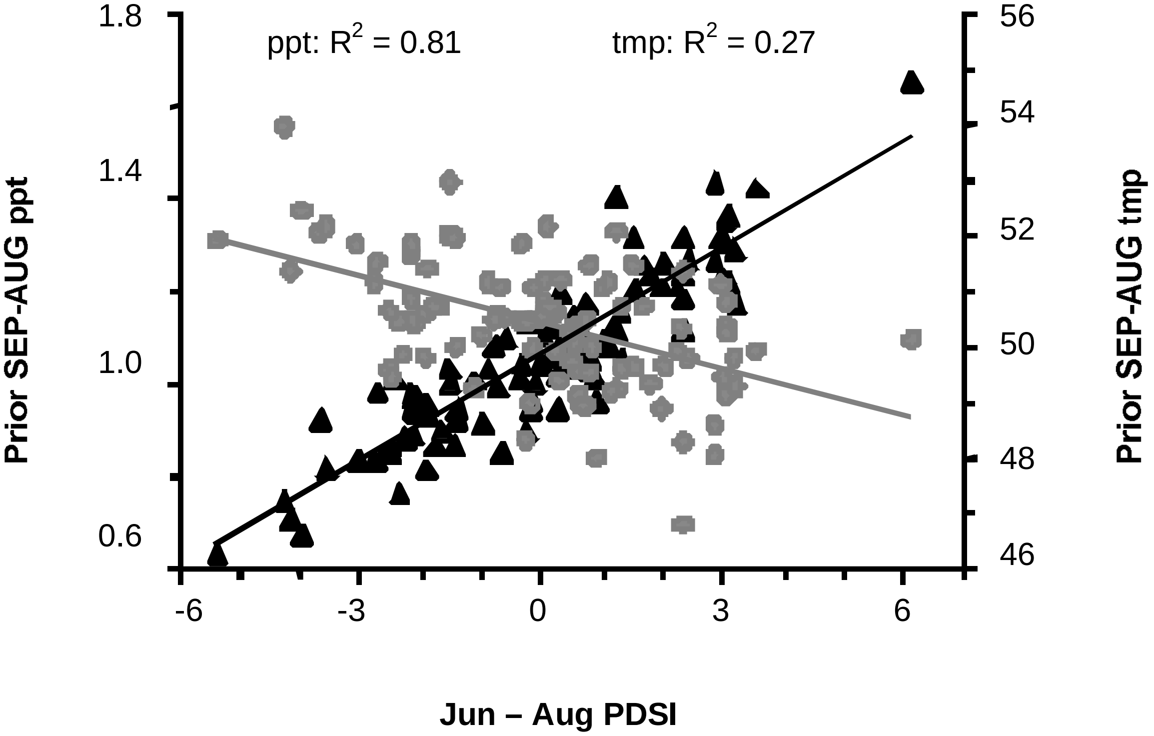

Figure 12. PDSI and Annual Precipitation and Temperature.

weaker in mountainous regions such as the Colorado Rocky Mountains. Just as with the tree-ring chronologies, 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 PDSI for the Southwest.

To dendrochronologically reconstruct Palmer Drought Severity Index, a so-called point-by-point regression technique was used whereby each grid point of 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 350-km radius of the grid point were selected; if that number of sites did not equal or exceed five, then the search radius was expanded until at least five 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.

The average series of reconstructed PDSI of the grid points of the Southwest correlates very highly with the average series of actual PDSI values from 20 meteorological stations located within the Four-Corner states (Figure 13). In general, the two series clearly share a high degree of annual variation, though the amplitude of 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 and Cleaveland 1992), and therefore the long-term reconstruction of PDSI of the Southwest merits close scrutiny as a

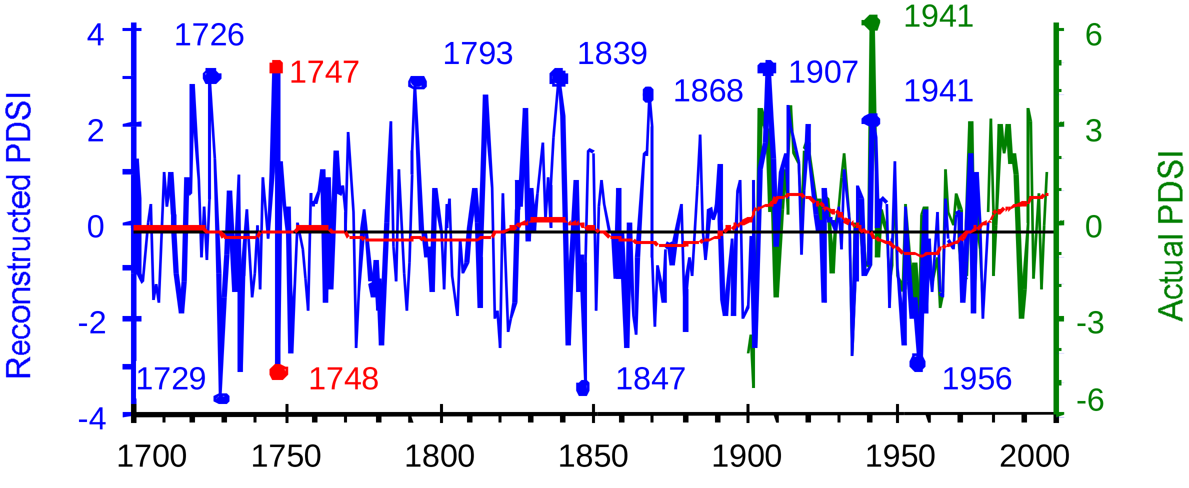

Figure 13. Southwest PDSI. Tree-ring reconstructed PDSI (blue) since 1700 with actual PDSI (green). During the period of overlap (1900 to 1978), the two series correlate strongly but have different ranges (note the different y-axis scales). The reconstructed series shows multi-decadal variation, that has been increasing in amplitude with time since the late 18th century.

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 (i.e., above average temperature increases 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 two 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" (Figure 10).

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 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 from 1951 to 1970.

CLIMATE VARIATION IN THE SOUTHWEST

Extreme Short-Term Climatic Events

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 thirteen episodes of drought and ten episodes with above average precipitation are reported for southeastern Arizona for the years from 1866 to 1961 (Cooke and Reeves 1976). Flooding events that resulted in 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-year average PDSI of below -3.0, was one of the worst 3-year-long periods of below average moisture availability since 1700 (Figure 13) (Meko and Graybill 1995). Other notable 3-year-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 and Betancourt 1998). Conversely, exceptional 3-year periods of above average moisture availability were centered on 1907, 1868, 1839, 1793, and 1726, with a frequency of one to two notable events per century (Stockton and 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 and Betancourt 1998).

As for temperatures, the coolest three-year-long temperature events of the 20th century (1906-1908 and 1964-1966) were exceeded by one reconstructed cool event 1725 to 1727 (Figure 14).

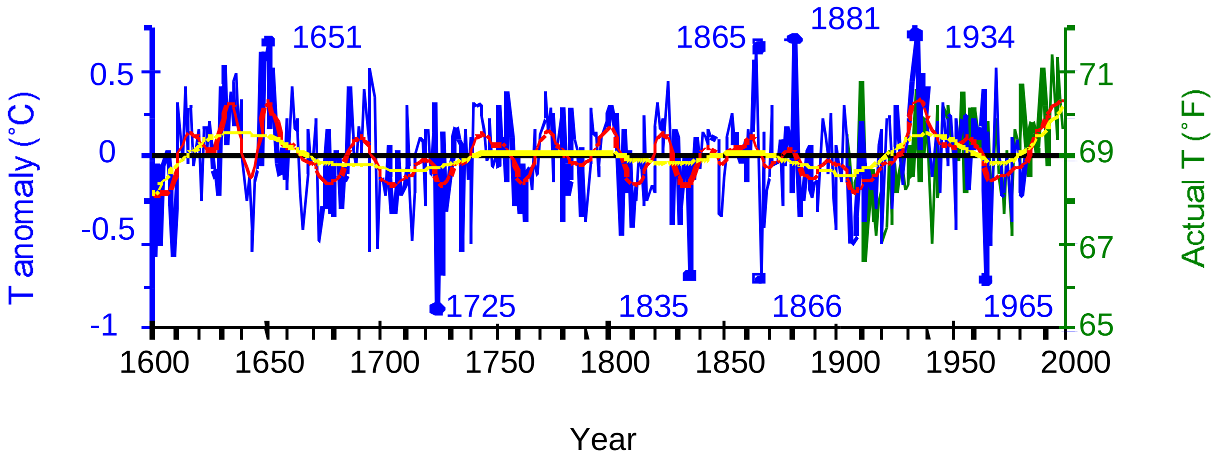

Figure 14. Southwest Temperature. Tree-ring reconstructed temperature (blue) and actual temperature (green). During the period of overlap (1900 to 1980), the two series correlate strongly. Red line shows 20-year-period variation, and yellow line shows multi-decadal-period variation.

The 1800s had two notable cool years in 1835 and 1866. Likewise, the warmest event of the 20th century (1934) was exceeded by one reconstructed warm event in 1651 and equaled by others in 1865 and 1881.

Multi-Decadal Climate Variations

Southwest Summer PDSI (Moisture Availability) Since A.D. 1700

During the 20th century, the Southwest experienced wet years in the early part of the century (1905-30), a mid-century dry period (1942-64), and warm, wet winters and erratic summers since 1976 (Figure 13), as has been shown by others (e.g., Swetnam and Betancourt 1998). The 20-year-long wet period of the early 20th century appears to be unprecedented in the paleoclimatic reconstruction of PDSI back to 1700. However, it was surpassed by a wet period of the early 1600s, as shown by a similar tree-ring reconstruction of PDSI back to A.D. 1000 that is composed of a smaller subset of tree-ring sites (D'Arrigo and Jacoby 1991). This specific climate feature has been noted in much past dendrochronological research of paleoclimate of the Southwest (Stockton and Meko 1975; Meko and Graybill 1995; Smith and 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 (Figure 13), and this feature has also been noted in past dendrochronological research of paleoclimate of the Southwest (Woodhouse and 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 1930-60, when zonal flow was common, appears to be climatically distinct from periods before 1930 or after 1960, when meridional flow and frontal storms were more common (Webb, R.H., and Betancourt 1992). The extended period of below average PDSI from ~1930 to ~1980 is precedented in the paleoclimatic reconstruction of PDSI back to 1700 (Figure 13). Similarly long periods of generally below average moisture availability occurred from 1850 to 1905 as well as from 1770 to 1825. However, other reconstructions back to A.D. 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 and Jacoby 1991).

Several tree-ring chronologies from the Southwest show an unprecedented trend of increasing tree growth beginning in the mid-1970s, possibly as a response to mild, wet winters and springs associated with El Niño events (Swetnam and Betancourt 1998) as well as the prevalence of the warm phase of the PDO that began in 1977 (Figure 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 (Figure 13), then the combined paleo-modern climate record has at least three 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 and Jacoby 1991; Sheppard 1996). In general, multi-decadal variability characterizes the climate changes over the North Pacific and North America from the late 19th century onward (Figure 7). This variability is likely to be an internal oscillation in the coupled atmosphere-ocean system, although it could be modulated by the external solar radiation heating in the present century (Minobe 1997).

This multi-decadal feature is curiously absent in the early part of the reconstruction since 1700 (Figure 13), though it is strong before 1700 in other reconstructions back to A.D. 1000 (e.g., D'Arrigo and Jacoby 1991). Other dendrochronological research has noted that droughts were relatively rare in the Southwest prior to 1800 (Meko and Graybill 1995). Thus, the amplitude of this multi-decadal variation seems to have increased since the 1700s (Fritts 1991, p. 133; Dettinger et al. 1998). Should this pattern persist into the future, then perhaps the American Southwest will next enter an extended period of declining to below average PDSI. Accordingly, this pattern merits further research in search of its cause or combination of causes. Possible natural climatic forcing factors include solar variation (McCormac and Seliga 1979; Shindell et al. 1999), ocean-atmosphere dynamics (Mitchell, J.M., Jr., 1976), and explosive volcanism (Kelly and Sear 1984). Solar variation is known to oscillate at a multi-decadal period, the so-called Gleissberg cycle (Garcia and 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 has yet to be clearly shown.

Another technique for viewing the variability of past climate is to calculate time series of standard deviation centered on some period of time, for example 21 years (Figure 15). The 21-year moving standard deviation of PDSI shows that the Southwest has experienced relatively low inter-annual variability in climate for much of the 20th century. 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. This period of high inter-annual variation is precedented, as the Southwest experienced similar climate variability in the early 1700s. Conversely, the early 1800s was a period of relatively stable moisture availability through time. Indeed, the period from 1794 to 1815 is remarkable for its lack of reconstructed PDSI values greater than +2 or less than –2 (Figure 13) (Swetnam and Betancourt 1998).

Southwest versus Upper Colorado River Basin PDSI

When looking at the separate subregions of the Southwest (Arizona and New Mexico) versus the Upper Colorado River Basin, the high- and low-frequency patterns of variation are similar (Figure 16). 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 ex-

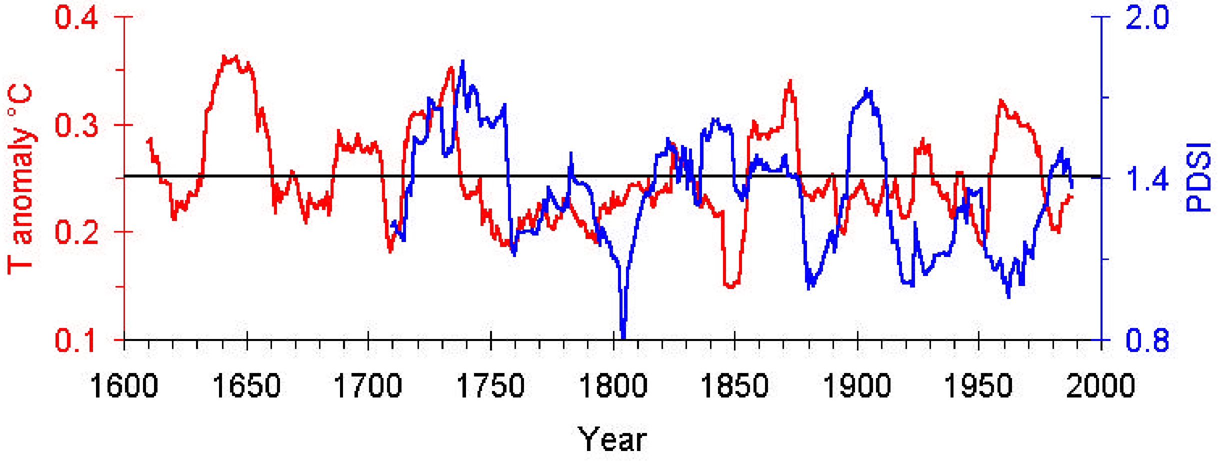

Figure 15. Temporal Variance. 21-year running standard deviations of Southwest PDSI (blue line) and temperature (red line).

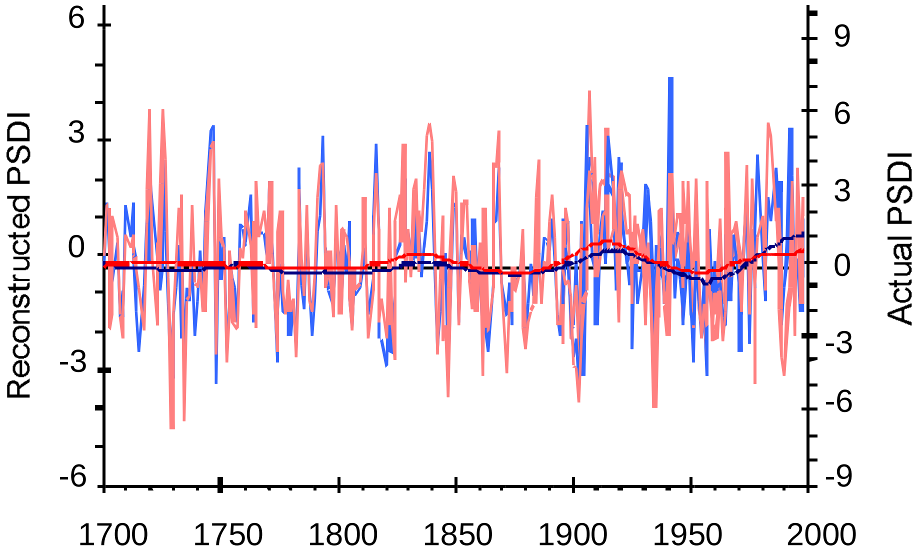

Figure 16. Southwest (blue) vs. Upper Colorado River Basin (red) PDSI. Dark lines track the multi-decadal variation of each long series.

pected because temperatures of the Southwest are higher than those of the UCRB. However, this pattern curiously changed in the last 20 years, 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.

Southwest Summer Temperature Since 1600

The paleo-temperature reconstruction for the Southwest has significant periods of variation at 80 and 20 years (Briffa et al. 1992) (Figure 14). The 1920s and 1930s stand out as unusually warm and have been noted as a dominant feature of the temperature record across the western

U.S. (Bradley et al. 1982). The 20-year-period variation has its highest peak of the entire reconstruction centered on 1935, but two 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).

The multi-decadal variation during the 20th century of cool-warm-cool is precedented by a similar pattern in the 17th century, but it is conspicuously reduced for most of the 18th and 19th centuries, which has also been noted for all of western North America (Fritts 1991, p. 131). The most obvious feature of the multi-decadal variation is the current increase in temperature to an extent unprecedented in the last four hundred years (Figure 14). This feature has been noted even at the global scale (Mann et al. 1998), and this regional pattern of warming merits further research into its cause or combination of causes (Tol and de Vos 1993).

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 (Figure 15). The current period of a high temporal variability since 1955 has been equaled or exceeded three times in the past, 1633-1661, 1715-1737, and 1856-1877.

CONCLUSIONS

Southwest climate may be characterized as semiarid and warm. An important feature of precipitation over most of Arizona and New Mexico is that it has two 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. Winter climate of the Southwest is affected primarily by what happens with easterly 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. ENSO plays a role in winter precipitation, with El Niño events typically resulting in wet winters and La Niña events resulting in dryer 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 multi-decadal. With respect to annual variation, the instrumental record of summer PDSI appears to be typical when compared to that the past 300 years. However, the recent multi-decadal pattern of PDSI shows a strong amplitude. Understanding the cause of this low-frequency variation could be critical in the future, especially if precipitation of the Southwest declines during the early 21st century, as the current trends suggest could happen.

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 improving our understanding of the causes of such temperature variation.

ACKNOWLEDGEMENTS

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APPENDIX I: GENERAL PALEOCLIMATOLOGY

Considering millennial time frames, alluvial stratigraphic records of alternating fine- and coarse-textured sediments reflect hydrologic variation throughout the entire Holocene, or roughly the last 10,000 years (Antevs 1955). However, these records typically are coarsely resolved temporally, dated with a precision of 100 years at best (Litherland and Beukens 1995), and are distributed somewhat sparsely throughout the Southwest (Haynes 1968). Similarly, accumulation of fine sediments with various faunal and, more importantly, floral and pollen assemblages also reflect climate variation throughout the Holocene (Bradley 1985). The fine-sediment paleoclimatic record is also coarsely resolved temporally with a dating precision of several decades, and it too is distributed relatively sparsely throughout the Southwest (Jacobs et al. 1985).

Another interesting type of natural paleoclimate archive are the plant macrofossils (leaves and fruit) collected by pack rats and preserved in their middens. An extensive spatial network of pack rat midden studies exists for the Southwest (Van Devender 1990; Betancourt 1990), but the paleoclimatic record inferred from pack rat midden material is somewhat discontinuous spatially and temporally (Webb and Betancourt 1990). In short, studies of stratigraphic sequences, fine-sediments with preserved pollen assemblages, and pack rat middens with plant macrofossils are not included in this white paper because their particular attributes do not match well with the objective of this assessment, which focuses on climate variation from the annual to multi-decadal or century time scales for the last several hundred to 1000 years.

As with tree rings, ice layers extend throughout the last 1000 years and can be dated precisely to the year. Ice can preserve its original annual resolution given the right set of climate and topographic circumstances (Bradley 1985), and ice typically contains isotopic and other evidence that relates to weather conditions at the time of formation of each layer. Unfortunately, permanent or even semi-permanent ice accumulations are rare in the Southwest. There are only very small semi-permanent ice fields at the highest elevations of Arizona and New Mexico, and ice appearing to be quite old exists in various lava caves of the Southwest, for example in the Candelaria Ice Cave of El Malpais, New Mexico (Dickfoss et al. 1997). However, virtually no useful paleoclimate research has come from ice of the American Southwest; rather, paleoclimatology from ice has been much more productive primarily at high-latitude sites of Greenland (Dansgaard 1985) and Antarctica (Lorius et al. 1985) and at extremely high-elevation sites of Asia (Thompson et al. 1989) and South America (Thompson et al. 1986).

APPENDIX II: 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 one band 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 as a radius from the tree's pith to its bark. To best sample ring growth, at least two replicate increment cores are collected from a tree, usually from opposite sides of the tree. Increment cores are roughly the diameter of a pencil, and the coring process is thought not to unduly harm the trees (Cleaveland 1998).

Although the individual tree may be considered the sampling unit in dendrochronology, sampling just one 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 hectares 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 presence or absence of past injuries.

After several steps of preserving and processing tree-ring samples (Swetnam et al. 1985; Phipps 1985), the rings of each sample are dated to the exact year of formation with a technique of pattern matching called crossdating (Douglass 1941). In crossdating, temporal patterns of relatively wide and narrow rings are matched across samples. An effective way to compare such patterns from trees that may have had different growth rates is to represent the ring-growth variation of each sample on separate strips of graph paper and then compare the graphical representations. In dendrochronology, the graph itself is called a skeleton plot, which has marks to represent primarily the relatively narrow rings (Figure 17). Very narrow rings are indicated with long marks and vice versa, and very wide rings are occasionally marked with a "b" (for big). Once all samples of a site are skeleton plotted, the plots are matched amongst each other or with a previously constructed chronology. When the marks of different skeleton plots match up across samples, then the actual year date of formation may be assigned to each ring.

After crossdating, all dated rings are measured, typically for ring width (Figure 11), which often relates strongly to moisture availability, i.e., precipitation. Precipitation-ring width relationships are especially notable in the Southwest where narrow rings indicate drought years and

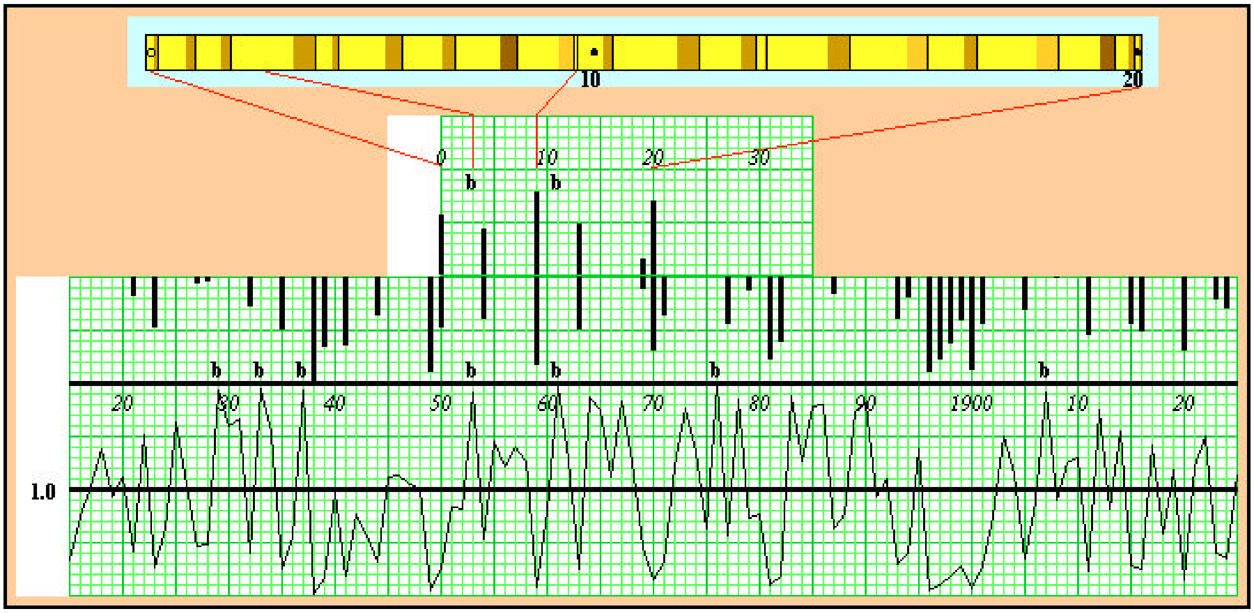

Figure 17. Tree-Ring Crossdating. The annual variation of a tree-ring sample, such as the virtual core above, is first depicted as a skeleton plot on graph paper. Only notable rings, especially the narrow rings, are marked, with the narrower ring, the longer mark; occasional wide rings are marked with a "b," indicating "big". Then, this skeleton plot is matched with either other plots of other samples or with a master chronology previously developed from other samples, as in the figure above. Master tree-ring chronologies are times series of dimensionless indices with a mean of 1.0 where indices above 1.0 represent above average growth and indices below 1.0 represent below average growth. Master chronologies are also represented with skeleton marks, and crossdating is finding the mirror image match of marks of the sample skeleton plot and the master chronology. When the match is found, actual year dates of formation of all rings are found. In this case, this 21-year sample dates from 1850 to 1870, inclusive.

wide rings indicate moist years (Schulman 1956). Ring width is measured quickly using a computer-linked linear encoding device along with a microscope (Robinson and Evans 1980). Additionally, other ring-growth features such as intra-ring wood density are often measured. Temperature-ring density relationships are notable in trees growing in mesic cool environments where dense latewoods indicate warm years and less dense latewoods indicate cool years (Briffa et al. 1992). 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 computationally for possible 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 measurement series is removed from each series. This trend is often best expressed as a negative exponential curve (Figure 18), which is logical biologically because the radial growth of a tree must decrease as the tree itself gets bigger through time (Fritts 1976). The trend is mathematically removed by dividing the actual measured value by the estimated curve value for each year. This step results in a time

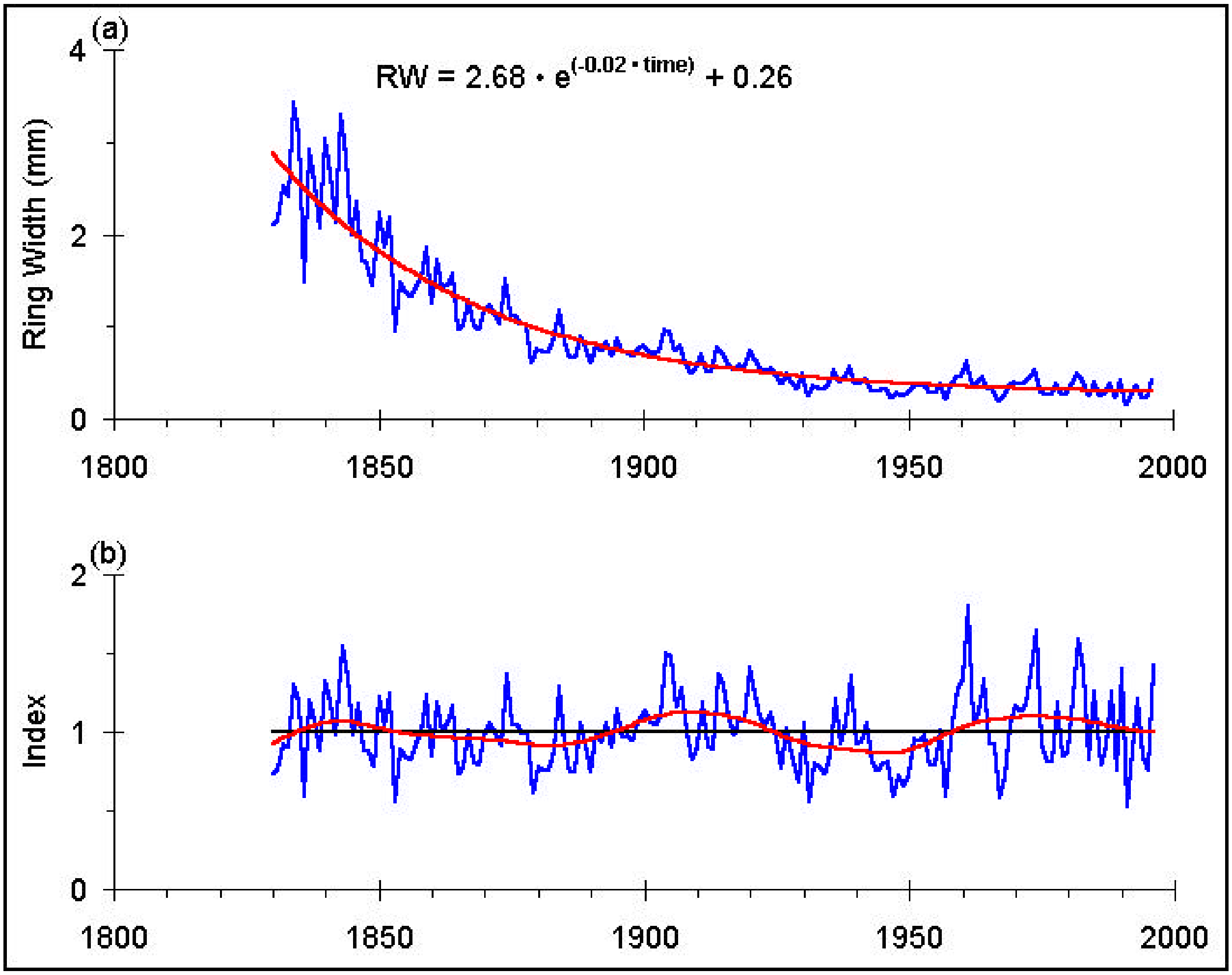

Figure 18. Tree-Ring detrending. The series-length trend of the series of measured ring widths (a) is best modeled with a modified negative exponential curve (red line and equation). The fit-line is divided out of the measured data, resulting in a stationary series of dimensionless indices with a mean of 1.0 (b). Even after this detrending process, low-frequency variation remains at decadal to multi-decadal scales (red line of b).

series of dimensionless indices with a mean value of 1.0. Note that detrending preserves low-frequency growth departures from the mean line of up to one-half the series length, which is multi-decadal in the figure example.

Step 2 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 mathematically removed from a site chronology by fitting a low-order autoregressive model. This single chronology is considered the best representation of ring-growth variation through time for the particular site from where the samples were collected.