Drought and Climate in Arizona:

Top Ten Questions & Answers

Final Report
March 2004

Jenna McPhee, Andrew Comrie, and Gregg Garfin

CLIMAS

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Executive Summary

Arizona's climate is characterized by a high degree of *interannual* (year to year) and *decadal* (decade to decade) variability. In other words the amount of precipitation between successive wet and dry years changes a lot. Interannual fluctuations account for the fact that climatic conditions in Arizona are hardly ever *average* (normal) over space or time. However, due to persistence in Pacific Ocean sea surface temperature conditions, which have a strong influence over the path of storms entering North America, interannual fluctuations in climate can be embedded within multi-year periods during which the duration and intensity of dry or wet conditions remains above or below average. *Droughts*, (multi-year dry periods), are, therefore, a normal and expected phenomenon.

The major multi-year statewide droughts since recordkeeping began over a century ago were in the early 1900s, the 1950s, and from 1998–present. In addition, there have been numerous shorter periods of intense drought (e.g., 1995–1996, 1989–1990), as well as droughts affecting only parts of the state. The intensity and location of major statewide droughts can also change during the course of a drought. Droughts covering more than half of the state have occurred in every decade but one over the last century. Generally, the driest parts of the state exhibit the greatest interannual variability in precipitation. Wetter parts of the state, however, can exhibit substantial interannual variability. Moreover, due to high interannual variability in precipitation, it is not unusual for one or more relatively wet years to occur during an otherwise prolonged drought.

Arizona's precipitation is characterized by two precipitation peaks each year; winter precipitation is produced primarily from large frontal systems moving over the Southwest, whereas summer precipitation results largely from thunderstorms within the North American monsoon circulation. These processes are almost entirely independent; in other words rarely do one season's conditions predict the conditions of the following season. Variations in winter precipitation are linked to the El Niño-Southern Oscillation (ENSO), a persistent Pacific Ocean circulation that recurs every two to seven years. The link between Arizona winter precipitation and ENSO is stronger for the La Niña phase, which is characterized by cool central Pacific sea surface temperatures (SSTs) and dry winters in Arizona, than for the El Niño phase, characterized by warm central Pacific SSTs and sometimes wetter Arizona winters.

There is no persistent long-term upward or downward trend in precipitation during the last century. However, there are 20–30 year periods characterized by relatively dry or wet conditions in Arizona. According to the best research available, these long-term dry and wet periods are caused by persistent, long-term changes in Pacific Ocean SSTs. These persistent 20–30 year regimes in Pacific Ocean circulation operate in a manner that tempers ENSO variations in order to produce multi-decade periods of relatively wet or dry conditions in Arizona.

Introduction

The Southwest is known for its diverse landscapes and semiarid climate. The frequent occurrence of extreme hot and dry conditions, such as drought, is a normal part of the region's climate. Following several years of below-average precipitation, Arizona faced extreme drought during the 2002 water year (i.e., October 2001–September 2002) the driest water year for many parts of the state. Impacts included 629,876 acres lost to wildland fire in 2002, water supply shortages, vegetation and wildlife mortality, and economic losses in the ranching, agriculture, and tourism sectors. As a result of these impacts, Arizona Governor Janet Napolitano created the Governor's Drought Task Force (GDTF) by executive order in March 2003, and empowered it to create short- and long-term drought mitigation and response plans within one year**.** Arizona is the 36th state to develop a state drought plan in the United States.

The information presented here highlights the findings of a drought history study in support of GDTF activities, such as determining triggers for drought mitigation and response actions, based on observed hydroclimatic and other information. The material is intended to provide the relevant climatology background for non-specialists, and it is presented in a top ten or frequently asked question format. The questions and answers cover the major climate-related aspects of drought including long-term averages, seasonality, interannual and long-term spatial and temporal drought variations, extremes, and causes of climatic variability.

The answers to each question include bulleted **Quick Answers** followed by a concise explanation of more detailed information. Example figures are presented within the text.

Data and Methods

We analyzed precipitation-related data for each of the seven NOAA climate divisions for Arizona, covering the period of record from 1895–2002. We used monthly precipitation data presented as *water year* (October–September totals) and Palmer Drought Severity Index (PDSI) data from the National Climatic Data Center (http://www.ncdc.noaa.gov). The monthly precipitation data was broken down into water years (Oct–Sept; 1896–2002) and the seasons of winter (Nov–Apr; 1896–2002) and summer (Jul–Sept; 1895–2002). We computed the Standardized Precipitation Index (SPI), an objective measure of drought that has garnered the endorsement of many in the disciplines of drought and climate analysis, using software from the National Drought Mitigation Center (http://www.ndmc.unl.edu). The Southern Oscillation Index, a measure of the strength and duration of the El Niño-Southern Oscillation phenomenon, was obtained for the period of January 1895–July 2002 from the NOAA Climate Diagnostics Center (http://www.cdc.noaa.gov).

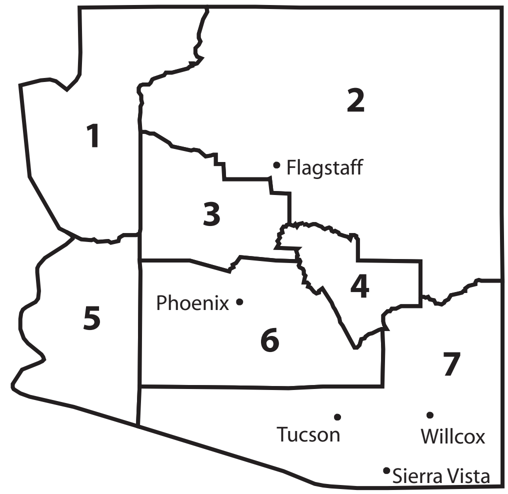

Figure 1. Seven Arizona climate divisions.

We occasionally refer to *correlation*, which is a statistical measure of the strength of linear relationship between two sets of data. The correlation coefficient, *r*, is used to show the degree of correlation; r values range between –1.0 and +1.0. A value of –1.0 means that when one variable increases, the other decreases; whereas, a value of +1.0 means that when one variable increases, the other variable also increases. For example, r = 0.80 for the correlation between precipitation in two regions of Arizona means that most of the time when precipitation in one region increases in a particular year, it also increases in the other region in that year; likewise r = 0.80 would denote that when precipitation decreases in one region in a particular year, it usually decreases in the other region in that year.

Climate divisions, as shown in Figure 1, are regions within a state that are "reasonably homogenous with respect to climatic and hydrologic characteristics" (Sheppard et al. 2002). However, particularly in Arizona, climate divisions are several hundred miles across, and they are characterized by great variation in topography; many have arbitrary or political boundaries, such as county lines. The divisional data represent an average of the observations reported by the many weather stations within that division. These data provide a shorthand method for representing climate variations over large regions, and are used as a baseline unit of analysis in many expert assessments, including the U.S. Drought Monitor.

The Palmer Drought Severity Index (PDSI) and the Standardized Precipitation Index (SPI) are two indices that are used to measure drought conditions. In short, the PDSI combines temperature, precipitation, and other factors to index medium-to-long-term variations in soil moisture. The SPI is focused solely on precipitation for user-selected periods of time (e.g., 12 months) in order to evaluate precipitation accumulations and deficits in a way that allows for direct (standardized) comparison between different climate regions. In both indices, positive values indicate wet conditions and negative values indicate dry conditions. The PDSI uses a subjective scale for classifying drought; values between –2.0 to –2.9 are considered to represent moderate drought, –3.0 to –3.9 for severe drought, and below –4.0 for extreme drought. The SPI objectively defines drought by values lower than –0.99. Values between –1.00 to –1.49 represent moderately dry conditions, –1.50 to –1.99 is severely dry, and below –2.00 is extremely dry.

1. What is the long-term precipitation average?

There is a broad range of water year precipitation totals between the climate divisions. Arizona's wettest climate division (CD 4; Gila County) receives 18.8 inches of precipitation per water year whereas the driest division (CD 5; Yuma and La Paz Counties) receives only 4.6 inches per year (Figure 2). This large variation in average precipitation reflects the differences in elevation, topography, and location. Mountain ranges have a large influence on precipitation, as they can enhance precipitation by forcing moist air upward (inducing windward side precipitation or summer *convection* [thunderstorms]), or they can block precipitation on their leeward aspects. In general, higher elevations receive more precipitation than lower elevations. The range in precipitation across Arizona climate divisions is evident in Figure 3. However, despite this large spread in annual rainfall, the interannual variations are quite similar between the divisions. For example, Figure 3 shows several multi-year sequences, such as 1940–1942, during which all Arizona climate divisions received below-average precipitation in 1940, above-average precipitation in 1941, and below-average precipitation in 1942.

Even though topographic differences play a major role in spatial patterns of precipitation, temporal variations in Arizona climate are mainly influenced by hemispheric atmospheric circulation patterns. Overall, the Southwest is under the influence of the North

Quick Answers

- Large spread in average annual water year (Oct–Sept) precipitation between climate divisions (CDs):
    - Wettest division – CD 4 (Gila County): 18.8 inches/water year.
    - Driest division – CD 5 (Yuma and La Paz Counties): 4.6 inches/water year.
- Differences in precipitation because of elevation, topography, location:
    - Higher elevations receive more precipitation than lower elevations.
    - *Rainshadow* effects (i.e., the tendency for the leeward sides of mountain ranges to receive less precipitation than the windward sides), mountain induced *convection* (i.e., rising atmospheric motion that produces, for example, towering summer thunderclouds), and proximity to *moisture sources* all affect how much rainfall a particular area receives.
- Even though there are significant differences in the amount of precipitation each climate division receives, the year-to-year variation is similar in most divisions, such that, generally, wet years match wet years in most of Arizona's climate divisions and dry years match dry years.
- The climate of the Southwest is controlled by the interactions between short- and long-term atmospheric circulation patterns, and variability in climate is a consequence of shifts in these patterns.

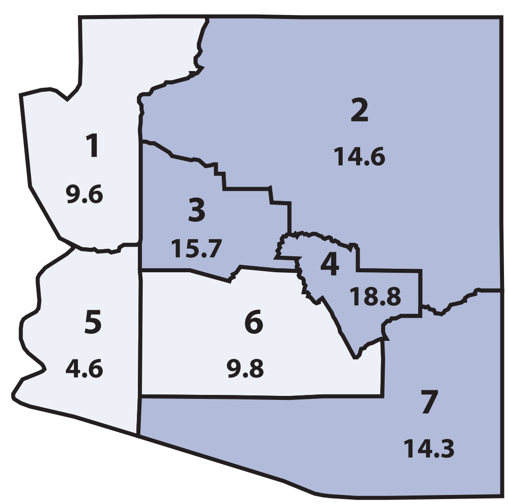

Figure 2. Water-year precipitation average (inches) for all seven Arizona climate divisions for the period 1896–2002.

Pacific and Bermuda high pressure systems, which give rise to low annual precipitation, warm temperatures, and clear skies for much of the year. Winter precipitation in the Southwest comes from the frontal storms of the mid-latitudes, while summer precipitation arrives via the thunderstorms of the North American monsoon, and occasional tropical storms. Seasonal and year-to-year changes in the north-south and east-west positions of these circulation patterns, their intensity, as well as the interactions between these features and long-term shifts in ocean circulation produce seasonal and annual climate variations (Sheppard et al. 2002).

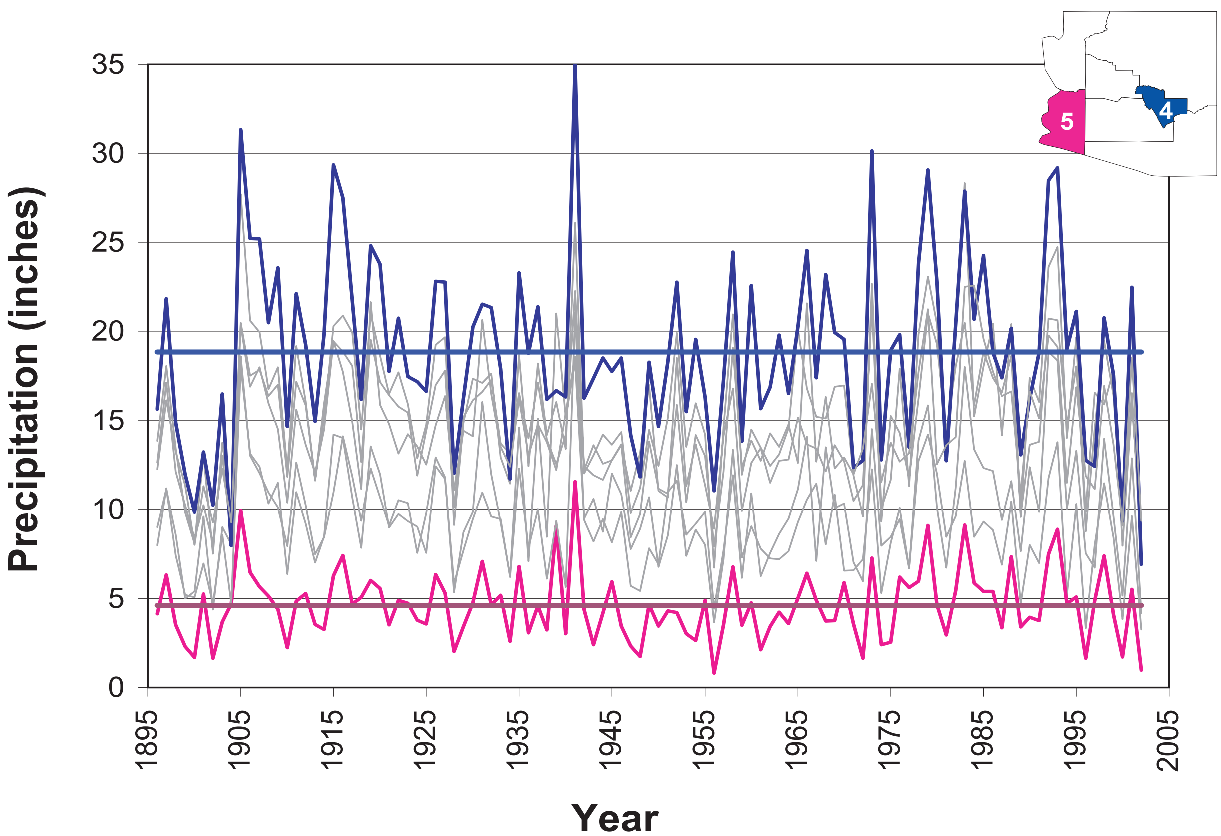

Figure 3. Water year precipitation for all Arizona climate divisions. The average water year precipitation for CD 4 (Gila County; blue; top line) and CD 5 (Yuma and La Paz Counties; pink; bottom line) is plotted (thick lines).

2. What is the historic record of drought over the past century?

In order to understand the future of drought, we must first understand drought history. Using water year precipitation, PDSI, and SPI data for the period of 1896–2002, we analyzed the temporal and spatial variation of drought across the Arizona climate divisions. Our analyses show three major statewide droughts, as follows: the late-1890s through the early 1900s, the late 1940s through the mid-1960s (henceforth, *the 1950s*), and the late 1990s to the present. Figure 4 clearly shows these droughts as well as several additional dry years of shorter duration.

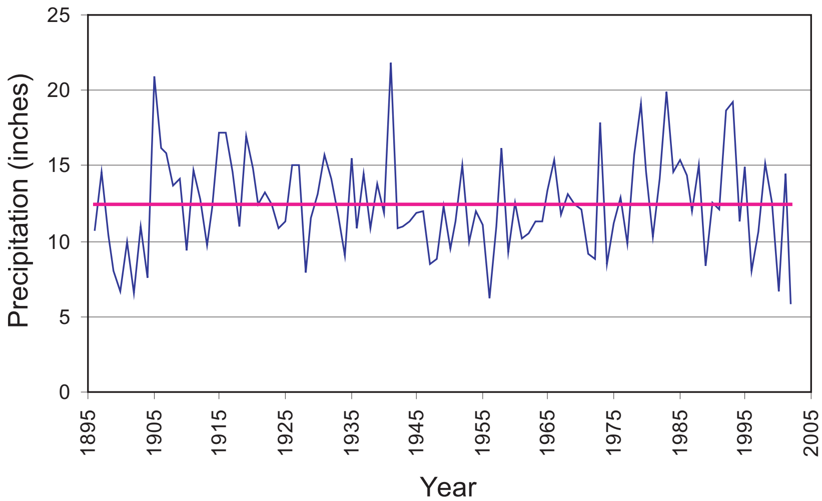

Figure 4. Arizona statewide water year precipitation, 1896-2002. The pink line shows long-term statewide average precipitation (12.5 inches).

The driest water year on record for each division reflects two of these extended dry periods, the 1950s and current drought (Figure 5). These individual dry water years are characterized by divisional precipitation totals that range from 17–56 percent of average. By averaging the amount of rain in each climate division, the average rainfall for Arizona is 12.5 inches. According to the Western Regional Climate Center, the area-weighted annual average in the state is 13.1 inches. Figure 6 highlights Arizona CD 6 (Maricopa and Pinal Counties) and shows the substantial year-to-year precipitation (6a), 12-month SPI (6b), and PDSI (6c) variation that is characteristic of the entire state. During times of below-average precipitation, the PDSI and SPI values are simultaneously low indicating a dry period; thus, PDSI and 12-month SPI are faithful recorders of drought on a time scale of approximately one year. Perhaps the most noticeable feature among these graphs is the extensive and sustained dry episode at the turn of the 20th century (1898–1905, circled in red), when conditions remained below average for eight consecutive years.

Quick Answers

- Drought is a normal part of Southwestern climate variability and has occurred throughout Arizona.
- Instrumental climate records show three major statewide droughts:
    - late 1890s to early 1900s
    - 1950s
    - late 1990s to present.
- Precipitation, PDSI, and SPI records all show substantial year-to-year variability.
- The extent of drought varies across the seven climate divisions.

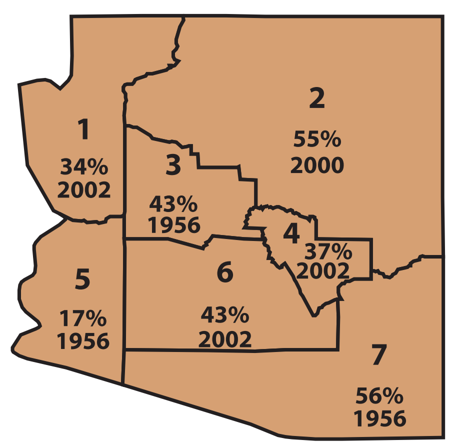

Figure 5. Driest water year on record for Arizona. The value represents the percent of average precipitation in a water year in each climate division.

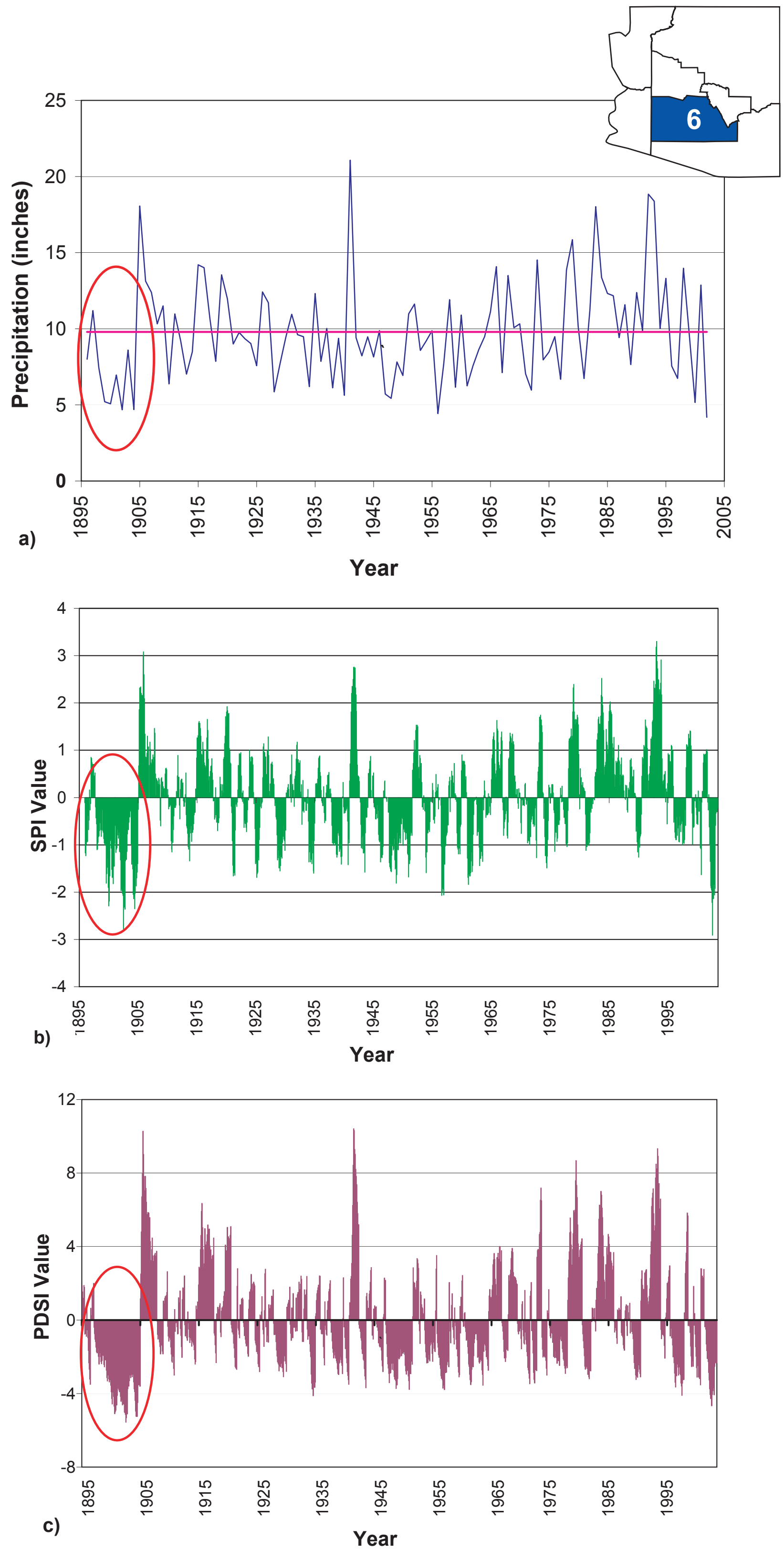

Figure 6. Different measures of drought for Arizona CD 6 (Maricopa and Pinal Counties): (a) annual water year precipitation plotted with average, (b) SPI 12-month, (c) PDSI. The red circles highlight the sustained drought at the turn of the 20th century.

3. How does drought intensity change with drought duration?

Drought *intensity* refers to the magnitude of dryness, regardless of *duration* (the length of a dry period). Drought *severity* is somewhat less specific, but it generally refers to a combination of intensity and duration. The nature of drought in terms of intensity and duration (and thus severity) varies somewhat across the seven Arizona climate divisions. To illustrate this, we used the percent of average precipitation to identify the 5- and 10-year periods that exhibited the most consistently below-average precipitation among the climate divisions (Figures 7 and 8).

The driest conditions for each climate division do not always occur during the same 5- or 10-year period; for example the driest 10-year period in CD 5 is 1947–1956, whereas the driest 10-year period for CD 1 is 1993–2002 (Figure 7). Major dry periods, however, *usually* exhibit below-average precipitation across the state. Progressive changes in drought status sometimes vary between CDs (e.g., CD precipitation during the early 1960s and late 1980s in Figure 3), probably due to changes in winter storm track (i.e., during some years storms may pass further north or south) and the extent of the North American monsoon (e.g., the north-south and east-west extent of the monsoon varies depending on a complex array of factors, including winter snowpack and Pacific and Atlantic Ocean temperatures). Spatial and temporal differences in precipitation variation are explained further under questions 4 and 5.

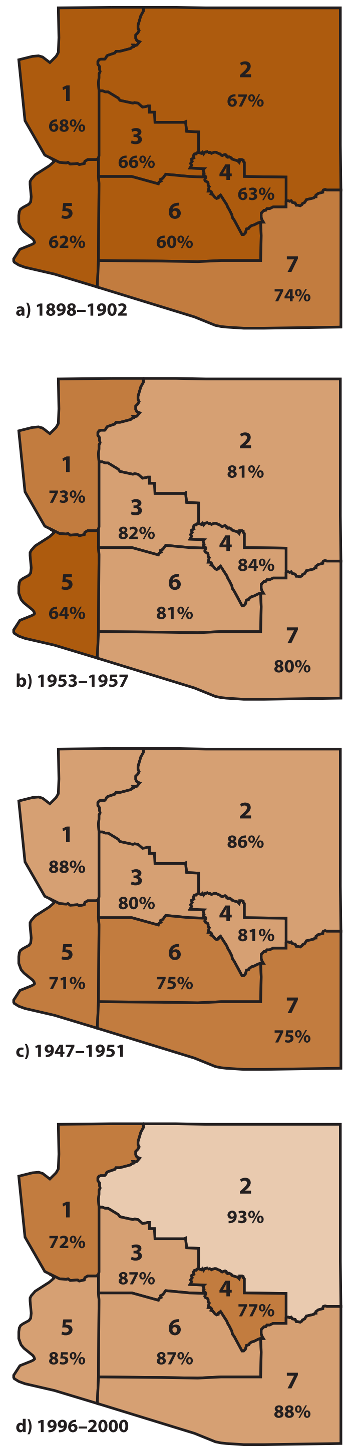

Figure 7. Top 4 driest 5-year annual precipitation periods, showing percent of long-term average precipitation: (a) 1898–1902, (b) 1953–1957, (c) 1947–1951, (d) 1996–2000.

Quick Answers

- The driest 5- and 10-year periods differ somewhat among the climate divisions.
- The severity of drought conditions also varies during different time periods.

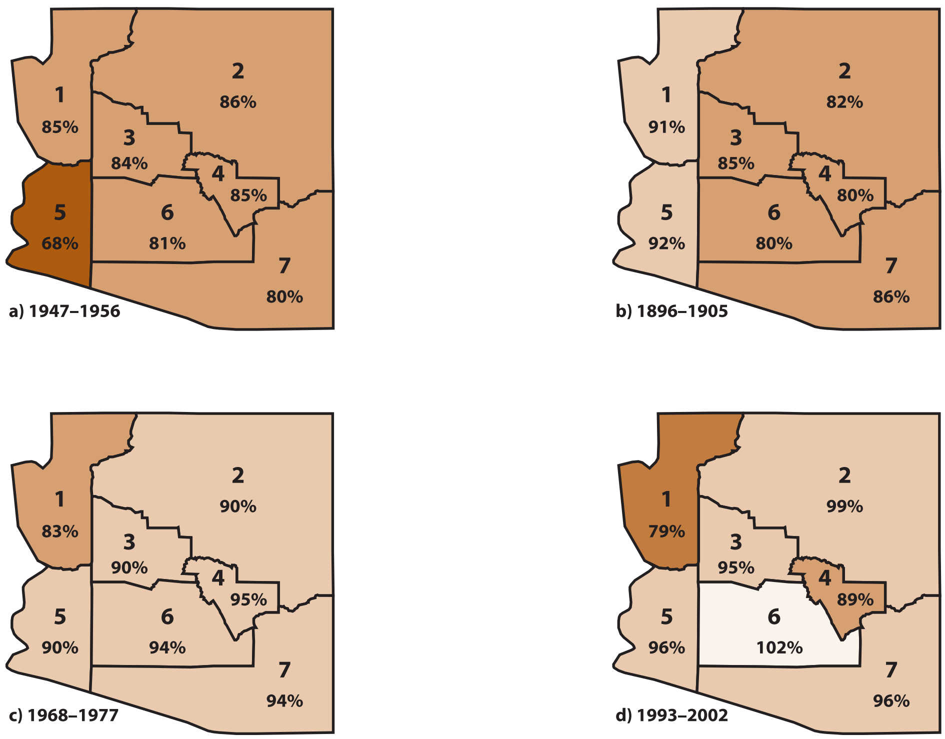

Figure 8. Top 4 driest 10-year periods, showing percent of long-term average precipitation. (a) 1947–1956, (b) 1896–1905, (c) 1968–1977, (d) 1993–2002.

4. Has precipitation variability changed over time?

The 21-year standard deviation (STDEV) and coefficient of variation (CV) for each climate division were used to interpret precipitation variability over the period of record. STDEV and CV are linear statistical measures of temporal variation within the data. The STDEV is calculated by obtaining the arithmetic average of the data and then measuring how much each value differs from that average. The CV is calculated by dividing the STDEV for a climate division by the average for that climate division. CV allows for more direct comparison between climate divisions with very different average precipitation.

Both the STDEV and CV are greater at the beginning, middle, and end of the 20th century and coincide with prolonged dry periods (Figures 9 and 10); in other words, precipitation is generally more variable during dry periods. On a *decadal* (10-year) time scale, precipitation varies between 20–50 percent of the average (Figure 10). For example, the CV remains close to 50 percent of average during the 1950s drought across all climate divisions. This degree of variation is quite high. An additional fact that comes to light from reviewing precipitation variability is that it is not uncommon for a single wet year or a couple of wet years to fall within an extended dry phase (Figure 11).

Quick Answers

- During the last 100+ years, precipitation has been highly variable from year to year.
- The degree of year-to-year precipitation variability changes over time.
- During prolonged dry periods, precipitation variability is greater.
- It is not uncommon for a single wet year or a couple of wet years to occur within an extended dry period.
- An example of a sustained dry period is the early 1900s, when water year precipitation remained below average for eight consecutive years (1898–1905).

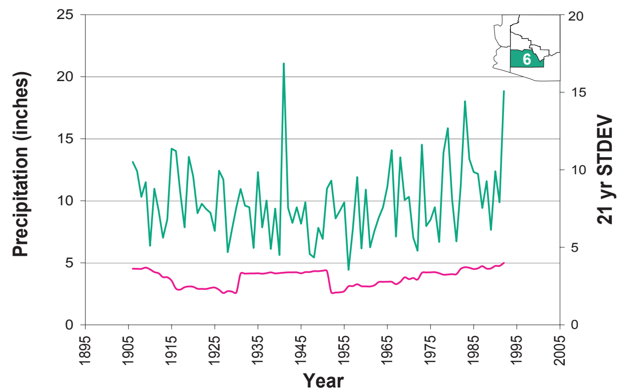

Figure 9. Arizona CD 6 (Maricopa and Pinal Counties) 21-year precipitation standard deviation (pink; bottom line) shown and water year precipitation totals (green; top line).

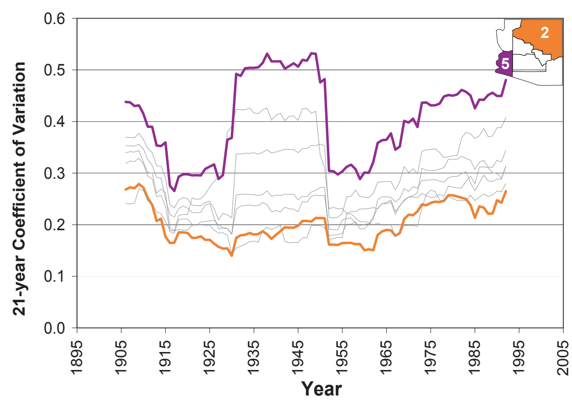

Figure 10. 21-year coefficient of variation (STDEV/mean) for all Arizona climate divisions. The CDs with the greatest (CD 5) and lowest (CD 2) variation are highlighted in pink (top line) and orange (bottom line), respectively.

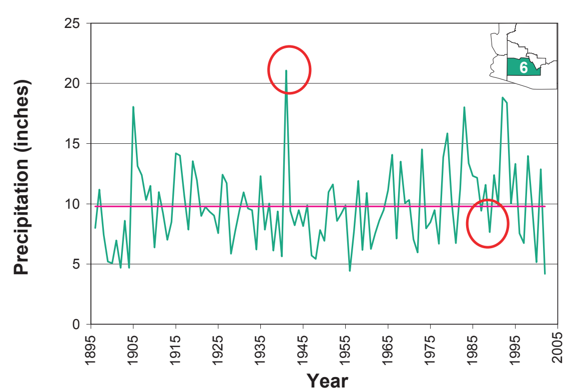

Figure 11. Arizona CD 6 water year precipitation (green line), red circles denote a dry year in a wet period (1989) and a wet year in a dry period (1941), and the pink line represents long-term CD 6 average precipitation (9.8 in.).

5. Has precipitation variability changed over space?

Precipitation totals differ across Arizona (Figure 3); the lowest precipitation totals are found in the low-lying areas of Arizona's western deserts, which are in the *rainshadow* of California and northern Mexico's coastal mountains. The state's highest precipitation totals are found along the Mogollon Rim, where high elevation strongly increases precipitation totals. Even though annual precipitation totals differ across the state, precipitation variability from year-to-year is generally quite similar. For example, dry and wet years correspond quite well between CD 4 (Gila County) and CD 5 (Yuma and La Paz Counties) (r = 0.80 for the period 1895-2002), despite a 14.2 inch difference in total annual precipitation and several hundred miles between the two divisions (Figure 12).

The most compelling example of similarity in precipitation variation among Arizona's CDs, however, is during the extreme precipitation years (very dry or very wet), when virtually all of Arizona experiences these related conditions simultaneously. For example, the entire state received above-average precipitation during the 1942 water year (October 1941–September 1942), and the entire state received below-average precipitation during the 1956 water year (October 1955–September 1956) (see Figure 3).

In contrast to strong similarity in the year-to-year geographic variation of precipitation, there can be geographic differences in drought *intensity* during prolonged drought. During the late-1940s to mid-1950s drought, southern Arizona experienced drier conditions then the rest of the state (Figures 7 and 8). Similarly, drought was more intense in northwestern Arizona (CD 1, Mohave County) than the rest of the state during the 10-year periods 1968–1977 and 1993–2002 (Figure 7c); drought was more intense in CD 4 (Gila County) during the period 1996–2000 than in adjacent parts of the state (Figure 8d). Perhaps the most notable example of geographic variation in precipitation and drought has been during the most recent 10 years (1993–2002), which is the driest 10-year period for record for CD 1 (Mohave County); during this same 10 years, CD 6 (Maricopa and Pinal Counties) had slightly above-average precipitation (Figure 7d). During an extended dry period, drought intensity can vary over space and time; for example, as the 1950s drought progressed, conditions ameliorated somewhat in southern Arizona and simultaneously conditions worsened somewhat in northern Arizona (Figure 8c and 8b).

Quick Answers

- Even though Arizona precipitation is characterized by different annual precipitation totals across the state, year-to-year precipitation variations are quite similar across the state.
- For the most part, a wet year in one part of the state is likely to be a wet year throughout the state; the same goes for dry years; this is especially true for extremely wet and extremely dry years.
- Long-term drought varies in intensity over time and across the state; for example, during the 1950s drought, southern Arizona experienced drier conditions than the rest of the state.
- It is common for the regions of Arizona that receive the lowest annual precipitation to have the highest year-to-year precipitation variations; however, the parts of the state that receive the highest annual precipitation do not necessarily have the lowest year-to-year precipitation variations.

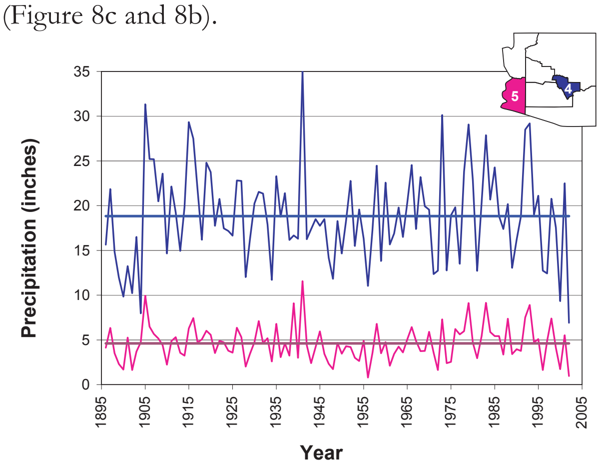

Figure 12. Water year precipitation for Arizona CD 4 (blue; top line) and CD 5 (pink; bottom line). The long-term precipitation average for each division is also shown (straight line).

6. How often is the entire state dry?

An important aspect of understanding the climatology of Arizona drought is to determine how often drought extends throughout the entire state, as opposed to when drought affects only part of the state. We found that there were 14 years when all seven climate divisions received below 85 percent of average water year precipitation (Table 1). The entire state experienced exceedingly dry conditions (less than 75 percent of average precipitation) during the following five years: 1900, 1902, 1956, 2000, and 2002 (Figure 13). These five years occurred during the three major drought periods of the last 107 years.

Table 1. Years when the water year precipitation was less than 85 percent of average for all seven climate divisions.

Years all 7 Climate Divisions below 85%		
1899	1928	1974
1900	1947	1989
1902	1950	1996
1910	1956	2002
1913	1971	

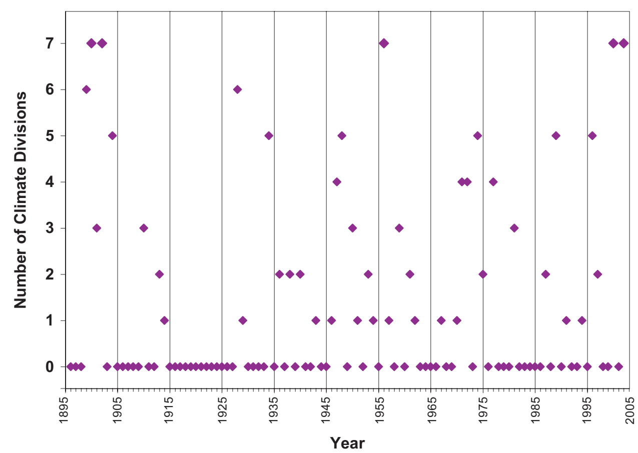

Figure 13. Number of Arizona climate divisions that received less than 75 percent average water year precipitation. The five red circles at top indicate the years when all climate divisions were simultaneously unusually dry (1900, 1902, 1956, 2000, and 2002).

Quick Answers

- All seven Arizona climate divisions were drier than 75 percent of the average water year precipitation occur during the following years:
    - 1900, 1902, 1956, 2000, and 2002.
    - these years occurred in the midst of the three major statewide droughts.
- During 14 years of the record all seven divisions fell below 85 percent of the average water year precipitation.
- There are many years where only 1 or 2 divisions received significantly below-average precipitation.

7. Are there differences in summer and winter drought?

Arizona has two seasonal precipitation peaks, one in winter and one in summer. However, these two seasonal precipitation regimes are the result of different atmospheric phenomena (Sheppard et al. 2002). Winter precipitation is generally associated with relatively long-lived frontal systems that approach Arizona from the west, coming off the Pacific Ocean. The North American monsoon is the major source of summer precipitation; the monsoon circulation, which brings short-lived summer thunderstorms, comes from the south, and precipitation results from *convection*, or rising motion, as warm moist air is lifted high in the atmosphere. Pacific Ocean tropical storms can also influence Arizona warm season rainfall. Nevertheless, it is important to note that summer precipitation is much less effective than winter precipitation in recharging soil moisture and water supplies. This is due chiefly to two factors: (1) summer precipitation is often very intense, falling at high rates in short periods of time over discontinuous areas, the water sometimes runs off the surface rather than sinking deep into the soil, (2) high summer temperatures cause high evaporation rates, leaving little or no surplus of surface moisture for storage.

Quick Answers

- Arizona has two precipitation peaks, occurring in the winter and summer.
- Different atmospheric circulation patterns create winter and summer precipitation regimes:
    - Winter precipitation is associated with large frontal systems traveling eastward from the Pacific Ocean.
    - Summer precipitation is associated with the North American monsoon, when a seasonal wind shift brings moisture and thunderstorm activity from the south between July and September.
- Sequential winter and summer precipitation totals are largely independent (uncorrelated); generally, one season's atmospheric conditions cannot be used to predict the conditions of the following season.
- Winter snowpack and spring snowmelt provide most of the water to recharge Arizona's reservoirs.

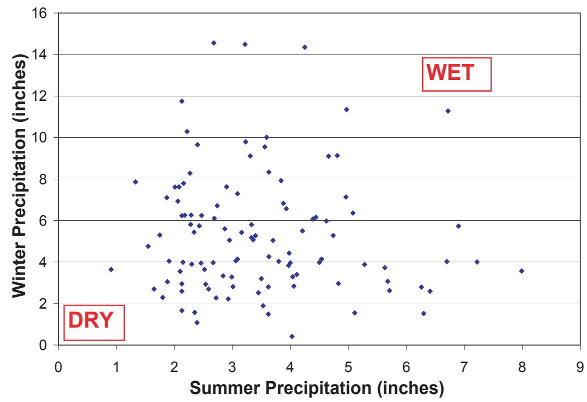

Figure 14. Arizona CD 6 (Maricopa and Pinal Counties) winter vs. summer precipitation for 1896–2002.

As noted above, the atmospheric processes that cause winter and summer precipitation differ significantly; as a result, seasonal precipitation totals are essentially independent of each other. This independence means that it is not unusual for a water year to be characterized by a dry summer and wet winter or a wet summer and dry winter. Moreover, atmospheric conditions in one season cannot necessarily be used to predict precipitation during the following season. Figure 14 illustrates the independence between the two seasons. The graph does not show any consistent relationship between seasonal precipitation totals. If there was a consistent relationship, then the points on the graph would be tightly packed along a line spanning from dry (lower left) to wet (upper right) or vice versa.

The driest summers were 1900, 1973, and 1994 (Figure 15). The driest winters were 1904, 1956, and 2002 (Figure 16). These figures demonstrate that the driest winters do not necessarily coincide with the driest summers. In addition, parts of the state exhibited record low summer precipitation during 1973, a year not associated with one of the three major statewide droughts. The driest winters on record are associated with the three major statewide droughts (Figure 16), which highlights the importance of winter precipitation in defining multi-year drought. Winter precipitation (Figure 17) is higher than summer precipitation (Figure 18) in every division except CD 7 (Pima, Santa Cruz, Cochise, Graham, and Greenlee Counties), which is at the "leading edge" of the North American monsoon circulation in Arizona. CD 4 (Gila County) consistently receives more winter than summer precipitation (Figure 19), whereas CD 7 mostly receives more summer than winter precipitation (Figure 20).

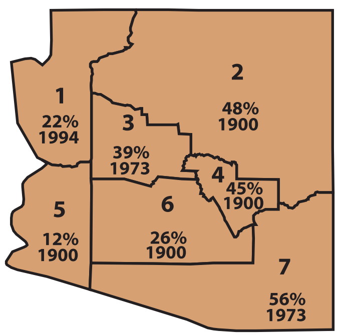

Figure 15. Driest summer (Jul–Sept) for the period 1896-2002.

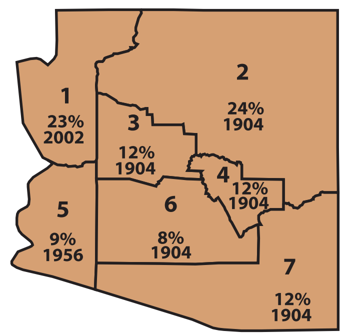

Figure 16. Driest winter (Nov–Apr) for the period 1896-2003.

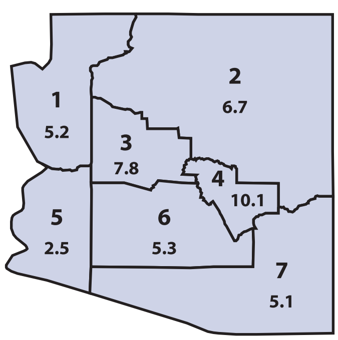

Figure 17. Winter average precipitation (inches).

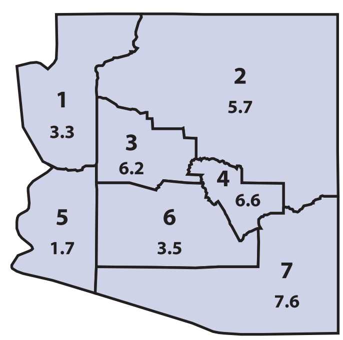

Figure 18. Summer average precipitation (inches).

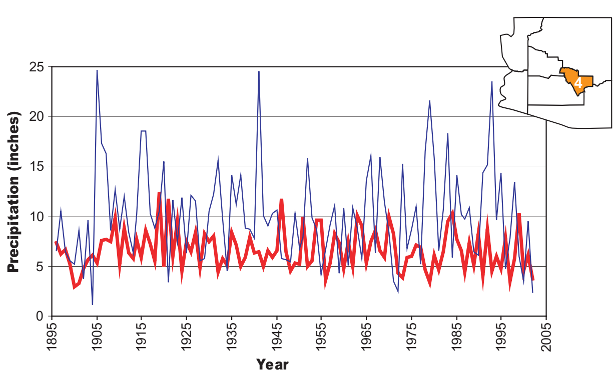

Figure 19. Winter (thin blue line) and summer (thick red line) precipitation totals for Arizona CD 4.

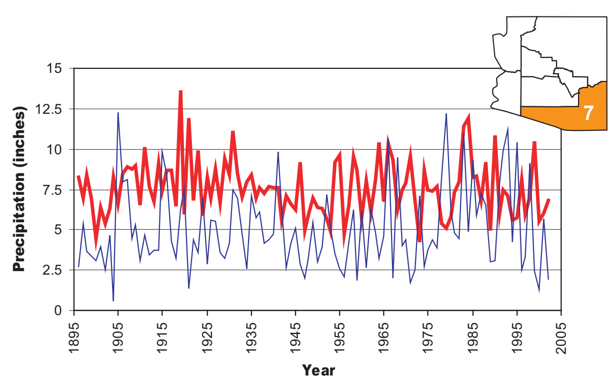

Figure 20. Winter (thin blue line) and summer (thick red line) precipitation totals for Arizona CD 7.

8. What are the links between El Niño-Southern Oscillation (ENSO) and drought?

Every two to seven years, the central and eastern equatorial Pacific Ocean warms significantly; this warming, called El Niño, is *quasi-periodic*—in other words the exact timing of when it might occur is irregular, but we can count on it occurring roughly 1–2 times each decade. A related cooling of central and eastern equatorial Pacific Ocean temperatures, occurring every two to seven years, is called La Niña. These phenomena are associated with the Southern Oscillation, a basin-wide change in atmospheric circulation across the Pacific Ocean. Collectively, these irregular ocean-atmosphere system changes are referred to as the El Niño-Southern Oscillation (ENSO). Shifts in atmospheric heating and wind that occur due to ENSO have profound effects on global climate and are powerful enough to shift storm tracks, including the paths of storms that affect the climate of North America. Many studies have demonstrated a relationship between Southwest United States climate variability and ENSO. These studies show that the strongest connections between ENSO and Arizona climate occur during the winter season. Generally, El Niño is associated with wet Arizona winters; however, dry winters can still occur during an El Niño year. La Niña years are generally associated with dry winters in Arizona.

Quick Answers

- Southwest winter precipitation is well correlated with ENSO variations:
    - The ENSO-Arizona winter precipitation signal is weakest in northeastern Arizona.
- Generally, El Niño winter precipitation totals vary more than La Niña winter precipitation totals:
    - Years that are characterized by neither El Niño or La Niña conditions exhibit the greatest variation.
- El Niño winters can range from very wet to very dry:
    - The greatest winter precipitation totals in the instrumental record are during El Niño years.
- La Niña winters are frequently associated with drought.
- In Arizona, La Niña winters are more consistently *not wet* (dry or near average), than El Niño winters are consistently *not dry* (wet or near average).

The Southern Oscillation Index (SOI) is one commonly used measure of the strength of the atmospheric effects of ENSO. Generally, an El Niño or La Niña event developing during the summer and early fall will have effects on Arizona precipitation during the subsequent winter. Thus, we analyzed the relationships between the June–November (pre-winter) SOI (1895–2001) and subsequent winter (November–April; 1896–2002) Arizona precipitation. We classified all years by their SOI values, as follows: El Niño (SOI < -0.5), Neutral (SOI -0.5 to +0.5), and La Niña (SOI > 0.5). Out of the 106 years in this dataset, there were 34 years classified as El Niño, 24 years classified as La Niña; the remaining 48 years were classified as neutral.

The results of our analyses show that variation in winter precipitation during El Niño years is greater than the variation in winter precipitation during La Niña years (Table 2). Neutral years show the greatest variation

Table 2. Percent of all winters that were dry or wet during El Niño, Neutral, and La Niña years for each Arizona climate division and for the whole state.

	CD 1	CD 2	CD 3	CD 4	CD 5	CD 6	CD 7	ALL
El Niño								
Dry	29%	24%	29%	24%	24%	26%	26%	26%
Wet	53%	44%	47%	47%	59%	53%	56%	51%
Neutral								
Dry	53%	49%	55%	45%	57%	57%	53%	53%
Wet	22%	18%	24%	18%	20%	24%	27%	22%
La Niña								
Dry	54%	33%	54%	42%	50%	67%	58%	51%
Wet	21%	13%	25%	25%	21%	21%	8%	19%

Note: Dry is defined as winter precipitation (Nov–Apr) totals less than 85 percent of average; wet is defined as winter precipitation greater than 115 percent of average.

in winter precipitation. Moreover, the range of winter precipitation totals is greater for El Niño years than for La Niña years (Figure 21). In CD 6 (Maricopa and Pinal Counties), El Niño winter precipitation totals range from 2.3 to 14.6 inches; thus, El Niño conditions can result in winter precipitation totals above and below the average. Nonetheless, the greatest CD 6 winter precipitation totals on record coincide with El Niño years. La Niña, on the other hand, is associated with a narrower range of winter precipitation totals ranging from 1.1 to 9.1 inches (Figure 21), and, in CD 6 very few La Niña winters received above-average precipitation.

Percentages of average winter (November–April) precipitation were calculated for El Niño, neutral, and La Niña years and are shown for each climate division and for the whole state in Table 2. Wet winters are defined as greater than 115 percent of average whereas dry winters are defined as less than 85 percent of average. Generally, La Niña winters are drier a greater percent of the time than El Niño winters are wet; this is true regardless of whether the thresholds for dry and wet are made more extreme (75 percent and lower = dry; 125 percent or higher = wet) or relaxed (99 percent or lower = dry; 101 percent or higher = wet).

The aforementioned relationships, and the ENSO signal, are weakest for northeastern Arizona (e.g., CD 2 and CD 4). La Niña is most reliably dry in southeastern Arizona (CD 6 and CD 7). La Niña is typically *not wet* (dry or near average), more so than El Niño is *not dry* (wet or near average). The rule that La Niña is reliably not wet seems to deteriorate for CD 4, Gila County, where there is a dramatic shift in topography. Perhaps most surprisingly, neutral Pacific Ocean conditions produce many more dry than wet winters in Arizona. Figure 22 illustrates precipitation as percentage of average during the strongest overall and most recent El Niño and La Niña events, with the expected wetter and drier conditions respectively.

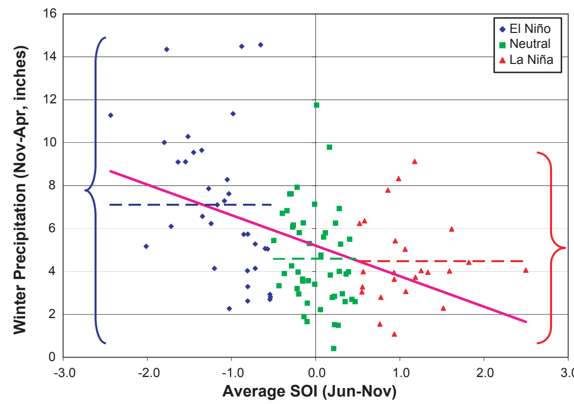

Figure 21. Arizona CD 6, Southern-Oscillation Index (SOI; 1896–2001) as a function of winter precipitation. Brackets illustrate the range of El Niño and La Niña winter precipitation totals. Average CD 6 winter precipitation is 5.4 inches. The El Niño, neutral, and La Niña average precipitation are represented by dashed lines. The pink line shows the overall trend.

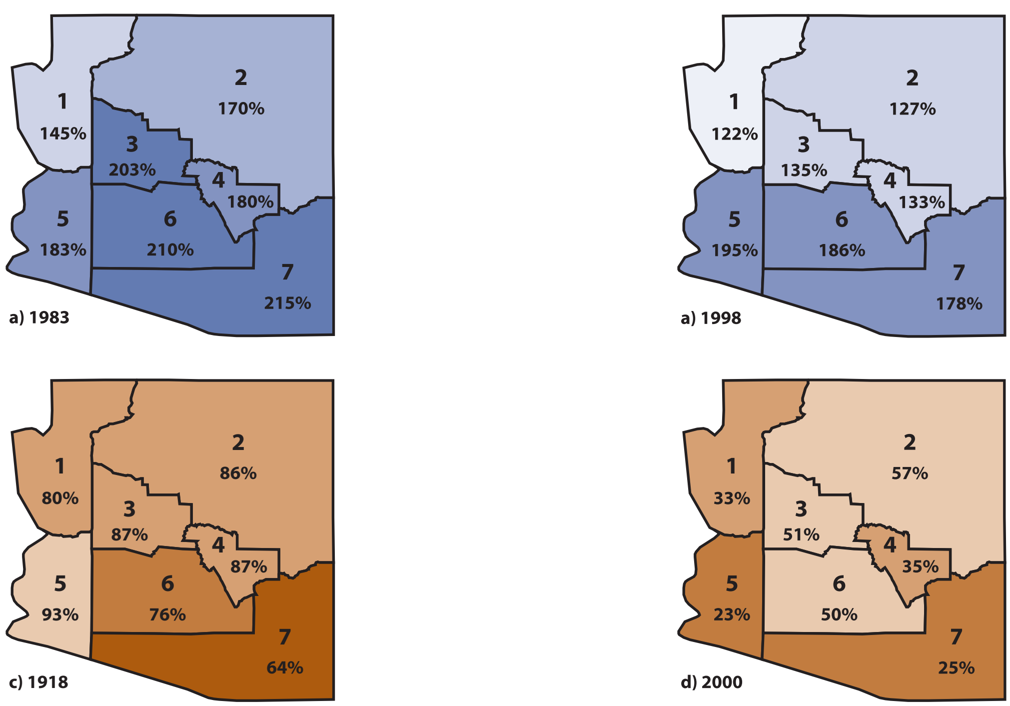

Figure 22. Percent of average winter precipitation during (a) the strongest El Niño (1983), (b) the most recent El Niño (1998), (c) the strongest La Niña (1918), and (d) the most recent La Niña (2000).

9. Are there any long-term oscillations or trends?

There are no significant long-term overall upward or downward trends in Arizona climate division precipitation (Figure 4). There are at least three distinct multi-decadal periods of winter precipitation variation (Figure 23). Although precipitation is highly variable from one winter to the next, there are periods of broadly lower-than-average and higher-than-average precipitation over periods spanning several decades. Following the drought at the turn of the 20th century, there was a period of wetter-than-average conditions until the 1940s. Drier-than-average conditions persisted throughout mid-century between the mid-1940s and the mid-1970s, followed by a wetter than average period through the mid-1990s.

A major challenge for climate researchers is to establish the cause of these almost cyclical long-term

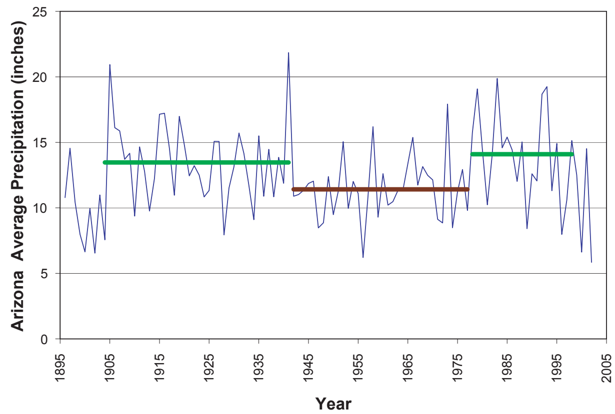

Figure 23. Arizona precipitation for 1895–2002 (averaged from all climate divisions). Wet multi-decadal periods, during the early 20th century and following the mid-1970s are marked with green lines and the dry 1940s–1970s period is marked with a brown line. These periods appear to be associated with shifts in the PDO.

changes in precipitation. For example, at the interannual scale, there are strong and well-established links between climate variability and ENSO. At the decadal scale, recent research (Mantua et al. 1997, Mantua and Hare 2002) shows that the kind of long-term variability described above is linked to a phenomenon known as the Pacific Decadal Oscillation (PDO). The PDO is somewhat like a multi-decadal version of ENSO. It is characterized by fluctuations in both Northern Pacific and Equatorial sea-surface temperatures occurring on long (e.g., 15–30 years) time scales (Figure 24). Recent research indicates that the two phenomena, ENSO and PDO, may be closely linked to one another (Newman, Compo and Alexander 2003). Like ENSO, the PDO varies between two modes, the *cool* (negative) and *warm* (positive) phases. In the past century, decadal climate fluctuations are evident for two full PDO "cycles" in the past century; cool phases occurred during the periods 1890–1924 and 1947–1976, and a warm phase occurred between 1925–1946 (Mantua et al. 1997).

The warm PDO phase closely corresponds to periods of generally wetter winters in Arizona, while the cool PDO phase closely corresponds to periods of generally drier conditions. The atmospheric and oceanic mechanisms causing the PDO are not well understood at this time, which presents a barrier to moni-

Quick Answers

- There are no significant long-term trends in Arizona precipitation.
- During the 20th century there are 3 distinct multi-decade periods in Arizona precipitation:
  - 1925–1946 WET
  - 1947–1976 DRY
  - 1977–1998 WET
- Southwest winter precipitation is associated with a multi-decadal fluctuation in North Pacific Ocean temperatures and atmospheric circulation climate called the Pacific Decadal Oscillation (PDO):
  - During the 20th century, positive PDO index values were associated with 20–30 year periods of relatively wet conditions in the Southwest and negative PDO index values were associated with 20–30 year periods of relatively dry conditions in the Southwest.
  - Some researchers believe that there was a shift to negative PDO index values during the late 1990s, which might explain recent drought conditions.

toring and forecasting these long-term climate shifts (Mantua and Hare 2002). Being able to monitor, model, and predict the PDO is important, because it will help enable climatologists to predict long-term winter precipitation in Arizona and the Southwest. Some researchers believe that the PDO and associated ocean and atmospheric circulation shifted to a cool phase during the late 1990s; if so, during the next several decades winter precipitation might be below average in the Southwest, which has widespread ramifications for water supply and land management. It will be some time before scientists can be sure if and how such a shift might have taken place.

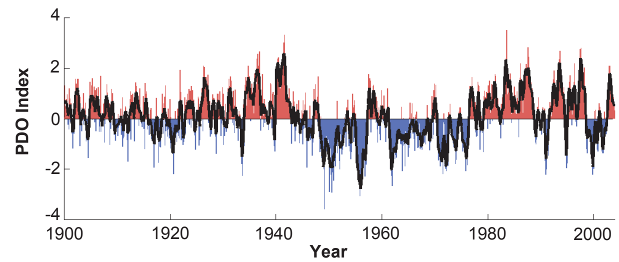

Figure 24. Pacific Decadal Oscillation index, 1900-2000 (courtesy of University of Washington). Monthly values for the PDO index from January 1900 through December 2000.

10. Where can I find drought information and forecasts?

During the past five years the percentage of the contiguous United States in severe or extreme drought has been as high or higher than any time since the drought of the mid-to-late 1980s which caused over $40 billion in damages/costs and an estimated several thousand deaths (NCDC 2003). Given the aforementioned, and recent improvements in access to information over the Internet, the recent drought has generated considerable interest in drought and in sources of information about drought monitoring and forecasts. A wide range of agencies and organizations provide such information for the United States (see list of internet sites on page 21).

Perhaps the most comprehensive current drought status assessment is the U.S. Drought Monitor. The Drought Monitor is a weekly synthesis of many kinds of climate information (such as drought indices, precipitation, snow, and temperature data), along with drought impact information and expert assessment by federal, state, and academic scientists (Figure 25). The website also provides access to current conditions and a variety of drought-related forecasts.

Further drought monitoring information and a monthly assessment of current drought conditions in comparison to historical information is available from the National Climatic Data Center (NCDC). The NCDC climate monitoring website (http://www.ncdc.noaa.gov/oa/climate/research/monitoring.html) provides monthly, regional, and statewide drought analyses and monthly climate division drought index maps.

The NOAA Drought Information Center website provides links to various drought and climate information websites. Official seasonal climate forecasts and drought outlooks are issued by the NOAA Climate Prediction Center (CPC).

The International Research Institute for Climate Prediction (IRI) issues experimental seasonal climate outlooks and climate impact information for North America and other regions.

Monthly syntheses of climate conditions and forecasts, with interpretations specific to the Southwest, are made available by the Climate Assessment for the Southwest (CLIMAS), a project at the Institute for the Study of Planet Earth (ISPE) at the University of Arizona. Shorter time-scale information and information about local climate and weather conditions in the Southwest can be obtained from the National Weather Service (NWS) forecast office websites in Arizona (Flagstaff, Phoenix, Tucson) and websites for adjacent states (e.g., information for northwestern Arizona can be obtained from the Las Vegas, Nevada NWS).

Quick Answers

- A comprehensive weekly drought status assessment is provided by the U.S. Drought Monitor.
- Official U.S. seasonal forecasts are made by the NOAA Climate Prediction Center..
- Interpretation of monthly climate conditions and forecasts, tailored for the southwestern United States, is provided by the CLIMAS project at the University of Arizona.

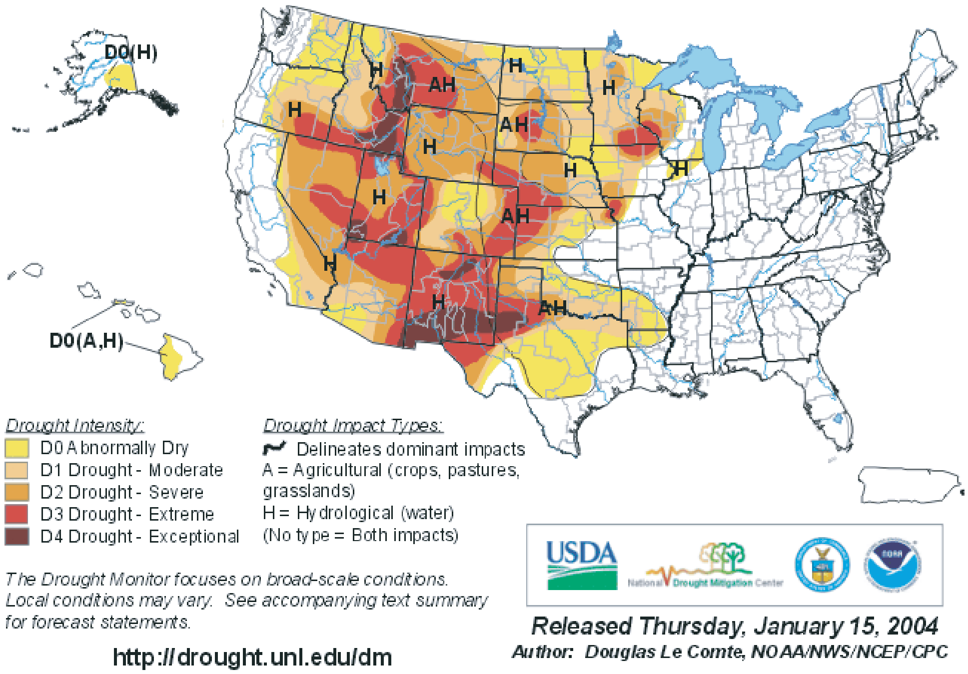

Figure 25. Example of the U.S. Drought Monitor from the National Drought Mitigation Center.

Internet Sites for further information:

Governors Drought Task Force, State of Arizona
http://www.water.az.gov/gdtf/

National Drought Mitigation Center
http://drought.unl.edu/index.htm

U.S. Drought Monitor
http://drought.unl.edu/dm/

NOAA CPC Drought Monitoring
http://www.cpc.ncep.noaa.gov/products/monitoring_and_data/drought.html

NOAA CPC Drought Monitor and Seasonal Outlook
http://www.cpc.noaa.gov/products/expert_assessment/drought_assessment.html

NOAA CPC Climate Outlooks
(e.g., El Niño, soil moisture, drought)
http://www.cpc.ncep.noaa.gov/products/OUTLOOKS_index.html

NOAA Drought Information Center
http://www.drought.noaa.gov/

NOAA-National Weather Service Flagstaff Forecast Office
http://www.wrh.noaa.gov/Flagstaff/

NOAA-National Weather Service Phoenix Forecast Office
http://www.wrh.noaa.gov/Phoenix/index.html

NOAA-National Weather Service Tucson Forecast Office
http://www.wrh.noaa.gov/tucson/

NCDC Climate Monitoring (with links to monthly and historical drought information)
http://lwf.ncdc.noaa.gov/oa/climate/research/monitoring.html

NCDC Drought Termination and Amelioration
http://lwf.ncdc.noaa.gov/oa/climate/research/drought/drought.html

International Research Institute for Climate Prediction
http://iri.columbia.edu/

CLIMAS Southwest Climate Outlook
http://www.ispe.arizona.edu/climas/forecasts/swoutlook.html

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