# Present Weather and Climate: Average Conditions

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# **Executive Summary**

This chapter describes the weather and climate of the Southwest, which straddles the mid- and subtropical latitudes and includes the greatest range of topographic relief in the contiguous United States. The key findings are as follows:

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- The climate of the Southwest United States is highly varied and strongly influenced by topographic and land-surface contrasts, the mid-latitude storm track, the North American monsoon, and proximity to the Pacific Ocean, Gulf of California, and Gulf of Mexico. (high confidence)
- The low-elevation Mojave and Sonoran Deserts of Southern California, Nevada, and Arizona are the hottest (based on July maximum temperatures), driest regions of the contiguous United States. The mountain and upper-elevation regions of the Southwest are much cooler, with the Sierra Nevada and mountains of Utah and Colorado receiving more than 60% of their annual precipitation in the form of snow. (high confidence)
- Storms originating over the Pacific Ocean produce most of the cool-season (November to April) precipitation, generating a mountain snowpack that provides much of the surface-water resources for the region as spring runoff. (high confidence)
- Persistent cold pools, also known as inversions, form in valleys and basins during quiescent wintertime weather periods, leading to a buildup of pollution in some areas. (high confidence)
- The North American monsoon is important during the warm season and is most prominent in Arizona and New Mexico where it produces up to half of the average annual precipitation from July to September. (high confidence)
- The Madden-Julian Oscillation (MJO), El Niño-Southern Oscillation (ENSO), Pacific Quasi-Decadal Oscillation (QDO), and Pacific Decadal Oscillation (PDO) contribute to but do not fully explain month-to-month, year-to-year, and decade-to-decade climate variability within the region. (medium-high confidence)

## 4.1 Introduction

The Southwest straddles the mid- and subtropical latitudes, with mountains, landsurface contrasts, and proximity to the Pacific Ocean, Gulf of California, and Gulf of Mexico having substantial impacts on climatic conditions (Sheppard et al. 2002). Much of California has a Mediterranean-like climate characterized by hot, dry summers and mild winters with episodic, but occasionally intense rainstorms. The interior, southern, low-elevation portion of the region, which includes the Mojave and Sonoran Deserts (see Chapter 3 for a geographic overview of the Southwest), contains the hottest (based on summertime maximum temperatures) and driest locations in the United States, a result of persistent subtropical high pressure and topographic effects. Interior northern and eastern portions of the Southwest have lower mean annual temperatures and see a larger seasonal temperature range, greater weather variability, and more frequent intrusions of cold air from the higher latitudes due to increased elevation and distance from the Pacific Ocean and Gulf of Mexico.

During winter, the mid-latitude storm track influences the region (Hoskins and Hodges 2002; Lareau and Horel 2012). Average cool-season precipitation is greatest in the coastal ranges and Sierra Nevada of California by virtue of their position as the first mountain barriers in the path of Pacific storms. Interior ranges receive less precipitation on average, but seasonal snow accumulations can still be quite large and are an essential source of water for the region. During the summer, a notable feature of the climate of the interior Southwest is a peak in precipitation caused by the North American monsoon, a shift in the large-scale atmospheric circulation that brings moisture originating from the Gulf of Mexico, Gulf of California, and Pacific Ocean into the Southwest (Adams and Comrie 1997; Higgins, Yao, and Wang 1997). The influence of the North American monsoon is strongest in Arizona and New Mexico, where up to 50% of the average annual precipitation falls from July to September (Douglas et al. 1993).

## 4.2 General Climate Characteristics

#### Surface-air temperature

The surface-air temperature (hereafter temperature) climatology of the Southwest varies with latitude, distance from large bodies of water, and altitude. The average annual temperature is highest (greater than 70°F) in the Mojave and Sonoran Deserts of southwestern Arizona, southeastern California, and extreme southern Nevada, including Death Valley and the lower Colorado River valley, and greater than 55°F in a swath extending from central California to southern New Mexico (Figure 4.1a). The highest average annual temperatures in the interior Southwest (greater than 50°F) occur in lower altitude regions of southern and western Nevada, the Great Salt Lake Basin, the Colorado Plateau, and the high plains of Colorado and New Mexico. Throughout the Southwest, the average annual temperature decreases with altitude and is lowest (less than 32°F) over the upper elevations of the Uinta Mountains of Utah and the Rocky Mountains of Colorado. The total spatial range in average annual temperature is very large and exceeds 40°F, which contributes to large ecosystem variations (see Chapter 8).

During July, climatologically the warmest month of the year across most of the region, average maximum temperatures exceed 100°F in the low basins and valleys of southeastern California, southern Nevada, and southern and western Arizona and exceed 85°F in lower altitude valleys, basins, and plains throughout the Southwest region (Figure 4.1b). Much lower average maximum temperatures are found along and near the California coast due to the influence of the Pacific Ocean, and at the upper elevations.

During January—climatologically the coldest month of the year across most of the region—average minimum temperatures are highest and above freezing (greater than 32°F) across lower-altitude regions of California, including the Pacific coast and Central Valley, southern Nevada, southern and western Arizona, and southern New Mexico (Figure 4.1c). Elsewhere, January minimum temperatures are below freezing. Although there is a tendency for temperature to decrease with increasing altitude, this relationship is weaker in the winter than in summer because of the tendency of cold-air pools to develop and persist over mountain valleys and basins (Wolyn and McKee 1989; Whiteman, Bian, and Zhong 1999; Reeves and Stensrud 2009). For example, the average minimum temperatures in the Uinta Basin of northeast Utah and the San Luis Valley of Colorado and New Mexico are comparable to those found in the surrounding higher terrain. Similar cold-air pools occur in valleys and basins throughout the Southwest region.

The difference between the average July maximum temperature and average January minimum temperature is smallest (less than 40°F) along and near the Pacific coast and generally smaller over much of California than the interior Southwest due to the moderating influence of the Pacific Ocean (Figure 4.1d). The largest annual temperature ranges are found in the interior mountain valleys and basins of Utah and Colorado that are prone to wintertime cold pools. Throughout the region, including California, the annual temperature range is generally larger in valleys and basins than in the surrounding higher topography.



**Figure 4.1 Temperature climatology of the Southwest (°F, 1971–2000).** Source: PRISM Climate Group, Oregon State University (http://prism.oregonstate.edu).



Figure 4.2 Annual average precipitation in the Southwest, 1971–2000 (in inches). Source: PRISM Climate Group, Oregon State

University (http://prism. oregonstate.edu).

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#### Precipitation

Average annual precipitation varies from less than 5 inches in the lower valleys and basins of southwestern Arizona, southeastern California, and extreme southern and western Nevada to more than 90 inches in portions of the coastal mountains, southern Cascade Mountains, and northern Sierra Nevada of Northern California (Figure 4.2). Large variations in precipitation exist throughout the region due to the influence of topography (Daly, Neilson, and Phillips 1994).

The seasonality of precipitation varies substantially across the Southwest depending on exposure to the mid-latitude westerly storm track during the cool season, the monsoon circulation during the warm season, and elevation. Most of California and portions of Nevada, Utah, and Colorado are strongly influenced by the mid-latitude storm track, with most precipitation falling during the cool season when the mid-latitude storm track is most active (Figure 4.3a). Monsoon precipitation in these areas is less abundant. Most of Arizona, western New Mexico, and portions of extreme southeast California, southern Nevada, southern Utah, and southwest Colorado observe a pronounced peak in precipitation in late summer due to the influence of the monsoon (Figure 4.3b). Since monsoon precipitation is produced primarily by thunderstorms, large spatial contrasts in seasonal precipitation can be found within these areas during individual summers. The high plains and tablelands of New Mexico and Colorado also observe a summer maximum, but with a broader peak due to frequent spring storms prior to the development of the monsoon (Figure 4.3c). This region also receives less wintertime precipitation due to the predominant westerly flow and drying influence of upstream mountain ranges. In central Nevada, Utah, and western Colorado, the seasonal cycle of precipitation is not as pronounced, but generally peaks from March to May (Figure 4.3d). Areas not identified in Figure 4.3 do not have strong seasonal precipitation variations.





#### Snowfall, snowpack, and water resources

A large fraction of the precipitation in the upper-elevations of the Southwest falls as snow, which serves as the primary source of water for the region and enables a winter tourism economy involving skiing, snowboarding, snowmobiling, and other recreational activities. In the Sierra Nevada and mountains of Utah and Colorado, more than 60% of the annual precipitation falls as snow (Serreze et al. 1999). Snowier locations in the Sierra Nevada, Wasatch Mountains, and Colorado Rockies average over thirty feet of snow annually, with lesser amounts in other ranges of the Southwest (Steenburgh and Alcott 2008). Snowfall provides a smaller fraction of the annual precipitation in the mountains of Arizona and southern New Mexico where winter storms are less frequent and the monsoon dominates in the summer (Serreze et al. 1999; Stewart, Cayan, and Dettinger 2004).

The mountain snowpack that develops during the winter serves as a natural water reservoir for the western United States. Snowmelt and runoff during the spring and summer provide most of the surface water resources for the region, with 50% to 90% of the total runoff occurring during the April to July snowmelt runoff season in most Southwest drainage basins (Serreze et al. 1999; Stewart, Cayan, and Dettinger 2004, 2005).

## 4.3 Major Climate and Weather Events

The Southwest is susceptible to hazardous and costly weather and climate events. The greatest social and environmental impacts come from drought, winter storms, floods, thunderstorms, temperature extremes, and air pollution.

#### Drought

The Southwest is susceptible to periods of dryness that can span months to years. The most significant and severe droughts persist for multiple years and result from a diminished frequency or intensity of winter storms (Cayan et al. 2010; Woodhouse et al. 2010). Although water storage and delivery infrastructure (such as dams, reservoirs, canals, and pipelines) helps stabilize municipal water supplies during these droughts, rural, agricultural, and recreational impacts are still sometimes substantial. Seasonal and multiyear droughts also affect wildfire severity (Westerling et al. 2003). Parts of the Southwest experienced relatively wet conditions during the 1980s and 1990s followed by reduced precipitation beginning around 2000 (Cayan et al. 2010). This, in combination with wildfire suppression and land management practices (Allen et al. 2002), contributed to wildfires of unprecedented size, with five states (Arizona in 2002 and 2011; Colorado in 2002; Utah in 2007; California in 2003; and New Mexico in 2011 and 2012) experiencing their largest fires on record at least once during the last decade. Past climatic conditions, reconstructed from tree rings, suggest that droughts lasting up to several decades have occurred in the Colorado River Basin approximately once or twice per century during the last 500 to 1,000 years (Figure 4.5) (Grissino-Mayer and Swetnam 2000; Woodhouse 2003; Meko et al. 2007; Woodhouse et al. 2010).

Drought characteristics vary across the Southwest. For example, Colorado, which has multiple sources of precipitation throughout the year, is less prone to lengthy droughts (Redmond 2003). Droughts in Arizona and New Mexico tend to be strongly related to

## Box 4.1

# Dust and Snow

How dust affects the timing and intensity of snowmelt and runoff in the Southwest is an area of emerging understanding. During the winter and spring, wind-blown dust from lowland regions can accumulate in the mountain snowpack (Figure 4.4) (Painter et al. 2007; Steenburgh, Massey, characteristics in the mountains of the Southwest are ongoing. Better understanding of these variations will help improve the prediction of spring runoff timing and volume, as well as projections of the impacts of climate change on mountain snowpack and ecosystems.



Efforts to better understand the spatial and year-to-year variations in dust accumulation and



Figure 4.4 Dust-covered snow in the Dolores River headwaters, San Juan Mountains, Colorado, 19 May 2009. Photo courtesy of T. H. Painter, Snow Optics Laboratory, JPL/Caltech.

large-scale shifts in the atmospheric circulation associated with the El Niño-Southern Oscillation (ENSO). ENSO refers collectively to episodes of warming and cooling of the equatorial Pacific Ocean and their related atmospheric circulation changes. Warm and cool ENSO episodes are known as El Niño and La Niña, respectively. La Niña years are associated with reduced cool-season precipitation over southern portions of the Southwest region (Redmond and Koch 1991; Cayan, Redmond, and Riddle 1999).

#### Winter storms

Winter storms in the Southwest can produce heavy snowfall, heavy rainfall, flooding, high winds, and large, abrupt temperature drops (Marwitz 1986; Marwitz and Toth 1993; Poulos et al. 2002; Schultz et al. 2002; Steenburgh 2003; White et al. 2003; Neiman et al. 2008; Shafer and Steenburgh 2008). With their close proximity to the Pacific Ocean,



Figure 4.5 25-year running mean of reconstructed (thin line) and observed (thick line) flows at Lees Ferry, Arizona. Adapted from Meko et al. (2007) with permission from the American Geophysical Union.

the coastal ranges and the Sierra Nevada of California experience episodes of heavy precipitation as impressive as any in the United States (Dettinger, Ralph, Das et al. 2011). Narrow corridors of moisture known as atmospheric rivers, which are typically found near or ahead of cold fronts, contribute to many of these episodes (Neiman et al. 2008). Mountains throughout the Southwest, as well as lowlands in the Southwest interior, can experience large, multiday snowstorms that produce hazardous travel and avalanche conditions and play an important role in the regional precipitation, runoff, and water balance (Poulos et al. 2002; Steenburgh 2003). Arctic outbreaks can produce large snow accumulations and blizzard conditions over the high plains and Front Range of eastern Colorado and New Mexico (Marwitz and Toth 1993; Rasmussen et al. 1995; Poulos et al. 2002).

Strong winds, which in some areas are enhanced by coastal and topographic effects, also occur throughout the region. Severe downslope winds occur along several mountain ranges in the Southwest including the Sierra Nevada, Wasatch Mountains, and Front Range of Colorado. These events can produce severe aircraft turbulence and surface wind gusts that exceed 100 miles per hour (Lilly and Zipser 1972; Clark et al. 2000; Grubišić et al. 2008). In Southern California, the Santa Ana winds can produce extreme wildfire behavior and have played important roles in recent megafires in the region (Keeley et al. 2009).

### Floods

Several mechanisms contribute to flooding in the Southwest (Hirschboeck 1988; Michaud, Hirshboeck, and Winchell 2001). During the winter, heavy precipitation associated with landfalling mid-latitude cyclones and concomitant atmospheric rivers can produce widespread flooding in California, Arizona, Nevada, Utah, and New Mexico. Because of its proximity to the Pacific Ocean, proclivity for slow moving, multi-day storms that tap into moisture from the tropics and subtropics, and high mountains with extensive cool-season snow cover, California is especially vulnerable to this type of flooding (Ralph et al. 2006; Dettinger 2011; Dettinger, Ralph, Das et al. 2011).

Climatologists have recently recognized that gigantic cool-season flooding events such as the California Flood of 1861–62 (Null and Hubert 2007; Porter et al. 2011) can be identified in paleoclimate evidence (such as tree rings and sediment layers), with an approximate average recurrence interval of about 300 years. California was sparsely populated during the 1861–62 winter, but recent exercises by the emergency response community suggest that damages and expenses from such a several-week sequence of major storms could today reach \$0.5 trillion to \$1.0 trillion (Dettinger, Ralph, Hughes et al. 2011; Porter et al. 2011).

Flooding can also occur during the spring runoff, especially in years in which the snowpack persists into the late spring and is followed by an early summer heat wave or rain-on-snow event. Such flooding occurred in Utah during the spring and summer of 2011 (FEMA 2011).

Flash floods associated with thunderstorms occur throughout the Southwest, many during the months of the North American monsoon (Hirschboeck 1987; Maddox, Canova, and Hoxit 1980). In some instances, moisture associated with the remnants of decaying tropical cyclones from the eastern Pacific contributes to the flooding (Ritchie et al. 2011). Because of heavy precipitation rates, topographic channeling, and the impervious nature of the land surface in some urban and desert areas, the flooding produced by these thunderstorms can be abrupt and severe. Along the Colorado Front Range, extensive complexes of nearly stationary heavy thunderstorms have produced very destructive flash floods, including the 1976 Big Thompson Flood that killed more than 125 people and the 1997 Fort Collins Flood that produced more than \$250 million in property damage (Maddox et al. 1978; Caracena et al. 1979; Weaver, Gruntfest, and Levy 2000). Given the localized nature of the rainfall produced by these thunderstorms, however, flooding is rarely severe in larger drainage basins.

#### Thunderstorms

Hazardous weather produced by thunderstorms does occur in the Southwest. Lightning, a primary concern for public safety, killed 49 people in the Southwest from 2001–2010, including 26 in Colorado (NWS 2012). Lightning also ignites wildfires and contributes to the regional wildfire climatology (Swetnam and Betancourt 1998). Although damaging hail is rare in most of the Southwest, the hail intensity in eastern Colorado and New Mexico is among the highest in North America (Changnon 1977). In Colorado, the Rocky Mountain Insurance Information Association reported \$3 billion in hail damage during the past 10 years (RMIIA 2012). Strong winds can also accompany thunderstorms and, in some instances, generate severe dust storms (Brazel and Nickling 1986), known as haboobs in Arizona. The dry, low-level environment commonly found over the Southwest during thunderstorms can contribute to the development of microbursts, localized areas of sinking air that generate strong straight-line winds at the surface and are a concern for public safety and aviation. Tornadoes are rare in California, Nevada, Utah, and

Arizona, but have been reported in all four states (NCDC 2012). The frequency of days with tornadoes is, however, much higher in eastern Colorado and New Mexico, which lie on the western edge of "Tornado Alley." In particular, the frequency of tornado days in northeast Colorado is among the highest in the United States (Brooks, Doswell, and Kay 2003).

#### Temperature extremes

Cold and heat waves occur in the Southwest (Golden et al. 2008; Grotjahn and Faure 2008; Gershunov, Cayan, and Iacobellis 2009). Much of California and portions of southern Nevada, southwest Utah, southern Arizona, and southern New Mexico experience generally mild winters, but are susceptible to hard freezes when the storm track plunges far to the south of its average position. Hard freezes damage agricultural crops, ornamental plants, and (through frozen pipes) public and household utilities. Hard freezes causing in excess of \$1 billion in damages and losses in California occurred in December 1990, December 1997, and January 2006 (NCDC 2011). Although net losses are not as great as those in California, early growing-season freezes can also produce agricultural damage in interior regions of the Southwest.

The Southwest also experiences episodes of extended high temperatures that affect ecosystems, hydrology, agriculture and livestock, and human comfort, health, and mortality (Gershunov, Cayan, and Iacobellis 2009; see also Chapter 15). For example, a 2006 California heat wave contributed to more than 140 deaths, 16,000 excess emergency department visits, and 1,000 excess hospitalizations (Knowlton et al. 2009). Such human health impacts are greatly exacerbated by high humidity and high nighttime temperatures (Golden et al. 2008; Gershunov, Cayan, and Iacobellis 2009). (See also the discussions of past and projected extreme climate events in the Southwest in Chapters 5 and 7.)

#### Air quality

As of August 2011, the Environmental Protection Agency had designated at least one county in each Southwest state as being in nonattainment for the National Ambient Air Quality Standards for one or more pollutants (Figure 4.6; see also EPA 2012). During the cool season, persistent cold-air pools that form in mountain valleys and basins can trap emissions (from motor vehicles, wood-burning stoves, industry, etc.) that lead to the formation of secondary particulate matter. During multi-day events, elevated particulate matter levels can develop in large urban areas (such as Salt Lake City, Utah). Even smaller cities in relatively confined valleys (such as Logan, Utah) may experience elevated particulate levels from urban and agricultural emissions (Malek et al. 2006; Silva et al. 2007; Gillies, Wang, and Booth 2010).

Elevated wintertime ozone levels have also been reported during intense temperature inversions in the vicinity of rural natural gas fields (Schnell et al. 2009). In the warm season, quiescent weather conditions, high temperatures, and intense solar radiation can lead to elevated ozone levels. In portions of coastal California, pollutants are often trapped beneath the marine inversion, which is a climatological feature over the eastern Pacific Ocean. Emissions from wildfires can also contribute to particulate matter or ozone production and wind-blown dust can produce elevated particulate matter levels in some areas (Pheleria et al. 2005; Steenburgh, Massey, and Painter 2012).



# 4.4 Climate Variability

The general climate characteristics of the Southwest described in section 4.2 reflect averages over a period of roughly 30 years. There is, however, considerable variability in the climate of the Southwest that occurs from month-to-month (intraseasonal), year-to-year (interannual), and decade-to-decade (interdecadal). In portions of the region, especially California, Nevada, and Arizona, this variability leads to the largest fluctuations relative to the mean in annual precipitation and streamflow in the contiguous United States, posing challenges for water-resource management and drought and flood mitigation (Dettinger, Ralph, Das et al. 2011).

Interannual and interdecadal climate variations in the Southwest are demonstrably related to fluctuations in Pacific sea-surface temperatures (SST) over periods of years to decades, such as the 2- to 7-year ENSO (Dettinger et al. 1998; Higgins and Shi 2001), the Pacific Quasi-Decadal Oscillation (QDO) (Tourre et al. 2001; Wang et al. 2009, 2010), and the Pacific Decadal Oscillation (PDO) (Mantua et al. 1997; Zhang, Wallace, and Battisti 1997). The occurrence and transition from long-lasting droughts to periods of above

normal rainfall have been linked to these very slow changes in the Pacific Ocean (Sangoyomi 1993; Gershunov and Barnett 1998; Brown and Comrie 2004; Zhang and Mann 2005; Wang et al. 2010).

The impact of ENSO on precipitation and drought anomalies over western North America has been studied extensively. It is now well established that ENSO tends to produce the so-called North American dipole, a situation in which relative conditions of precipitation and temperature (high vs. low) occur in opposition simultaneously for the Pacific Northwest and for the Southern California-Arizona-New Mexico area (Dettinger at al. 1998), with marginal influence on conditions for areas in between (Rajagopalan and Lall 1998). This yields a tendency for above-average precipitation and temperatures over the southern Southwest during El Niño winters and below-average precipitation during La Niña winters. Despite these shifts relative to average, extreme episodic precipitation events can occur in either El Niño and La Niña winters (Feldl and Roe 2010, 2011).

Intraseasonal (that is, time scales beyond a few days and shorter than a season) variations in precipitation have been examined for the summer North American monsoon and winter season precipitation (Mo 1999, 2000; Higgins and Shi 2001; Mo and Nogues-Paegle 2005; Becker, Berbery, and Higgins 2011). Over California during winter, these variations have been linked to the Madden-Julian Oscillation (MJO), an atmospheric phenomenon that contributes to cyclical outbreaks of convection near the equator that in turn affect atmospheric circulations over the midlatitude Pacific Ocean (Mo 1999; Becker, Berbery, and Higgins 2011; Guan et al. 2012).

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