

HOPI CLIMATE

AN OVERVIEW TO SUPPORT
DROUGHT MONITORING
AND MANAGEMENT

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The climate of the Hopi Reservation is one of extremes. Situated on the Colorado Plateau in northeastern Arizona (Figure 1) it can experience very cold winters, hot summers, and exceptional variability in precipitation amounts across the reservation and between seasons and years. The landscape reflects the climate, with vegetation communities varying from conifer (i.e., piñon-juniper) woodlands at cooler and wetter higher elevations to grasslands and desertscrub communities at warmer and drier lower elevations

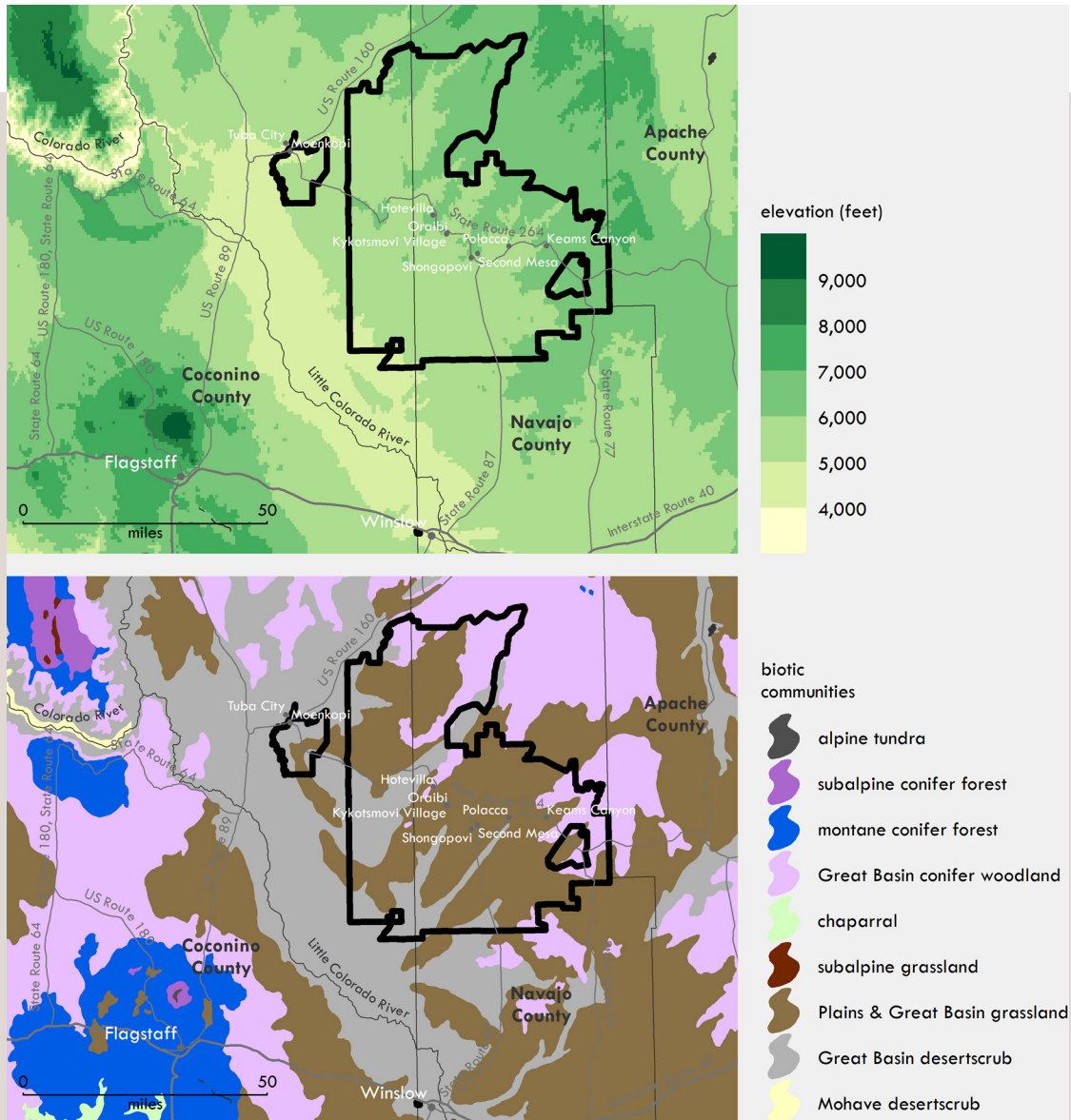


Figure 1. Elevations (top) and biotic communities (bottom) within and around the Hopi Reservation. Elevation data are available at <http://www.prism.oregonstate.edu/normals/> (Daly et al. 2002). The Nature Conservancy provided biotic community (i.e., biome) data that are based on Brown (1994).

CLIMATOLOGY OF MONTHLY TEMPERATURE AND PRECIPITATION

On average, the Hopi Reservation receives about 8.5 inches of precipitation each year with higher elevation areas typically receiving more and lower elevation areas less (Figure 1). Temperatures also vary with topography and throughout the year, but the annual average high temperature is 67°F and the annual average low temperature is 37°F, a climate pattern typical of a cool, high desert location.

Another unique feature of the climate of the Hopi Reservation is that it varies seasonally between winter and summer wet seasons and dry intervening seasons in the spring and fall. This seasonal-transitional climate is unique to the southwest U.S. where winter storms from the west and northwest bring much of the cool season precipitation to the region and the North American Monsoon System brings moisture and convective thunderstorm activity from the south into Arizona and New Mexico. Figure 2 shows the long-term average monthly precipitation and temperature for the Hopi Reservation for each month of the year. The bars depict higher precipitation from December through March and drier conditions in the spring (April-June) as the

winter storm track shifts to the north away from the region. A dramatic increase in precipitation is observed at the onset of the monsoon season in early July that typically lasts through late September (Crimmins 2006). A shift towards climatologically drier conditions occurs again in October and November, which are transition months away from monsoon and tropical-type precipitation back into a winter storm pattern. The two wet seasons of December–March and July–September are a key feature of the region’s seasonal-transitional climate. The characteristics of precipitation between the two seasons is also dramatically different. Winter storms typically bring precipitation in the form of snow or long duration, low intensity precipitation events that can recharge soil moisture reserves and contribute to replenishing local water resources. Summer precipitation typically arrives as highly localized, intense convective storms that can produce high levels of runoff and erosion, but also is important moisture for warm season range grasses. This seasonality in precipitation can drive both short and long term drought cycles and requires careful monitoring to track potential impacts at different timescales.

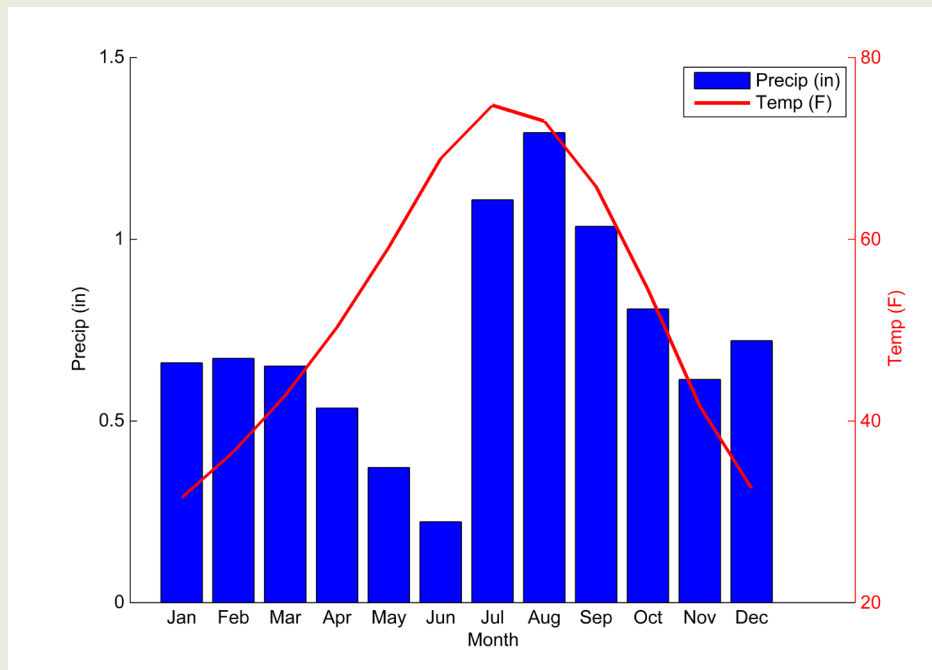


Figure 2. Monthly average temperature and precipitation for Hopi (calculated from PRISM gridded climate data, Daly et al. 2002)

A CLOSER LOOK AT CLIMATE EXTREMES

Data from two long-term weather stations on and around the Hopi Reservation allow for a closer examination at what types of climate extremes may be expected for this region. Figure 3 shows climate summary plots for Tuba City (4,988 ft. above sea level), and Keams Canyon (6,205 ft. above sea level) both with data extending back to the late 1800s. These plots show the daily averages and extremes for several climate variables including temperature (top plots) and precipitation (bottom). These stations are only 60 miles apart and have very similar climates, but the data reveal important differences as well. For example, Tuba City (at a lower elevation) observes much warmer temperatures and fewer cold extremes than Keams Canyon. Many of Tuba City's record temperatures are well above 100 °F in the months of June and July (red bars in top-left plot), while Keams Canyon has observed many record lows below 0 °F (blue bars in top-right plot). These record highs and lows for these two relatively close locations represent a temperature range of over 120 °F. More statistics for these stations can be found at <http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?az4586> for Keams Canyon and <http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?az8792> for Tuba City.

The seasonality of precipitation between the winter and summer seasons is also evident in the bottom two plots that show daily average (very small green bars) and record precipitation amounts (blue bars) for the two stations. As expected, winter precipitation amounts and extremes are slightly higher for the higher elevation Keams Canyon station with daily record amounts regularly above 0.5 inches and several instances of total daily precipitation in excess of 1.5 inches. This is less the case during the summer and fall seasons when convective thunderstorms bring extreme precipitation to both stations. Keams Canyon has observed several days during the summer season with total precipitation in excess of 1.5 inches, but so has Tuba City. Interestingly Tuba City has observed much higher precipitation extremes in the summer than Keams Canyon with several daily precipitation amounts in excess of 2 inches. All of these daily records occurred in the month of September and were most likely associated with late monsoon season thunderstorm activity and tropical storm systems (Hereford and Webb 1992).

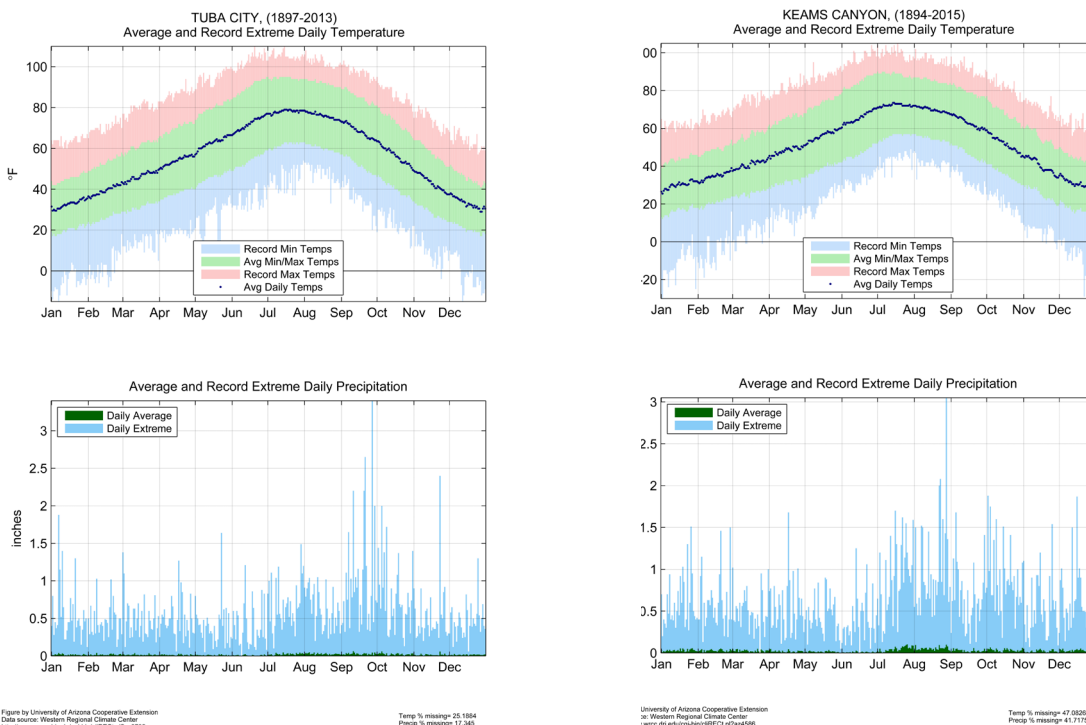


Figure 3. Daily temperature and precipitation summary plots for Tuba City and Keams Canyon, AZ.

MEASURES OF ARIDITY

Another subtle difference related to elevation differences between these two stations and the seasonality of precipitation is in the levels of the aridity these two locations experience. Aridity is the degree of dryness a location experiences and is a typical feature of desert locations. The level of aridity is controlled by the interplay between local levels of precipitation and levels of potential evapotranspiration throughout the annual cycle. Potential evapotranspiration is a measure of the amount of water that would evaporate from soils and water bodies and transpire from plants if sufficient water were available (which is almost always never present in an arid climate). The level of potential evapotranspiration is controlled by several factors including amount of sunshine, relative humidity levels, wind speed, and temperatures. High amounts of sunshine, high wind speeds, low relative humidity, and high temperatures can drive high levels of potential evapotranspiration. The plots in Figure 4 show estimates of average daily potential evapotranspiration (calculated only from temperature values) through the calendar year for Tuba City and Keams Canyon. The light tan bars in both of the top plots indicate the average daily potential evapotranspiration (PET) amounts for each day of the year. Note how PET values peak at over 0.25 inches per day in the June and early July period, the hottest and driest part of the year. These values can be totaled over the year (bottom plots) to get a rough estimate of the average water balance between incoming precipitation and atmospheric demand on this water through evaporation and transpiration from plants. On average Tuba City observes 6 inches of precipitation each year, but given its hot and dry climate through the spring and early summer has a total estimated PET value of 57 inches indicating a huge climatological water deficit or high level of aridity (bottom-left plot). Keams Canyon which is slightly higher in elevation and slightly wetter and cooler observes about 11 inches of precipitation on average each year and a PET value of 52 inches; a slightly lower deficit, but still indicative of an arid climate. A basic understanding of aridity and the interplay between temperature and precipitation can be a useful tool in tracking potential drought impacts. *Drought events accompanied by temperatures that are much above-average can have much higher levels of PET as well. This could drive higher levels of stress on vegetation and water resources much more quickly than simple precipitation monitoring may indicate.*

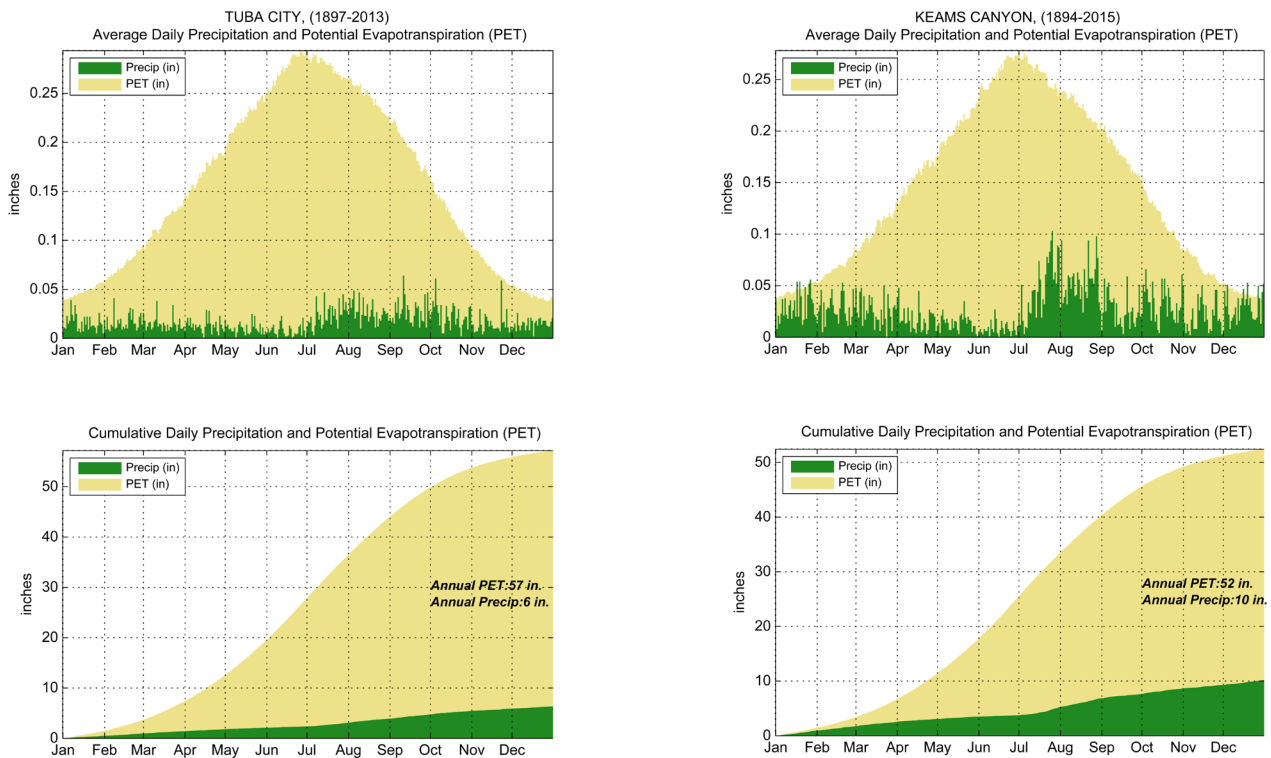


Figure by University of Arizona Cooperative Extension
Data source: Western Regional Climate Center
<http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?az07192>

Temp % missing= 25.1884
Precip % missing= 17.345

Figure by University of Arizona Cooperative Extension
Data source: Western Regional Climate Center
<http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?az4586>

Temp % missing= 47.0826
Precip % missing= 41.7175

Figure 4. Daily precipitation and potential evapotranspiration summary plots for Tuba City and Keams Canyon, AZ.

PALEOCLIMATE VARIABILITY

The southwest U.S. is subject to large amounts of natural variability in precipitation amounts from year to year (Woodhouse et al. 2010). This is especially true for the Hopi Reservation when considering the importance of winter and summer precipitation separately and how these seasons vary over time. A recent study (Faulstich et al. 2013) examined tree-ring based reconstructions of both cool (October-April) and warm (July-August) season precipitation for the Four Corners region. By examining the width of tree ring samples collected across northeast Arizona and northwest New Mexico they were able to estimate seasonal precipitation amounts for the period of 1597-2008. A key finding from this study was that drought occurring in both the winter and following summer, or dual-season droughts, was more common over the past 400 years than has been observed over the past 100 years. In this study dual-season droughts were also linked to historical and archaeological evidence of major impacts to Native American communities across the Four Corners region including famines and migrations. The fact that dual-season droughts were more common in the extended precipitation record than in more recent records suggests that the risk of dual-season droughts is much higher than has been typically expected and requires special attention in planning and preparedness efforts.

YEAR-TO-YEAR VARIATIONS IN ANNUAL TEMPERATURE AND PRECIPITATION, 1900-2014

Over the past century, the lands that now make up the Hopi Reservation have experienced two distinct wet periods comprised of several consecutive years of above-average precipitation, one starting in 1905 and running through the early 1910s and again in the late 1970s through the late 1980s. Droughts were also very common over the past century with a pronounced dry period in the early 1900s, deep drought conditions through the 1950s and early 1960s, and again in the late 1990s up through the end of the data record in 2014. The data in Table 1 shows that the two driest years in the 115-year record are 2009 with only 4.6 inches of precipitation observed (53% of average) and 1989 with 4.65 inches of total precipitation observed.

Precipitation variability over the past two decades (i.e., 1990s and 2000s) is somewhat different than the patterns observed earlier in the record. Since the wet period observed in the 1980s, annual precipitation amounts have switched rapidly between above-average and below-average levels leading to rapid swings between intense short-term drought conditions and unusually wet conditions. Overall, 11 of the 15 years between 2000 and 2014 were below average indicating the extended duration of the current drought even with intervening near-average or above-average precipitation years. The 24-month Standardized Precipitation Index (SPI) time series depicts this rapid switching between unusually wet and dry conditions especially evident between 1990 and 2014 with increasing drought intensity and duration (Figure 6). Note how the cumulative effect of multiple dry years from 1999 to 2003 led to the most intense drought conditions observed in the entire period of record. Even though 2002 wasn't the driest year on record, it was the peak of the driest multi-year drought in the past 115 years across the region.

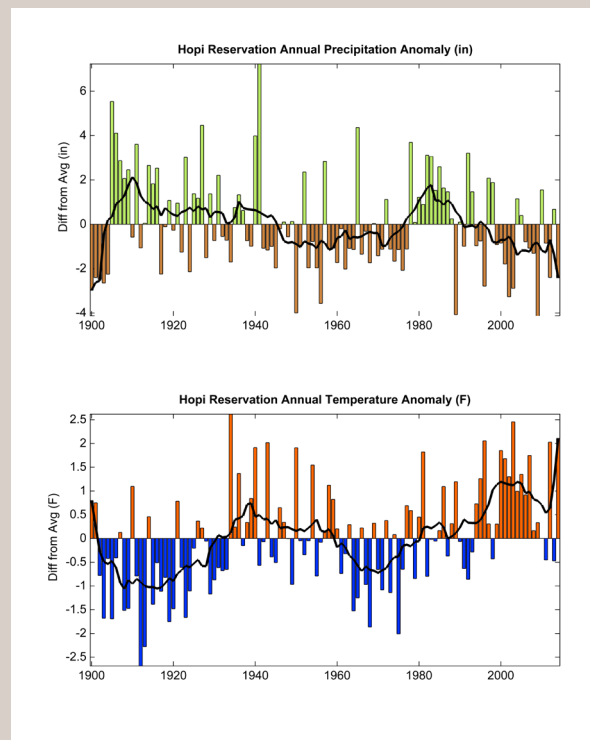


Figure 5. Annual precipitation and temperature differences from long-term averages

Much of the inter-annual variability and longer-term wet and drought cycles are related to the El Niño-Southern Oscillation or ENSO (see <http://www.climas.arizona.edu/sw-climate/el-ni%C3%B1o-southern-oscillation> for more information) and its well-known impact on influencing the winter weather pattern across the southwest U.S. (e.g. Hereford et al. 2002). Strong El Niño events typically bring wetter than average winter conditions while La Niña events tend to bring the opposite with drier winters. The relationship between ENSO and summer precipitation is much weaker and less clear. Overall the most recent drought conditions (since the late 1990s) are well connected with several strong La Niña events (e.g., 2011 and 2012) that predictably led to drier than average conditions, reinforcing the nearly two decades-long drought.

This period has also been much warmer than any other period in the past 115 years (bottom panel, Figure 5) with 12 of 15 years between 2000 and 2014 logging above-average temperatures. Four of the top five warmest years on the Hopi Reservation (Table 2) all occurred since the late 1990s with two near the end of the record. This warming observed at the regional level is consistent with trends related to human-caused global warming and is expected to continue well into the future (Garfin et al. 2013). As discussed earlier, warmer temperatures lead to higher rates of evapotranspiration creating additional water stress on plants and water resources. Several studies focusing on the southwest U.S. have demonstrated that the above-average temperatures observed in the past decade coincident with recent drought conditions have exacerbated drought stress and impacts across the region (Breshears et al. 2005, Weiss et al. 2009, 2012).

Year	Total precipitation (in.)	Difference from average (in.)	Percent of average
2009	4.60	-4.13	52.7
1989	4.65	-4.07	53.3
1950	4.73	-3.99	54.2
1956	5.15	-3.57	59.1
2002	5.46	-3.26	62.6
1900	5.75	-2.97	65.9
2003	5.84	-2.89	66.9
1996	5.94	-2.79	68.0
1903	6.08	-2.65	69.7
1902	6.24	-2.49	71.5

Table 1 Top ten driest years for Hopi Reservation from 1900-2014.

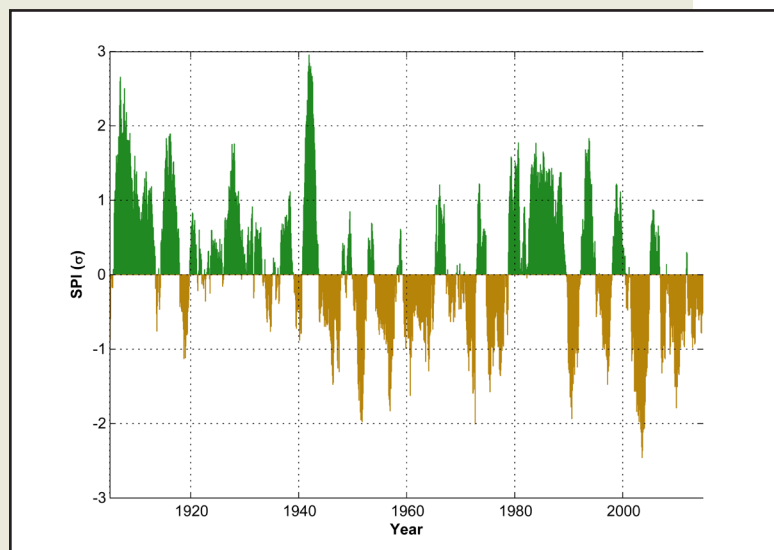


Figure 6. Long-term drought conditions depicted by the 24-month Standardized Precipitation Index.

SHORT- VS. LONG-TERM DROUGHT

Long-term cycles in wet and dry periods, the constant seasonal shift from wet to dry seasons, and different characteristics of precipitation between winter and summer can create a complex picture with respect to drought impacts and drought monitoring. Drought is typically tracked at timescales of seasons to years, but given the nature of the seasonal-transitional climate of the region, drought impacts may emerge or disappear at different timescales, necessitating tools that can track both short and long timescales of drought. For example, multiple years of below-average precipitation during the winter may impact local water resources and are indicative of a longer-term drought impact. During this same time period, plentiful summer rains may lead to average or even above-average range conditions, but may not improve the longer-term deficits impacting water resources. In other words, long-term drought conditions may exist even when short-term drought conditions may not. An index that can capture different timescales of precipitation variability, like the SPI, can help detect and track situations when short- and long-term drought do not necessarily match.

Figure 4 is an illustration of how short- versus long-term drought conditions can differ at any given point in time. The graphic depicts monthly SPI values calculated from 1 to 60 months with longer time scales (longer-term drought) towards the top of the graphic. Green colors indicate wet conditions and yellows and browns indicate drought conditions. The color patterns lean to the right because immediate changes in monthly precipitation, either unusually wet or dry (Figure 4, bottom panel), impact slowly varying systems like surface water systems and ecosystems. With this drought index, what matters most is both the intensity of the monthly anomaly (whether a given month was above- or below-average) and how many months were above or below average in a row. Note how intense drought conditions developed in 2002 over many months leading to very low SPI values at short and long timescales. This intense drought period was followed by the very wet winter season of late 2004 and 2005.

The monthly precipitation values (bottom plot) show several months of above-average precipitation which undoubtedly brought short-term drought relief as indicated by the positive SPI values and green colors at timescales less

Year	Average annual temperature (F)	Difference from average (F)
1934	55.3	2.6
2003	55.1	2.5
2014	54.8	2.1
1996	54.7	2.1
2012	54.7	2.0
1943	54.7	2.0
1940	54.6	1.9
1950	54.6	1.9
2000	54.5	1.9
1981	54.5	1.8

Table 2. Top ten warmest years for Hopi Reservation from 1900-2014.

WHAT IS THE STANDARDIZED PRECIPITATION (SPI) INDEX?

The SPI takes precipitation data (typically at the monthly timescale) and converts it into standard deviation units and can do so for different window lengths of time. For example, a 1-month SPI for January 2014 is the value of the total precipitation observed for that month converted into standard deviation units. If the total precipitation was exactly the average, the SPI value would be 0 or positive if above-average and negative for a below-average value. This can also be done at longer timescales (multiple months to years) to track longer-term drought conditions. For example, the 12-month SPI ending on December of 2014 would represent the annual total precipitation and whether it was above-average ($SPI > 0$) or below-average ($SPI < 0$). Since SPI values are standard deviation units, they communicate additional information about the intensity or rareness of drought conditions. Values above or below 2 standard deviations would be expected to be very rare events (less than 3% of the time in the historical record), indicating very wet or dry conditions when examining a long data set.

than 20 months, but did not fully erase drought at longer timescales. Long-term drought conditions remained at longer timescales that integrated the earlier deep drought conditions that developed in 1999 and peaked during 2002. These longer-term drought conditions may have been further relieved if wet conditions would have continued beyond 2005, but both the monthly plot (bottom) and SPI values show that drought conditions returned later in the year and continued for the next several years. The plot of SPI values provides a visual depiction of how multiple timescales of drought and no-drought can coexist and why tracking at least two timescales of drought (e.g. 6 month for short-term drought and 24 month for long-term drought) can provide important insight into why differential drought impacts may exist. See http://cals.arizona.edu/climate/misc/spi/spicont_Arizona2.png for a near-real time monitoring product at the climate division scale.

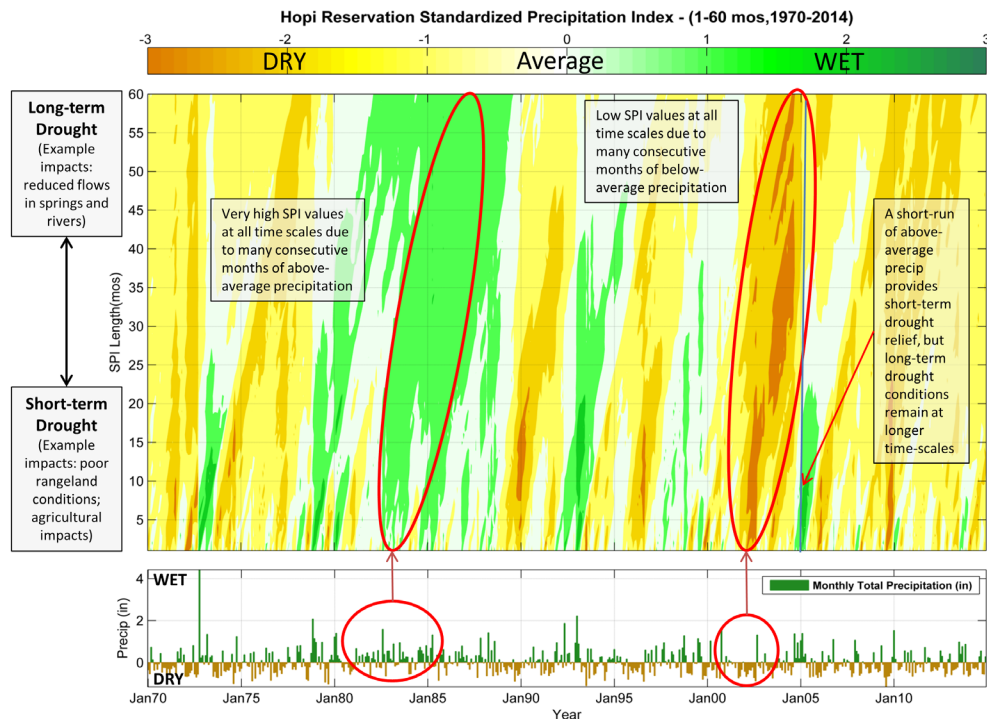


Figure 7. Multi-scale Standardized Precipitation Index plot for Hopi - 1970-2014

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ACKNOWLEDGEMENTS

This work was supported by the National Oceanic and Atmospheric Administration’s Climate Program Office through grants NA10OAR4310183 and NA13OAR4310166 to the Climate Assessment for the Southwest program at the University of Arizona.

SUGGESTED CITATION

Crimmins, M.A., D.B. Ferguson, J.L. Weiss, and H. Faulstich. 2015. *Hopi Climate: An Overview to Support Drought Monitoring and Management*. Tucson, AZ: Climate Assessment for the Southwest.

