Temperature and Drought in the Southwest

Identification

1. Description

This regional feature measures trends in drought conditions and temperature in six states: Arizona, California, Colorado, Nevada, New Mexico, and Utah. The metrics presented in this feature provide insight into how climate change is affecting areas of vulnerability in the U.S. Southwest. The Southwest is particularly vulnerable to the effects of drought because water is already scarce in this region and because the region is particularly dependent on surface water supplies like Lake Mead, which are vulnerable to evaporation. As described in the U.S. and Global Temperature indicator and the Drought indicator, climate change can result in changes in temperature and drought conditions.

Components of this regional feature include:

- Spatial and temporal trends in temperature anomalies from 1895 to 2020 (Figure 1).
- Percent of lands classified under drought conditions in recent years, based on the U.S. Drought Monitor Drought Severity Classification system (Figure 2).
- Spatial and temporal trends in drought severity from 1895 to 2020, based on the Palmer Drought Severity Index (PDSI) (Figure 3).

2. Revision History

May 2014:	Feature published.
June 2015:	Updated feature with data through 2014.
August 2016:	Updated feature with data through 2015.
April 2021:	Updated feature with data through 2020.

Data Sources

3. Data Sources

Data for Figures 1 and 3 were obtained from the National Oceanic and Atmospheric Administration's (NOAA's) National Centers for Environmental Information (NCEI) (formerly the National Climatic Data Center). This data set provides information on average temperatures, precipitation, and several comparative measures of precipitation (e.g., Standardized Precipitation Index) and drought severity (e.g., Palmer's Drought Severity Index). Data have been compiled for individual climate divisions (each state has up to 10 climate divisions; see: www.ncdc.noaa.gov/monitoring-references/maps/us-climate-divisions.php) and are available from 1895 to the present.

Data for Figure 2 were provided by the U.S. Drought Monitor, which maintains current and archived data at: http://droughtmonitor.unl.edu.

4. Data Availability

Data for Figures 1 and 3 are derived from tabular data available through the NCEI's Climate at a Glance online data portal at divisional, state, regional, and national scales from 1895 through the present. The entire data set is available at: www.ncdc.noaa.gov/cag.

U.S. Drought Monitor data for Figure 2 can be obtained from: https://droughtmonitor.unl.edu/DmData/DataTables.aspx. For each week, the data table shows what percentage of land area was under drought conditions D0 (abnormally dry) through D4 (exceptional drought). This component of the regional feature covers the time period from 2000 to 2020. Although data were available for part of 2021 at the time EPA last updated this feature, EPA chose to report only full years.

Drought Monitor data are based on a wide variety of underlying sources. Some are readily available from public websites; others might require specific database queries or assistance from the agencies that collect and/or compile the data. For links to many of the data sources, see: https://droughtmonitor.unl.edu/nadm/Home.aspx.

Methodology

5. Data Collection

Figure 1. Average Temperatures in the Southwestern United States, 2000–2020 Versus Long-Term Average

This figure was developed by analyzing temperature records from thousands of weather stations that constitute NCEI's *n*ClimDiv data set. These stations are overseen by NOAA, and they use standard instruments to measure temperature and precipitation. Some of these stations are first-order stations operated by NOAA's National Weather Service (NWS). The remainder are Cooperative Observer Program (COOP) stations operated by other organizations using trained observers and equipment and procedures prescribed by NOAA. These stations generally measure temperature at least hourly, and they record the minimum temperature for each 24-hour time span. Cooperative observers include state universities, state and federal agencies, and private individuals whose stations are managed and maintained by NWS. Observers are trained to collect data, and the NWS provides and maintains standard equipment to gather these data. The NWS/COOP data set represents the core climate network of the United States (Kunkel et al., 2005). Data collected by these sites are referred to as U.S. Daily Surface Data or Summary of the Day data.

Altogether, the six states covered in this feature are home to more than 6,100 past and present NWS and COOP stations. For an inventory of U.S. weather stations and information about data collection methods, see: https://www.ncei.noaa.gov/products/land-based-station, the technical reports and peer-reviewed papers cited therein, and the NWS technical manuals at: www.weather.gov/coop. This indicator is derived from a specific quality-controlled subset of long-term stations that NCEI has designated as its *n*ClimDiv data set (www.ncdc.noaa.gov/monitoring-references/maps/us-climate-divisions.php). Additional information about the NWS COOP data set is available at: www.weather.gov/coop/Overview. Sampling procedures are also described in Kunkel et al. (2005) and in the full metadata for the COOP data set, available at: www.weather.gov/coop.

Figure 2. Southwestern U.S. Lands Under Drought Conditions, 2000–2020

Figure 2 is based on the U.S. Drought Monitor, which uses a comprehensive definition of drought that accounts for a large number of different physical variables. Many of the underlying variables reflect weather and climate, including daily precipitation totals collected at thousands of weather stations, as described for Figures 1 and 3. Other parameters include measurements of soil moisture, streamflow, reservoir and groundwater levels, and vegetation health. These measurements are generally collected by government agencies following standard methods, such as a national network of stream gauges that measure daily (and weekly) flows, comprehensive satellite mapping programs, and other systematic monitoring networks. Each program has its own sampling or monitoring design. The Drought Monitor and the other drought indices that contribute to it have been formulated such that they rely on measurements that offer sufficient temporal and spatial resolution.

The U.S. Drought Monitor has five primary inputs:

- The PDSI.
- The Soil Moisture Model, from NOAA's Climate Prediction Center.
- Weekly streamflow data from the U.S. Geological Survey.
- The Standardized Precipitation Index (SPI), compiled by NOAA and the Western Regional Climate Center (WRCC).
- A blend of objective short- and long-term drought indicators (short-term drought indicator blends focus on 1- to 3-month precipitation totals; long-term blends focus on 6 to 60 months).

At certain times and in certain locations, the Drought Monitor also incorporates one or more of the following additional indices, some of which are particularly well-suited to the growing season and others of which are ideal for snowy areas or ideal for the arid West:

- A topsoil moisture index from the U.S. Department of Agriculture's National Agricultural Statistics Service.
- The Keetch-Byram Drought Index.
- Vegetation health indices based on satellite imagery from NOAA's National Environmental Satellite, Data, and Information Service (NESDIS).
- Snow water content.
- River basin precipitation.
- The Surface Water Supply Index (SWSI).
- Groundwater levels.
- Reservoir storage.
- Pasture or range conditions.

For more information on some of the other drought metrics listed above, including the data used as inputs to these other indices, see: https://droughtmonitor.unl.edu/nadm/Home.aspx.

To find information on underlying sampling methods and procedures for constructing some of the component indices that go into determining the U.S. Drought Monitor, one will need to consult a variety of additional sources. For example, as described for Figures 1 and 3, NCEI has published extensive documentation about methods for collecting precipitation data.

Figure 3. Drought Severity in the Southwestern United States, 1895–2020

The PDSI is calculated from daily temperature measurements and precipitation totals collected at thousands of weather stations, as described above for Figure 2. See the description for Figure 1 above for more information about these data collection networks.

6. Derivation

Figure 1. Average Temperatures in the Southwestern United States, 2000–2020 Versus Long-Term Average

NOAA used monthly mean temperatures at each weather station to calculate annual averages. Next, an annual average was determined for each climate division. To perform this step, NOAA used a grid-based computational approach known as climatologically-aided interpolation (Willmott & Robeson, 1995), which helps to address topographic variability. This technique is the hallmark of NOAA's *n*ClimDiv data product. Data from individual stations are combined in a grid with 5-kilometer resolution. To learn more about *n*ClimDiv, see: https://www.ncei.noaa.gov/access/monitoring/national-temperature-index/background and www.ncdc.noaa.gov/monitoring-references/maps/us-climate-divisions.php.

EPA calculated multi-year averages for each climate division, covering the full period of record (1895–2020) and the 21st century to date (2000–2020). The difference between the 21st century average and the 1895–2020 average is the anomaly shown in the Figure 1 map.

Figure 2. Southwestern U.S. Lands Under Drought Conditions, 2000–2020

The National Drought Mitigation Center at the University of Nebraska–Lincoln produces the U.S. Drought Monitor with assistance from many other climate and water experts at the federal, regional, state, and local levels. For each week, the Drought Monitor labels areas of the country according to the intensity of any drought conditions that may be present. An area experiencing drought is assigned a score ranging from D0, the least severe drought, to D4, the most severe. For definitions of these classifications, see: https://droughtmonitor.unl.edu/About/WhatistheUSDM.aspx.

Drought Monitor values are determined from the five major components and other supplementary factors listed in Section 5. A table on the Drought Monitor website (https://droughtmonitor.unl.edu/About/WhatistheUSDM.aspx) explains the range of observed values for each major component that would result in a particular Drought Monitor score. The final index score is based to some degree on expert judgment, however. For example, expert analysts resolve discrepancies in cases where the five major components might not coincide with one another. They might assign a final Drought Monitor score based on what the majority of the components suggest, or they might weight the components differently according to how well they perform in various parts of the country and at different times of the year. Experts also determine what additional factors to consider for a given time and place and how heavily to weight these supplemental factors. For example, snowpack is particularly important in the West, where it has a strong bearing on water supplies.

From the Drought Monitor's public website, EPA obtained weekly state-level Drought Monitor data for Arizona, California, Colorado, Nevada, New Mexico, and Utah. These data indicate the percentage of each state's area that falls into each of the Drought Monitor intensity classifications. To derive totals for the entire six-state region, EPA averaged the state-level data together for each week, weighted by total state area. This procedure used state areas as defined by the U.S. Census Bureau at: www.census.gov/geographies/reference-files/2010/geo/state-area.html.

No attempt has been made to portray data outside the time and space where measurements were made. Measurements are collected at least weekly (in the case of some variables like precipitation and streamflow, at least daily) and used to derive weekly maps for the U.S. Drought Monitor. Values are generalized over space by weighting the different factors that go into calculating the overall index and applying expert judgment to derive the final weekly map and the corresponding totals for affected area.

For more information about how the Drought Monitor is calculated, including percentiles associated with the occurrence of each of the D0–D4 classifications, see Svoboda et al. (2002) along with the documentation provided on the Drought Monitor website at: https://droughtmonitor.unl.edu.

Figure 3. Drought Severity in the Southwestern United States, 1895–2020

PDSI calculations are designed to reflect the amount of moisture available at a particular place and time, based on the amount of precipitation received as well as the temperature, which influences evaporation rates. The formula for creating this index was originally proposed in the 1960s (Palmer, 1965). Since then, the methods have been tested extensively and used to support hundreds of published studies. The PDSI is the most widespread and scientifically vetted drought index in use today.

The PDSI was designed to characterize long-term drought (i.e., patterns lasting a month or more). Because drought is cumulative, the formula takes precipitation and temperature data from previous weeks and months into account. Thus, a single rainy day is unlikely to cause a dramatic shift in the index.

PDSI values are normalized relative to long-term average conditions at each location, which means this method can be applied to any location regardless of how wet or dry it typically is. NOAA currently uses 1931–1990 as its long-term baseline. The index essentially measures deviation from normal conditions. The PDSI takes the form of a numerical value, generally ranging from -6 to +6. A value of zero reflects average conditions. Negative values indicate drier-than-average conditions and positive values indicate wetter-than-average conditions. NOAA provides the following interpretations for specific ranges of the index:

- 0 to -0.5 = normal
- -0.5 to -1.0 = incipient drought
- -1.0 to -2.0 = mild drought
- -2.0 to -3.0 = moderate drought
- -3.0 to -4.0 = severe drought
- < -4.0 = extreme drought

Similar adjectives can be applied to positive (wet) values.

NOAA calculates monthly values of the PDSI for each of the 344 climate divisions within the contiguous 48 states and corrects these data for time biases. These values are calculated from weather stations reporting both temperature and precipitation. As part of its *n*ClimDiv analysis, NOAA uses station data and interpolation between stations to create a 5-km grid across the contiguous 48 states for each variable in the data set, including PDSI. Divisional averages are derived by averaging the grid cells within each climate division. NOAA also combines PDSI values from all climate divisions, weighted by area, to derive state-level averages for every month. These methods ensure that PDSI values are not biased towards areas that happen to have more stations clustered close together.

EPA obtained monthly state-level PDSI values from NOAA, then calculated annual averages for each state. To derive totals for the entire six-state region, EPA averaged the state-level data together for each year, weighted by state area. This procedure used total state areas as defined by the U.S. Census Bureau at: www.census.gov/geographies/reference-files/2010/geo/state-area.html.

To smooth out some of the year-to-year variability, EPA applied a nine-point binomial filter, which is plotted at the center of each nine-year window. For example, the smoothed value from 2011 to 2019 is plotted at year 2015. NOAA's NCEI recommends this approach. Figure 3 shows both the annual values and the smoothed curve.

EPA used endpoint padding to extend the nine-year smoothed lines all the way to the ends of the period of record. As recommended by NCEI, EPA calculated smoothed values as follows: if 2020 was the most recent year with data available, EPA calculated smoothed values to be centered at 2017, 2018, 2019, and 2020 by inserting the 2020 data point into the equation in place of the as-yet-unreported annual data points for 2021 and beyond. EPA used an equivalent approach at the beginning of the time series.

For more information about NOAA's processing methods, see the metadata file at: www1.ncdc.noaa.gov/pub/data/cirs/climdiv/divisional-readme.txt. NOAA's website provides additional information regarding the PDSI at: www.ncdc.noaa.gov/sotc/drought/201606.

Feature Development

Various organizations define the Southwest in different ways—sometimes along political boundaries, sometimes along biogeographic or climatological boundaries. For this regional feature, EPA chose to focus on six states that are commonly thought of as "southwestern" and characterized at least in part by arid landscapes and scarce water supplies: Arizona, California, Colorado, Nevada, New Mexico, and Utah. EPA elected to follow state boundaries because several of the data sets are provided in the form of state averages, and because state boundaries are easily understood and relatable to a broad audience.

7. Quality Assurance and Quality Control

NOAA follows extensive quality assurance and quality control (QA/QC) procedures for collecting and compiling COOP weather station data. For documentation of COOP methods, including training manuals and maintenance of equipment, see: www.weather.gov/coop. These training materials also discuss QC of the underlying data set. Pre-1948 COOP data were recently digitized from hard copy. Kunkel et al. (2005) discuss QC steps associated with digitization and other factors that might introduce error into an analysis.

When compiling NWS/COOP records into the *n*ClimDiv data set, NOAA employed a series of corrections to reduce potential biases. Steps include:

- Removal of duplicate records.

- Procedures to deal with missing data.
- Adjusting for changes in observing practices, such as changes in observation time.
- Testing and correcting for artificial discontinuities in a local station record, which might reflect station relocation, instrumentation changes, or urbanization (e.g., heat island effects).

For more information about these bias adjustments, see: www.ncdc.noaa.gov/monitoring-references/maps/us-climate-divisions.php and the references cited therein.

As described in NOAA's metadata file (www1.ncdc.noaa.gov/pub/data/cirs/climdiv/divisional-readme.txt), the Time Bias Corrected Divisional PDSI data set has been adjusted to account for possible biases caused by differences in the time of reporting. A model by Karl et al. (1986) is used to adjust values so that all stations end their climatological day at midnight.

QA/QC procedures for Drought Monitor data are not readily available. Each underlying data source has its own methodology, which typically includes some degree of QA/QC. For example, precipitation and temperature data are verified and corrected by NOAA. Some of the other underlying data sources have QA/QC procedures available online, but others do not.

Analysis

8. Comparability Over Time and Space

Figures 1 and 3. Average Temperatures and Drought Severity

PDSI and temperature calculation methods, as obtained from NOAA's NWS/COOP data set, have been applied consistently over time and space. Although the equipment used may have varied, temperature readings are comparable for the entirety of the data set. The PDSI relies on the same underlying measurements (precipitation and temperature) in all cases. Although fewer stations were collecting weather data during the first few decades of the analysis, NOAA has determined that enough stations were available starting in 1895 to calculate valid index and temperature values for the six states presented in this regional feature.

Figure 2. Southwestern U.S. Lands Under Drought Conditions, 2000–2020

The resolution of the U.S. Drought Monitor has improved over time. When Drought Monitor calculations began, many of the component indicators used to determine drought conditions were reported at the climate division level. Many of these component indicators now include data from the county and sub-county level. This change in resolution over time can be seen in the methods used to draw contour lines on Drought Monitor maps.

The drought classification scheme used for the Drought Monitor is produced by combining data from several different sources. Different locations may use different primary sources, or they may use the same sources, but weighted differently. These data are combined to reflect the collective judgment of experts, and in some cases are adjusted to reconcile conflicting trends shown by different data sources over different time periods.

Though data resolution and mapping procedures have varied somewhat over time and space, the fundamental construction of the Drought Monitor has remained consistent.

9. Data Limitations

Factors that may impact the confidence, application, or conclusions drawn from this regional feature are as follows:

1. The feature gives a broad overview of drought conditions in the Southwest and is not intended to replace local or state information that might describe conditions more precisely. Local entities might monitor different variables to meet specific needs or to address local problems. As a consequence, there could be water shortages or crop failures within an area not designated as a drought area, just as there could be locations with adequate water supplies in an area designated as D3 or D4 (extreme or exceptional) drought.

2. Although the PDSI is arguably the most widely used drought index, it has some limitations that have been documented extensively in the literature. While the use of just two variables (precipitation and temperature) makes this index relatively easy to calculate over time and space, drought can have many other dimensions that these two variables do not fully capture. For example, the PDSI loses accuracy in areas where a substantial portion of the water supply comes from snowpack, which includes major portions of the Southwest.

3. Because this feature focuses on regional trends, it does not show how drought conditions vary by state or sub-state jurisdiction. For example, even if half of the Southwest suffered from severe drought, Figure 3 could show an average index value close to zero if the rest of the region was wetter than average. Thus, Figure 3 might understate the degree to which droughts are becoming more severe in some areas while other places receive more rain as a result of climate change.

4. Indices such as the U.S. Drought Monitor seek to address the limitations of the PDSI by incorporating many more variables. The Drought Monitor is relatively new, however, and cannot yet be used to assess long-term climate trends. With several decades of data collection, future versions of Figure 2 should be able to paint a more complete picture of trends over time.

5. The drought classification scheme used for Figure 2 is produced by combining data from several different sources. These data are combined to reflect the collective judgment of experts and in some cases are adjusted to reconcile conflicting trends shown by different data sources over different time periods.

6. Uncertainties in surface temperature data increase as one goes back in time, as there are fewer stations earlier in the record; however, these uncertainties are not likely to mislead the user about fundamental trends in the data.

7. Biases in temperature measurements may have occurred as a result of changes over time in instrumentation, measuring procedures (e.g., time of day), and the exposure and location of the instruments. Where possible, data have been adjusted to account for changes in these variables. For more information on these corrections, see Section 7.

10. Sources of Uncertainty

Time biases for COOP temperature data are known to be small (< 0.3°F), while error estimates for the PDSI and Drought Monitor are unavailable. It is not clear how much uncertainty might be associated with the component indices that go into formulating the Drought Monitor or the process of compiling these indices into a single set of weekly values through averaging, weighting, and expert judgment.

11. Sources of Variability

Conditions associated with drought naturally vary from place to place and from one day to the next, depending on weather patterns and other factors. Figure 1 deliberately shows spatial variations, while addressing temporal variations through the use of multi-year averages. Figures 2 and 3 address spatial variability by presenting aggregate regional trends. Figure 2 smooths out some of the inherent variability in drought measurement by relying on many indices, including several with a long-term focus. While Figure 2 shows noticeable week-to-week variability, it also reveals larger year-to-year patterns. Figure 3 addresses temporal variability by using an index that is designed to measure long-term drought and is not easily swayed by short-term conditions. Figure 3 also provides an annual average, along with a nine-year smoothed average.

12. Statistical/Trend Analysis

The statistical significance of the division-level temperature changes in Figure 1 has been assessed using ordinary least-squares linear regression of the annual data over the full period of record (1895–2020). Of the 38 climate divisions shown, all have positive long-term trends (i.e., increasing temperatures) that are significant at the 95 percent level.

Because data from the U.S. Drought Monitor (Figure 2) are only available starting in the year 2000, this metric is too short-lived to be used for assessing long-term climate trends.

Ordinary least squares linear regression was used to estimate trends in drought according to the PDSI (Figure 3). For this six-state region as a whole, the long-term (1895–2020) trend is statistically significant at the 95 percent level (slope = -0.013 PDSI units per year; $p = 0.002$). Among individual states, all states except for Colorado have experienced statistically significant trends ($p < 0.05$) toward more drought. State-level results are shown in Table TD-1.

Table TD-1. State-Level Linear Regressions for PDSI Drought, 1895–2020

State	Slope	P-value
Arizona	-0.015	0.006
California	-0.013	0.006
Colorado	-0.010	0.088
Nevada	-0.013	0.021
New Mexico	-0.014	0.020
Utah	-0.014	0.023

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