Colorado River Basin Climate and Hydrology
State of the Science

April 2020
Western Water Assessment

Chapter 2
Current Understanding of Colorado River Basin Climate and Hydrology

WESTERN WATER ASSESSMENT
A NOAA RISA TEAM

CIRES

CU University of Colorado **Boulder**

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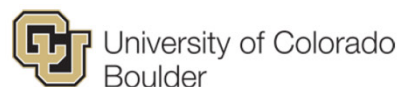
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Volume I
Background and Context

Chapter 1. Introduction

Chapter 2. Current Understanding of Colorado River Basin Climate and Hydrology

Chapter 3. Primary Planning Tools

Volume I of the Colorado River Basin State of the Science report provides important background and context for considering the different datasets, models, and tools described in the subsequent volumes and chapters. Chapter 1 succinctly lays out the need for the report as well as its objectives, intended audience, approach, and organization. It also contains a primer on sources of uncertainty to help readers navigate more focused discussions of uncertainty in later chapters.

Chapter 2 is a technical report unto itself; it describes what is known about the fundamental features of the Colorado River Basin's hydroclimate, their spatial and temporal variability, and the mechanisms behind that variability. This knowledge base is dependent on the primary datasets and models described in Volume II (Chapters 4, 5, and 6) while also informing the productive application of those data and models, and similarly it underpins the application of the weather, climate, and streamflow forecasting methods described in Volume III (Chapters 7 & 8). The chapter concludes with a detailed discussion of recent trends in basin hydroclimate and their likely causes, which provides critical context for the long-term planning datasets described in Volume IV (Chapters 9–11).

Chapter 3 provides a detailed overview of the three primary Reclamation operations and planning models that support basin decision making. It describes the underlying configurations, assumptions, and applications of the three models. The chapter details how these models use observational data, streamflow forecasts, and planning hydrologies as a prelude to the discussion of those inputs in subsequent chapters.

Chapter 2

Current Understanding of Colorado River Basin Climate and Hydrology

Author

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Key points

- On average, about 170 million acre-feet (maf) of precipitation falls over the Colorado River Basin annually, but only about 10% (17 maf) becomes natural streamflow available for use.
- The Upper Basin contributes the vast majority, about 92%, of the total basin natural streamflow as measured at Imperial Dam.
- Elevation dramatically shapes the amount of precipitation and its relative contribution to runoff, so that 85% of annual runoff comes from the 15% of the basin's area that is located in the mountain headwaters.
- The position and activity of the mid-latitude storm track from October through May is the critical climatic driver of annual precipitation in the basin's headwaters.
- Snowmelt is the primary source of annual runoff from those mountain headwaters, as reflected in the prominent late-spring peak in the annual hydrograph.
- Year-to-year variability in runoff is high and is mainly driven by variability in precipitation; decadal and multi-decadal variability in precipitation and in runoff is also present but no consistent cycles have been identified.
- The predictability that does exist at shorter time scales (up to 1 year) comes mainly from the El Niño-Southern Oscillation (ENSO); the ENSO signal is generally weak in the Upper Basin but stronger in the Lower Basin.
- Predictability at decadal and longer time scales using longer-lived climate phenomena (e.g., Atlantic Multidecadal Oscillation, Pacific Decadal Oscillation, etc.) has proven elusive.
- The period since 2000 has been unusually drought-prone, but even more severe and sustained droughts occurred before 1900.
- There has been a substantial warming trend over the past 40 years; the period since 2000 has been about 2°F warmer than the 20th-century average, and likely warmer than at any time in the past 2000 years.
- Decreases in spring snowpack and shifts to earlier runoff timing in many parts of the Upper Basin, as well as decreases in annual Colorado River flows at Lees Ferry, Arizona, have occurred in recent decades. These changes in hydrology can be linked, at least in part, to the warming trend.

2.1   Introduction

Describing the spatial and temporal variability of the Colorado River Basin's hydroclimate, and recent trends in hydroclimate, can help frame expectations of future basin hydrology even before consulting the tools explicitly designed for forecasting and projection. It also provides context for the different datasets and modeling platforms that are considered in

much greater detail in later chapters. Understanding the physical mechanisms that drive basin climate and hydrology, and their links with the global climate system, can also help identify and understand issues with the output of both hydrology models (Chapter 6) and global climate models (Chapter 11).

2.2 Overview of the basin

Within its 240,000 square miles, the Colorado River Basin hosts an extraordinary diversity of hydroclimatic environments across an elevation range from sea level to over 14,000' (4300 m). Some of the mountain headwaters receive over 60" of precipitation per year and have annual average temperatures well below freezing, while the driest desert valleys see 4" of precipitation per year and maximum daily temperatures over 120°F (Figure 2.1). Due to the rugged topography, abrupt climatic gradients are common, with annual precipitation increasing by a factor of up to 5 over less than 20 miles from base to summit of mountain ranges and high plateaus.

The large majority of the basin has an arid or semi-arid climate—that is, under 20" of annual precipitation—and produces little or no runoff. The precipitation returns to the atmosphere as water vapor before reaching a stream by evaporating from soil and open water, sublimating from the snowpack, or transpiring from natural vegetation and crops—processes collectively known as evapotranspiration, or ET. The relatively spatially restricted mountain areas at high elevations, that are wet and cold enough to allow a seasonal snowpack to accumulate, produce a highly disproportionate amount of total basin runoff; about 85% of the average annual runoff is contributed by 15% of the surface area of the basin (Christensen and Lettenmaier 2007). The vast majority of these highly productive headwaters are located in the Upper Basin, primarily in western Colorado, and also in southwestern Wyoming and northeastern Utah. Accordingly, the Upper Basin accounts for, on average, 92% of the total natural streamflow as measured at Imperial Dam (Table 2.1).

Runoff efficiency is highest in the mountainous northern and eastern sub-basins of the Upper Basin (Figure 2.1), averaging 25–30% averaged across those basins. The highest elevation catchments within those sub-basins may see runoff efficiencies of 40–60%. Averaged across the Upper Basin, runoff efficiency is about 16%, and for the entire basin, it is only around 10% (Table 2.1). Both values are comparable to the runoff efficiency estimated for the Upper Missouri basin (about 12%; McCabe and Wolock 2019), but far lower than the runoff efficiency for the Columbia River Basin and the river basins that head in California's Sierra Nevada (40–50%; Das et al. 2011). Significantly, basins with relatively low runoff efficiency have higher

Colorado River at Lees Ferry

The USGS gage at Lees Ferry, Arizona, number 09380000, records Colorado River streamflows immediately above the mouth of the Paria River, 16 miles downstream from Glen Canyon Dam, and 1 mile above the Colorado River Compact point at Lee Ferry, Arizona.

sensitivity of runoff to variability and changes in both temperature and precipitation (Das et al. 2011).
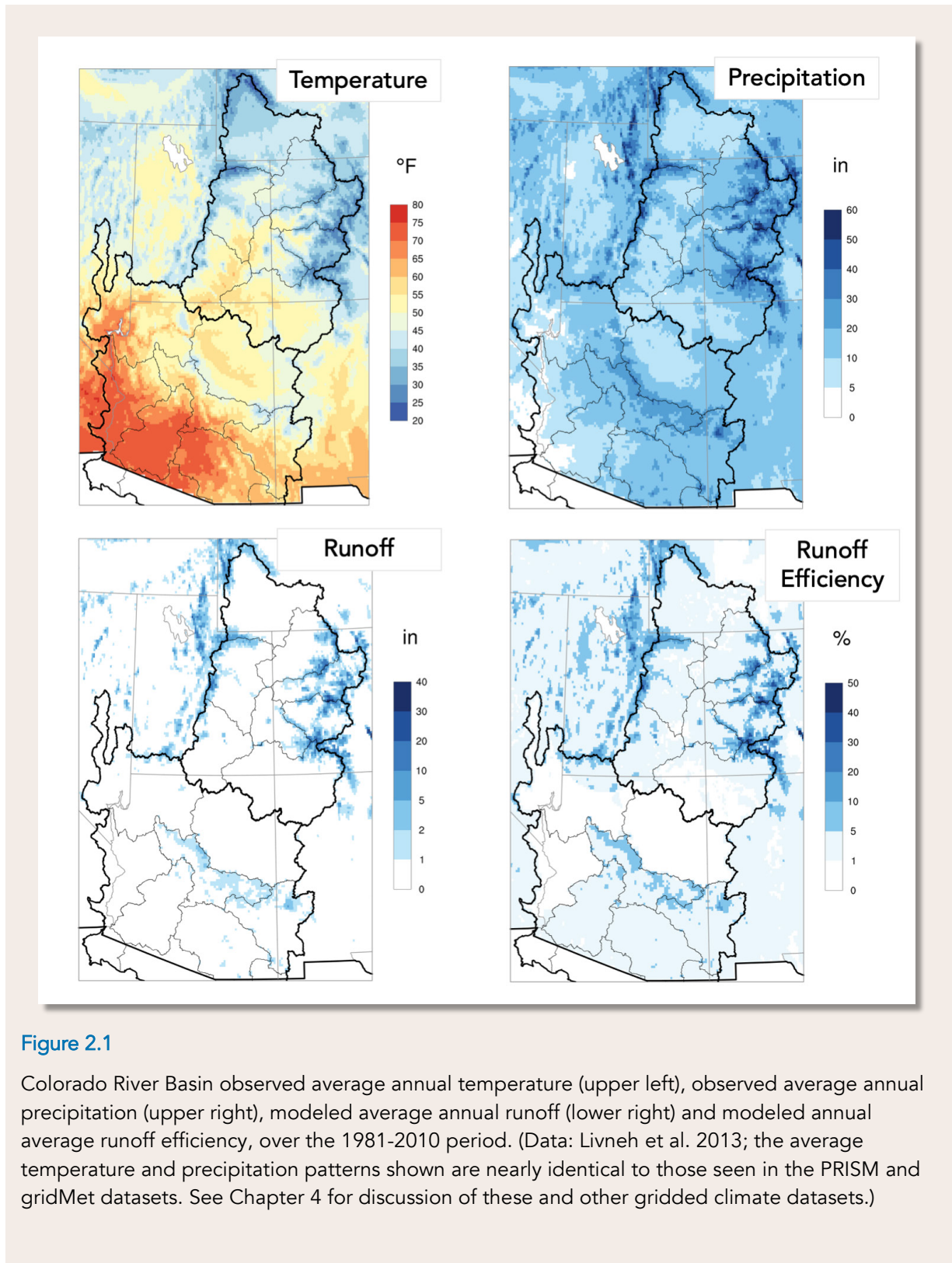
Figure 2.1

Colorado River Basin observed average annual temperature (upper left), observed average annual precipitation (upper right), modeled average annual runoff (lower right) and modeled annual average runoff efficiency, over the 1981-2010 period. (Data: Livneh et al. 2013; the average temperature and precipitation patterns shown are nearly identical to those seen in the PRISM and gridMet datasets. See Chapter 4 for discussion of these and other gridded climate datasets.)

Table 2.1

Long-term (1906–2017) average water-year natural runoff, average water-year precipitation, and calculated runoff efficiency for sub-basins of the Colorado River. (Data: Runoff from Reclamation, after Prairie and Callejo (2005) except for Gila River; Gila River from Lukas, Wade, and Rajagopalan (2013); Precipitation from NOAA NCEI).

Basin or Sub-basin (gage)	Natural Streamflow (maf)	Proportion of Colorado River at Imperial Runoff (%)	Precipitation (maf)	Runoff Efficiency (%)
Green River (nr Green River, UT)	5.4	34%	92 maf Upper Basin Total	16%
Colorado River (nr Cisco, UT)	6.8	42%		
San Juan River (nr Bluff, UT)	2.1	13%		
Total Upper Basin (Colorado River at Lees Ferry)	14.8	92%		
Inflows between Powell and Mead	0.8	5%	78 maf Lower Basin Total (includes Gila River Basin)	3%
Inflows between Mead and Imperial Dam	0.4	3%		
Total inflows between Powell and Imperial Dam	1.3	8%		
Total Colorado River above Imperial Dam	16.1	100%		
Gila River (nr Dome, AZ at mouth)	1.1			
Total Colorado River at Yuma, AZ	17.2		170 maf	10%

Because the vast majority of basin-wide runoff comes from mountain headwaters that are mainly restricted to the periphery of the Upper Basin, the assessment of past variability and likely future changes in Colorado River hydrology will be more meaningful if focused on these headwaters areas. However, these critical mountain areas have fewer and shorter observational records, and are more difficult to represent in models than the more extensive low- and mid-elevation regions of the basin.

2.3 Moisture sources, storm tracks, and seasonality of precipitation

The broad spatial patterns of annual precipitation and runoff in the Colorado River Basin described above, while largely driven by topography, also result from the dynamic motions of the atmosphere over the basin, including upper-level winds, storm tracks, and convergence of air masses. These atmospheric dynamics, while very chaotic on shorter time scales (i.e., weather), have some regularity on seasonal time scales. Accordingly, they help create distinct patterns of seasonality in precipitation across the basin (Figure 2.2), as well as some of the broad gradients in average annual precipitation (Sheppard et al. 2002).

During the cool season, the primary moisture source for precipitation over the basin is the Pacific Ocean. In summer, the Gulf of California is the main source of moisture for the Lower Basin (Jana et al. 2018). In spring and summer, the Gulf of Mexico becomes a secondary moisture source for the far eastern portions of the basin. Also during spring and summer, a considerable fraction of precipitation across the basin is "recycled"— derived from moisture that has evaporated from the land surface (Jana et al. 2018).

Starting off the water year, October is usually a transitional month as the atmospheric patterns characteristic of winter emerge. Rapid cooling in the Arctic drives increasingly large north-south contrasts in temperature between the tropics and the polar regions. This temperature contrast both strengthens the prevailing westerly winds and promotes the development of mid-latitude cyclonic storms and other disturbances. The core of the upper-level westerly winds, the polar jet stream, also shifts southward at this time. Storms preferentially form along the jet stream's path, and then tend to follow that path eastward, so the "storm track" or preferred pathway for storms is largely determined by the jet stream's location throughout the cool season.
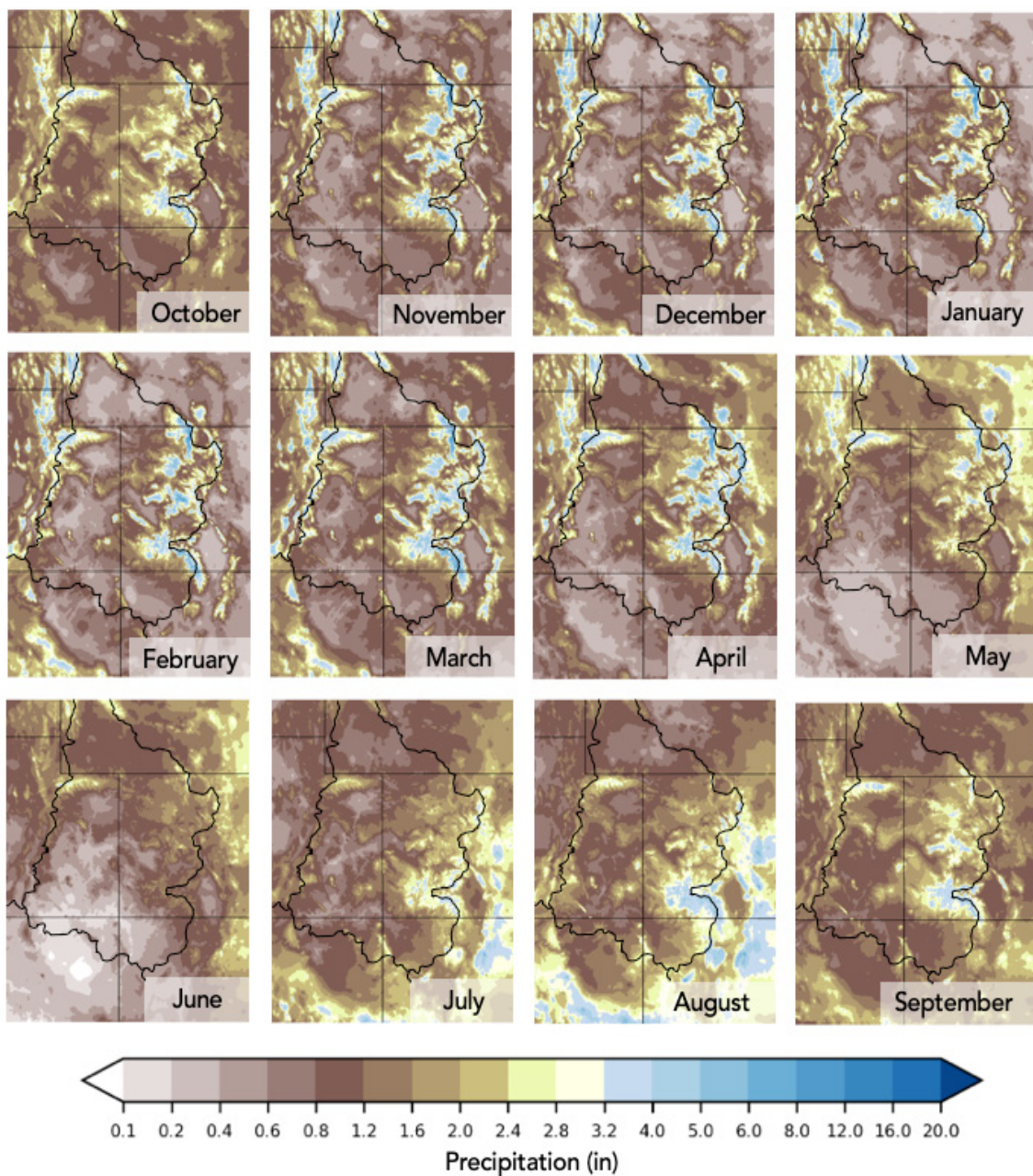
Figure 2.2

Average monthly precipitation (1981–2010) for the Upper Basin and headwaters of the Lower Basin. See text for description of the seasonally varying processes that contribute to these patterns. (Source: PRISM 800-m gridded data http://prism.oregonstate.edu; maps were generated by the Western Regional Climate Center https://wrcc.dri.edu/Climate/prism_precip_maps.php).

The position and activity of the storm track from October through May is the critical climatic driver of annual precipitation in the basin's headwaters, and thus of annual runoff. A single winter storm may bring 5–10% of annual precipitation to portions of the Upper Basin headwaters, so the occurrence of a handful of strong storms can make the difference between a drought year and a normal runoff year for the basin, or between a normal year and a wet year (Bolinger, Kummerow, and Doesken 2014). While individual storms move across the basin in 1–2 days, the storm track that they follow may persist in one location for several days to a few weeks.

In midwinter (December–February), as the north-south temperature gradients reach their maximum, the mid-latitude storm track can split, and storms that follow the southern track will impact Lower Basin headwaters such as the Mogollon Plateau. These storms are less frequent than those affecting the Upper Basin but usually carry more moisture, drawing from more southerly and thus warmer Pacific moisture sources. Some of the storms reaching the West Coast along either pathway may entrain very long and concentrated plumes of low-level (<5,000') moisture, known as atmospheric rivers, or AR, originating in the tropical Pacific. AR events have been recognized as the primary mechanism of extreme wintertime precipitation and flooding along the West Coast (Cayan et al. 2016). While the moisture transport in AR events is much reduced by interaction with the Coast Range and Sierra Nevada in California as the storm supporting the AR moves inland, of the 30–60 AR events that reach the West Coast annually, roughly 5–10 events bring substantial precipitation to at least some of the Lower Basin, and 3–6 to the Upper Basin (Ralph et al. 2019).

In April and May, storms affecting the Upper Basin become less frequent as the westerly winds begin to weaken and shift northward, but tend to carry more moisture per storm because of the warmer springtime temperatures. In the Lower Basin, the southern storm track can still be active but the individual storms dry out (Lareau and Horel 2012), initiating a spring dry period of 2–3 months between winter and summer peaks in precipitation. Throughout the entire basin, especially in the Lower Basin, June is a relatively dry month, with infrequent large-scale storm systems and scattered convective storms (i.e., thunderstorms).

In mid to late summer (July–September), intense heating of the land surface of northern Mexico and the Southwest induces a shift in the prevailing winds to southerly, drawing moist subtropical air northward. This pattern is known as the North American Monsoon or NAM (Adams and Comrie 1997; Sheppard et al. 2002). The often-daily convective storms associated with the NAM primarily affect the Lower Basin, with nearly all locations in Arizona and western New Mexico receiving 35–50% of the annual precipitation during the July–September period (Sheppard et al. 2002). As the intrusion of the NAM moisture plume advances northward in late

summer, the southern half of the Upper Basin sees increasing convective activity and precipitation as well (Jana et al. 2018). During the late summer and fall, landfalling Pacific tropical cyclones bring additional substantial moisture to the Lower Basin in some years (Hereford and Webb 1992). The net effect of these typical seasonal spatial patterns (Figure 2.2) is that different parts of the basin have characteristic precipitation seasonality, reflecting both north-south and elevational gradients (Sheppard et al. 2002; Lukas et al. 2014).

The high-elevation headwaters of the Upper Basin have consistently high monthly precipitation from November through April, with generally lower precipitation in the other months. The low and mid-elevations of the Upper Basin have a more even distribution, with a May peak from northern Colorado northward, and a fall peak to the south. Locations in the Lower Basin at all elevations have a pronounced peak in July–September associated with the NAM, and a secondary peak in December–March.

2.4   Influence of topography and elevation

As described above, there are general differences between Upper Basin and Lower Basin precipitation and its seasonality that reflect latitudinal (north-south) differences in key atmospheric dynamics. But the land itself—topography and elevation—is even more important in driving the sharp local and regional gradients in precipitation and temperature, with profound implications for water supply.

The key mechanism is *orographic lift*: Moist air masses are forced upslope by the terrain, cooling as they rise above the condensation level, where precipitation can occur (Barry and Chorley 2010). For a given parcel of moist air, the more rapid the vertical uplift, the greater the precipitation rate. Most mountain ranges in the Upper Basin are oriented north-south, creating abrupt barriers to the prevailing westerly moisture flow and enhancing orographic lift. Precipitation rates in a given storm event generally increase with increasing elevation on the windward (usually west-facing) mountainside. This is mirrored on the leeward (usually east-facing) side of the range; the upper elevations of the leeward side generally receive 'spillover' precipitation, but further downslope the air mass becomes progressively drier during its descent, creating a rain shadow effect. These orographic effects on precipitation are most pronounced in the winter when winds are the strongest (Redmond 2003). In the summer, although winds are weaker and tend to be more southerly or easterly, upslope forcing of moist air masses still occurs and can initiate convective storms over high terrain, such as the Mogollon Rim in Arizona.

The aggregate of these orographic effects accounts for nearly all of the local-scale variability in annual and monthly precipitation shown in Figures

orographic lift

A process in which air is forced to rise and subsequently cool due to physical barriers such as hills or mountains. This mechanism leads to increased condensation and precipitation in higher terrain.

2.1 and 2.2. Typically, range and plateau crests receive 2–5 times more precipitation than the adjacent basins or valley bottoms (Redmond 2003). The familiar gradient in temperature with increasing elevation also has a predictable physical basis; temperatures cool by about 3.5°F per 1000' of elevation gain due to falling atmospheric pressures with elevation (Sospedra-Alfonso, Melton, and Merryfield 2015). In winter, this relationship weakens at lower elevations due to the propensity for denser cold air to pool in basins and valley bottoms, leading to localized temperature inversions, especially when snow is on the ground. But on an annual basis, the observed gradient in temperature mirrors the gradient in precipitation in that both very closely reflect the topography (Figure 2.1). Gridded climate data products (see Chapter 4) must emulate these gradients in order to realistically interpolate temperature and precipitation values between weather stations.

From the standpoint of water balance and runoff, the elevation-related precipitation and temperature gradients operate in the same direction: compared to lower elevations, higher elevations see both greater moisture inputs (i.e., precipitation) *and* lower ET losses, due to cooler temperatures and increased cloudiness reducing incoming solar radiation. Also, at higher elevations, a greater fraction of precipitation falls as snow, which is less susceptible to atmospheric re-uptake than rain. As an example, elevations near treeline (about 11,500') in western Colorado typically receive about 40" of precipitation annually, mostly as snow, and hydrologic modeling (Chapter 6) suggests that roughly 50% (20") of that is lost to ET, leaving 20" of runoff (Figure 2.1). A nearby mid-elevation site at 8000' may receive about 20" of precipitation annually, about half as snow, but roughly 80% of the precipitation (16") is lost to ET, leaving 4" of runoff—80% less runoff than the high-elevation case.

2.5   The basin's snowmelt-dominated hydrology

As indicated in the previous discussion, a disproportionate share of basin-wide precipitation falls in the high-elevation headwaters, where it also falls primarily as snow (Figure 2.3). These cooler mountain areas see lower fractional ET losses in all seasons, and precipitation falling as snow is less prone to ET losses than rain, particularly when falling on a snowpack surface and insulated from ground warmth. Accordingly, like most other basins in the western U.S., the primary component of runoff in the Colorado River Basin is snowmelt. Multiple studies have estimated the contribution of snowmelt to annual streamflow for portions, or all, of the mountainous West ranging from 60% to 85%, as compiled in Li et al. (2017). The most recent West-wide modeling analysis estimated that the contribution of snowmelt to total Upper Basin runoff is 71%, with a higher fraction (>80%) in the high-elevation headwaters sub-basins (Li et al. 2017).

For comparison, just about 50% of the total Upper Basin precipitation falls as snow (Rumsey et al. 2015); thus, the snow fraction of basin-wide annual precipitation has over twice the runoff efficiency of the rain fraction.
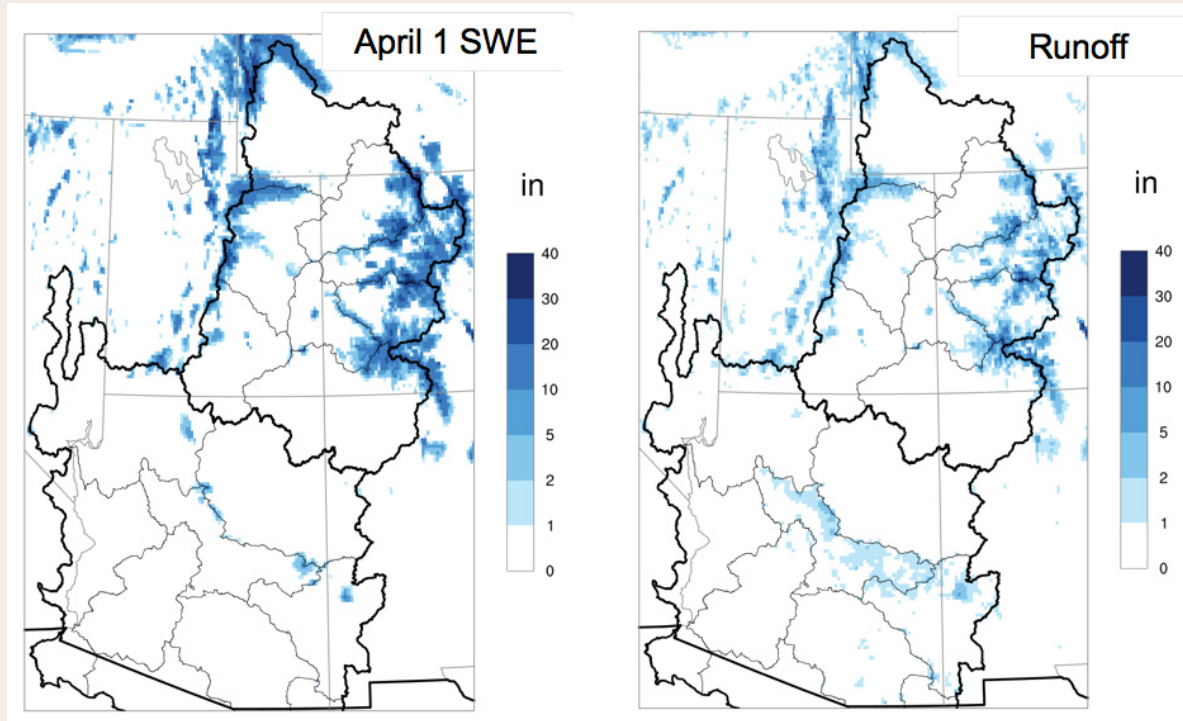
Figure 2.3

Colorado River Basin modeled average April 1 snow water equivalent (SWE; left), and modeled average annual runoff (right). Note that the areas producing >1" of runoff in the Upper Basin closely coincide with the areas in which a seasonal snowpack builds. In the Lower Basin, much of the snowpack has already melted out by April 1; the snowpack is more extensive on March 1. (Data: Livneh et al. 2013)

The peak value of seasonal snow water equivalent (SWE), which usually occurs within 3–4 weeks of April 1 for most of the Upper Basin's headwaters (see Figure 2.4), is an excellent predictor of April–July runoff and thus is closely monitored (Chapter 5) for runoff forecasting and water-supply planning (Chapter 8). The snowpack of the basin is effectively an enormous seasonal reservoir that fills and empties every year. This reservoir has average seasonal peak volume of 17–18 maf in the Upper Basin, equivalent to 70% of the capacity of Lake Powell, according to spatial SWE estimates (Schneider and Molotch 2016; see Chapter 5).

The basin's snowpack accumulates over a 4- to 7-month period, with accumulation typically beginning in October at higher elevations in the Upper Basin, and beginning increasingly later in the fall or winter as one

moves downslope and southward in the basin. The winter climate (November–March) in the Upper Basin is colder than in the other mountain regions of the western U.S. (Lute, Abatzoglou, and Hegewisch 2015) and so the snowpack is less prone to melt loss prior to the spring peak. The peak SWE value in wind-sheltered locations at high elevations (e.g., SNOTEL sites, Chapter 5) typically averages 15"–50" in the Upper Basin, and 3"–10" in the Lower Basin (Figures 2.3 and 2.4).
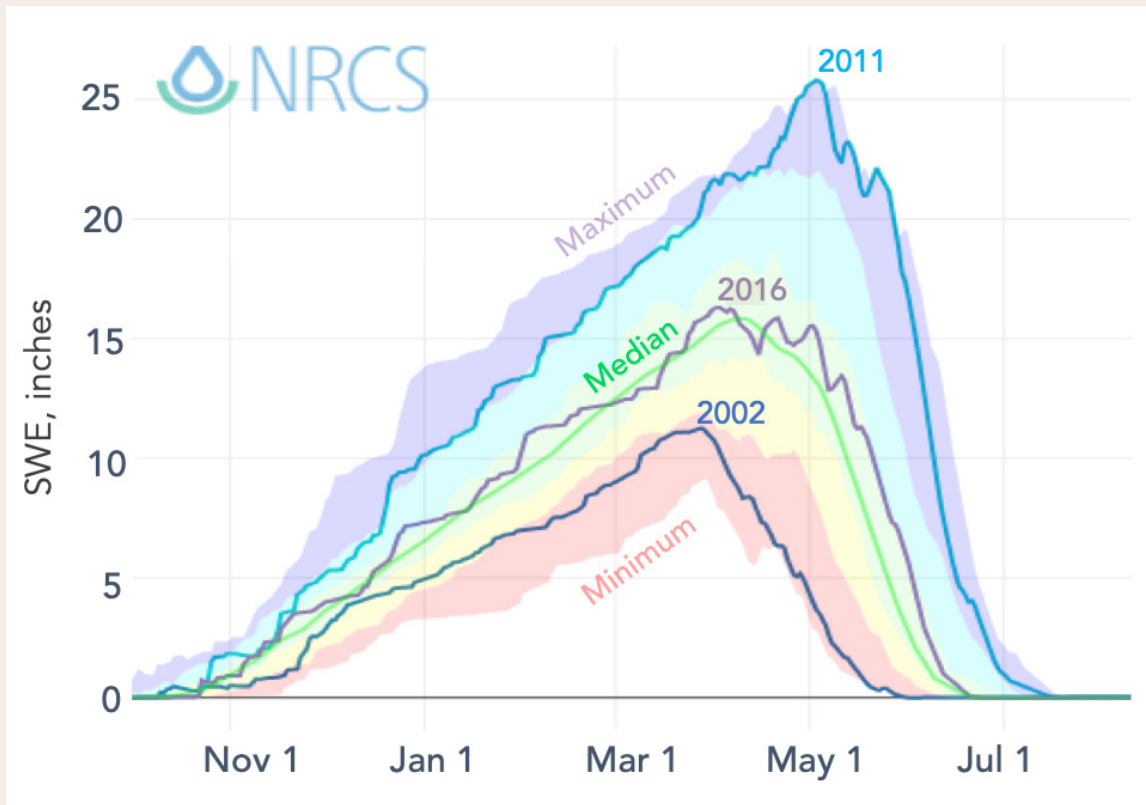
Figure 2.4

Historical snowpack accumulation and melt curves for the Colorado River headwaters above Cameo (average of ~30 SNOTEL sites), shown in inches of snow water equivalent (SWE). The colored shaded bands are bounded by the following percentiles (1981-2010): 1st (minimum), 10th, 30th, 70th, 90th, and 100th (maximum). Selected years are shown to illustrate a much-above-normal snowpack (2011), a near-normal snowpack (2016), and a much-below-normal snowpack (2002). Note that larger snowpacks tend to peak later, and that smaller snowpacks have slower daily melt rates, i.e., the declining limb is not as steep. (Source: adapted from NRCS Colorado Snow Survey)

Field studies and modeling suggest that the equivalent of 10–20% of peak SWE over the basin is lost to sublimation—the transition of water from solid phase directly to gaseous phase—during the course of the season (Hood, Williams, and Cline 1999; Phillips 2013; Hultstrand and Fassnacht 2018). The highest losses occur during the spring months (March–May) when air

temperatures and shortwave (solar) radiation are higher. The meltout of the snowpack occurs over 1-2 months, much faster than accumulation. Snowmelt typically begins in earnest in February or March in the Lower Basin, and in April or May in the Upper Basin. Snowmelt is driven primarily by greater shortwave radiation due to higher sun angles and longer days, though warmer air temperatures, especially above-freezing air temperatures at night, prime the snowpack for faster melt.

The snowmelt rate is enhanced when the snow surface is dusty; typically, 3–10 dust-on-snow events affect parts of the Upper Basin each spring, particularly the San Juan Basin, with the aggregate dust loading and thus impact on melt rates varying substantially from year to year (Deems et al. 2013; Clow, Williams, and Schuster 2016; Painter et al. 2018). See the sidebar in Chapter 5 for further description of the dust-on-snow phenomenon and its effect on basin hydrology.
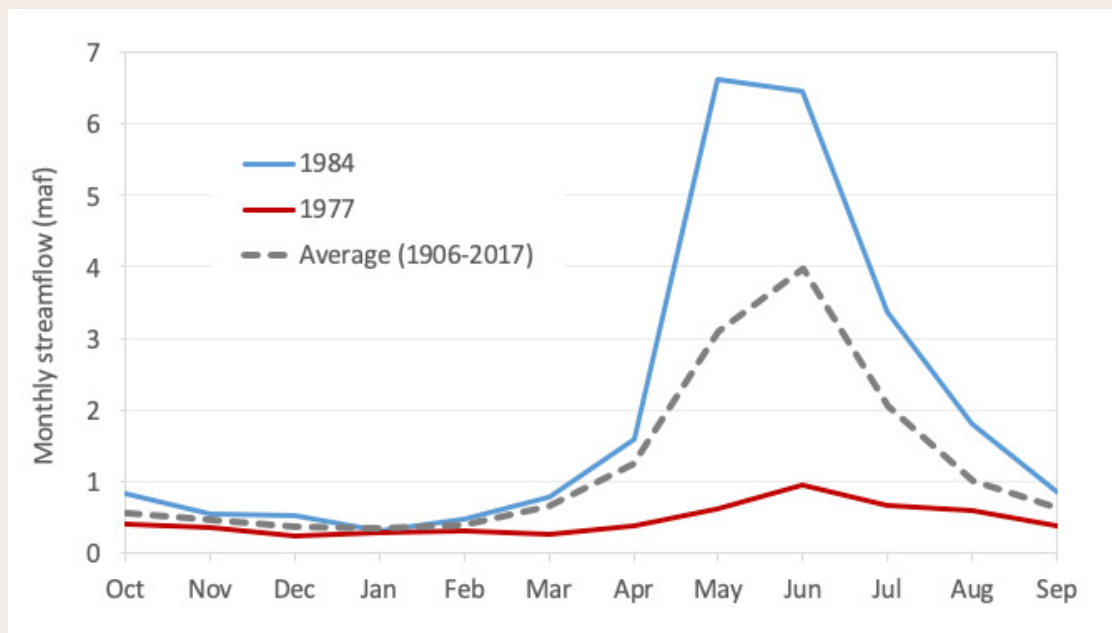
Figure 2.5

Average annual hydrograph (monthly natural flows) for the Colorado River at Lees Ferry for the 1906–2017 period, compared with the annual hydrographs for the lowest-flow year (1977) and the highest-flow year (1984) on record. All three traces show low flows in winter and early spring, the rise to a May/June peak, and declining limb in summer and early fall. (Data: Reclamation, after Prairie and Callejo 2005)

The dominance of snowmelt in driving annual runoff is clearly expressed in the shape of the annual hydrograph for all streams and rivers in the Upper Basin, and for many streams and rivers in the Lower Basin as well. Figure 2.5 shows the long-term average hydrograph for natural flows at Lees

Ferry, with the characteristic rapid rise in spring with snowmelt, a peak typically in May or June, and an equally steep declining limb back to baseflows by late summer. About 70% of the annual flow, on average, occurs during the April–July period typically used for seasonal water supply forecasting, while over 80% of the annual flow occurs during a longer period (March–August) that is more inclusive of snowmelt processes.

While snowmelt contributes the large majority of total runoff in the basin, cool-season (October–April) rainfall at lower elevations can make substantial contributions to runoff in some years, particularly in the Lower Basin. Warm-season (May–September) rain generally makes very little contribution to the basin runoff, because ET rates are much higher during those months, especially during June, July, and August (Julander and Clayton 2018). However, rain during the growing season does play an important role in moderating water demand for agriculture and urban outdoor use.

2.6   Groundwater and surface water

In the Colorado River Basin, as elsewhere, groundwater resources are not quantified or understood nearly as well as surface water resources (Rumsey et al. 2015)—and are not well integrated into basinwide modeling, management, and planning. Groundwater is difficult to observe and manifests in extremely diverse forms, frustrating clear conceptualization and effective management. On one end of the spectrum, a groundwater body (i.e., aquifer) may have very high connectivity with surface waters (streams, rivers, lakes), a residence time of the water measured in weeks or months, and high temporal variability; on the other end, an aquifer may have little connectivity with surface waters, a residence time of thousands of years, and little variability over time apart from withdrawals for human use (Maxwell et al. 2016). In the latter case, the stored water represents recharge accumulated over millennia, including under different climate regimes than at present. Both of these extremes are present in the Colorado River Basin and other basins around the West.

Given the scope of this report, a central question regarding groundwater in the basin is its role in the availability, variability, and predictability of surface water. Using geochemical tracers in stream water that provide evidence of subsurface contact, Miller et al. (2016) estimated that on average about 50% of the (surface) streamflow of the Upper Basin derives from groundwater. In just the high-elevation catchments producing most of the Upper Basin's runoff, the groundwater fraction of streamflow is lower, around 30% (Miller et al. 2016; Carroll et al. 2018).

These may seem like unexpectedly high fractions for a basin with a snowmelt-dominated hydrologic regime, in which the annual streamflow

volume is very strongly correlated with that year's snowpack volume. Groundwater contributions to streamflow in mountain catchments were long believed to be minimal because of low aquifer storage potential and steep hydraulic gradients (Carroll et al. 2018). The resolution of this apparent conundrum is that only a portion of each spring's snowmelt runs off on the surface directly to streams and rivers that same season; instead, much of the snowmelt enters the subsurface and becomes new groundwater. Stored groundwater in high-elevation catchments is displaced by this new snowmelt recharge and discharged to the stream channel as groundwater (Williams et al. 2015). In other words, the new snowmelt volume enters aquifers that have relatively high connectivity, and pushes out a proportional volume of older groundwater to streams.

Miller et al. (2016) also show, as would be expected, that the high-elevation catchments have the highest groundwater discharge to surface water per unit area. In these catchments, the surface drainage network is denser than at lower elevations, and thus subsurface flow paths are generally shorter and shallower, with shorter residence times, mainly on the order of months to several years (Williams et al. 2015; Maxwell et al. 2016). In the lower-elevation catchments of the Upper Basin, which collectively contribute much less to overall basin streamflow, the percentage of surface flow deriving from groundwater is greater, reflecting longer and deeper subsurface flow paths of groundwater to streams, with longer residence times (Miller et al. 2016; Maxwell et al. 2016).

These findings collectively indicate that groundwater is tightly coupled to surface water in the most hydrologically productive catchments in the basin. It also appears that groundwater residence does not significantly modify the climate-driven signal of interannual variability as manifested in snowmelt-runoff volumes. Rosenberg et al. (2013) found that hydrologic model simulations of historical streamflows in the Upper Basin yielded similar skill regardless of whether a representation of groundwater was included in the model. They concluded that the absence of explicit groundwater information in the seasonal streamflow forecast models currently used by the Colorado Basin River Forecast Center (CBRFC) and Natural Resource Conservation Service (NRCS) was probably not detrimental to those forecasts, at least in the Upper Basin (Chapter 8). The CBRFC does model the initial (fall) soil moisture state in their streamflow forecast model (Chapter 5), which may capture variations in shallow groundwater storage as well. Groundwater is closely tied to soil moisture, since most groundwater comes from the fraction of soil moisture that escapes evapotranspiration and percolates down through the unsaturated vadose zone to the water table, recharging the fully saturated groundwater aquifer (Shelton et al. 2009).

2.7 Hydroclimatic variability of the basin

Interannual variability

A critical feature of the natural river system has been the large variability in hydroclimate conditions. Looking first at interannual variability (Figure 2.6), annual precipitation in the Upper Basin has varied by over a factor of 2.1 from the driest water year in the historical record (1977; 11.4") to the wettest water year (1997; 24.4"). Because the fraction of precipitation lost to ET is large (on average, 80% across the Upper Basin) and this fraction is greater in dry years and lower in wet years, the natural streamflow of the Upper Basin is even more variable than precipitation, varying by a factor of about 4.5 from the lowest-flow water year (1977; 5.4 maf) to the highest-flow water year (1984; 24.4 maf).

This difference in the respective extremes of variability implies that the precipitation sensitivity (or elasticity) of streamflow is roughly 2, since a 2-fold change in precipitation is associated with about a 4-fold change in streamflow (Figure 2.6). More explicit assessments using empirical analyses or hydrologic models across the full range of variability suggest that the precipitation sensitivity of streamflow in the Upper Basin is likely between 2.0 and 3.0; i.e., a 10% change in precipitation is associated with a 20-30% change in streamflow (Vano, Das, and Lettenmaier 2012; Hoerling et al. 2019).

The very close similarity between the variability in Upper Basin precipitation and Upper Basin (Lees Ferry) natural streamflow is apparent in Figure 2.6. Statistically, the precipitation record explains 61% of the variance in streamflow over the full period of overlap (1906–2019), and an even higher proportion (74%) over the 1980–2019 period. It is not clear if this apparent increase in the strength of the relationship between precipitation and streamflow in recent decades is a function of increasing robustness of the data underlying the basin-wide precipitation record (see Chapter 4) and the natural streamflow record, or actual changes in the physical relationship.

Temperature does covary with precipitation during the warm season (i.e., dry April–September periods tend to also be warmer than normal, and wet April–September periods tend to also be cooler than normal). Also, temperature has an independent influence on streamflow, as will be detailed later in this chapter. Even so, precipitation is the most important driver of interannual streamflow variability in the basin, by a wide margin (Nowak et al. 2012; Woodhouse et al. 2016; McCabe et al. 2017), which makes it challenging to accurately assess the role of other factors, such as temperature or antecedent (previous fall) soil moisture.
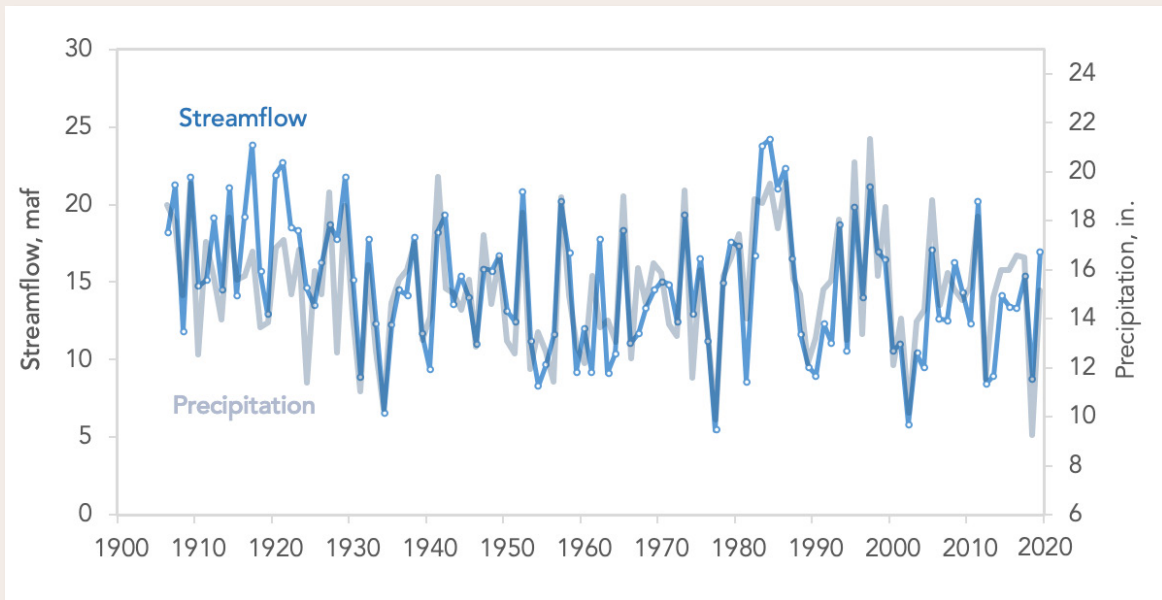
Figure 2.6

Upper Basin water-year precipitation compared with Colorado River at Lees Ferry water-year natural streamflow, 1906–2019. The correlation between the two time-series is 0.77 (R^2 = 0.61) over the entire record, with higher correlations over more recent periods. (Data: precipitation, NOAA NCEI; streamflow, Reclamation)

A common measure of the magnitude of interannual variability in a time-series is the coefficient of variation (CV), which is the ratio of the standard deviation to the mean. A higher CV indicates greater variability. The CV of annual precipitation is 0.16 in the Upper Basin, and slightly higher in the Lower Basin (Table 2.2). As noted above, the variability of annual streamflow is higher than that of precipitation; the CV of Upper Basin (Lees Ferry) annual natural streamflow (1906–2016) is 0.29. This is greater than for annual streamflow of the Columbia River (CV: 0.18; Vano, Das, and Lettenmaier 2012) but similar to the median CV (0.31) of the annual streamflow of 1,221 rivers in a global database (McMahon et al. 2007). Variability in annual streamflow is much higher in the Lower Basin compared to the Upper Basin, because the warmer climate and greater fractional ET losses further accentuate the variability in precipitation. For example, Little Colorado River annual gaged streamflow has a CV of 0.73 (1906–2016), comparable to the CV for the relatively unimpaired headwaters of the Salt River, which share a watershed divide with the Little Colorado. The interannual variability in streamflow itself varies in magnitude over time (Pagano and Garen 2005).

Table 2.2

Variability and persistence in basin precipitation and streamflow over the 1906–2016 period. See text for explanation of indices. (Data: runoff from Reclamation, after Prairie and Callejo (2005); precipitation from NOAA NCEI)

Region/gage and variable	Coefficient of Variation (CV)	Lag-1 Persistence
Upper Basin annual precipitation	0.16	-0.10
Lees Ferry annual natural streamflow	0.29	0.23
Lower Basin annual precipitation	0.21	-0.01
Little Colorado annual gaged streamflow	0.73	0.05

Another important dimension of variability is persistence: the degree to which one year's value is similar to the previous year's value. Greater persistence indicates a tendency toward longer runs of wet years and dry years, with implications for storage needs and reservoir management. In both the Upper and Lower Basins, this year-on-year persistence (lag-1 autocorrelation) of Upper Basin annual precipitation over the 1906–2016 period is not statistically significant (Table 2.2); in other words, there is no meaningful relationship between current-year precipitation and the next year's precipitation.

Persistence in streamflow is often greater than that for precipitation, since soil moisture and groundwater storage anomalies generally produce a carry-over effect after wet years, as well as after dry years. Upper Basin (Lees Ferry) annual natural streamflow does have significant persistence over the 1906–2016 period, with a lag-1 autocorrelation of 0.23. Lower Basin gaged annual streamflows show less short-term persistence, with lag-1 autocorrelations ranging from 0.05 to 0.10 over the 1906–2016 period for the Little Colorado, Bill Williams, and Virgin Rivers.

Decadal-scale and longer variability

While the large storage capacity of Colorado River Basin reservoirs buffers the system from many impacts of extreme annual variability (e.g., the record low flow year of 1977), departures from average conditions over several years and longer can accumulate into deficits of 20 to 40 maf that heavily deplete system storage, as with the most recent period. Thus, it is important to consider decadal-scale variability in basin precipitation and streamflow, which can be very simply depicted by a 10-year running average on the annual values, as in Figure 2.7 for Upper Basin streamflow.

Over the observed Lees Ferry record, the 10-year running average has varied by about +/-20% of the long-term average streamflow, with peaks above 18 maf in the 1920s and 1980s, and low points of 12.0–12.5 maf in the 1960s and 2000s. The longest excursions away from the long-term average have been on the order of 20–30 years, and occurred roughly around 1906–1930 (above), 1955–1980 (below), and 2000–2019 (below). With so few of these excursions to examine, it is difficult to say from the observed record alone if the 25-year period of 17–18 maf at the beginning of the record is unusual behavior for the system; however, as described below, tree-ring data suggests that it is unusual.

Another way of examining decadal-scale variability is to use a weighted smoothing filter that emphasizes the values occurring in the middle of the smoothing period. This will make apparent any cyclical behavior that has a wavelength similar to the smoothing period. Figure 2.7 shows a 9-year weighted filter applied to the Lees Ferry streamflow record. While the filtered record stays close to the running average for most of the record, after 1980 the filtered record departs from the running average and shows stronger peaks and troughs up through the late 2000s. This quasi-decadal oscillation after 1980 was also seen in a wavelet analysis performed by Nowak et al. (2012). They found this oscillation to be the strongest periodic variability at any wavelength in the observed Lees Ferry streamflow record—but it was only active over the most recent three decades of the record.
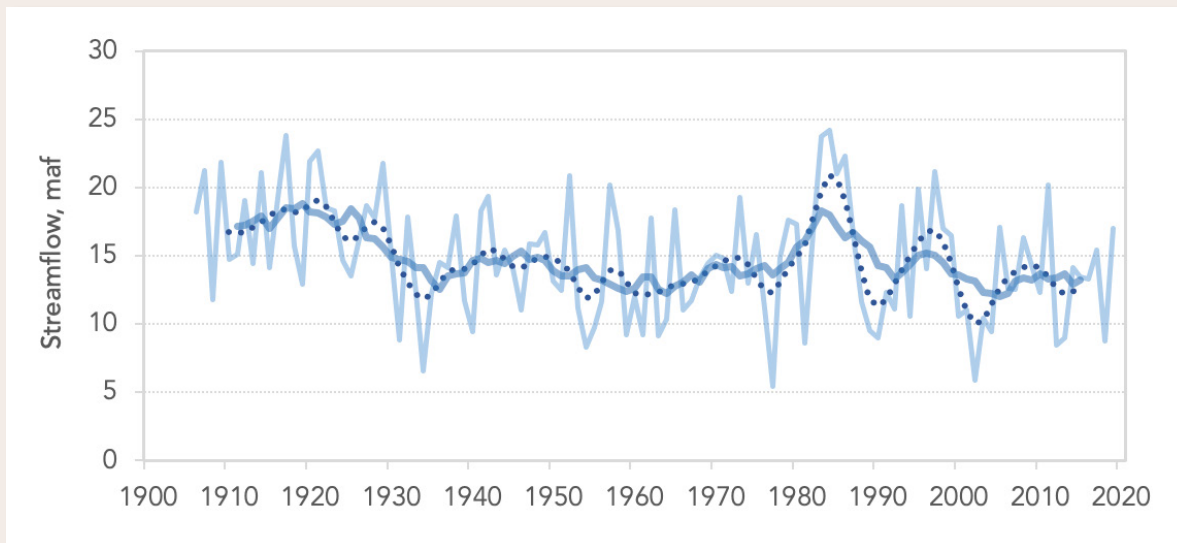
Figure 2.7

Colorado River at Lees Ferry water-year natural streamflow (light blue), with a 10-year running average plotted on the 6th year (dark blue), and a 9-year Gaussian weighted filter (dotted), 1906–2019. (Data: Reclamation)

A much longer perspective on decadal-scale variability in the Upper Basin can be seen in the 10-year running mean of a tree-ring reconstruction of Lees Ferry natural streamflow that spans from the years 762 to 2005 (Figure 2.8; Meko et al. 2007). With this much longer context—about 10 times longer than the observed record—the extended high-flow period from 1906–1930 appears to be quite unusual, with only two prior periods (late 1100s and early 1600s) that appear to be comparable. On the opposite extreme, there appear to be many extended low-flow periods with greater cumulative deficits than the 1955–1980 period, or the current 2000–2018 period. Most notable among these are the low-flow periods of roughly 1865–1905 and 1130–1160. Nowak et al. (2012) also performed a wavelet analysis on a shorter tree-ring reconstruction of Lees Ferry flows (back to 1490) and found that a quasi-decadal oscillation was present only intermittently, for no more than 30–40 years at a time, most prominently in the early 1500s, early 1700s, and mid-1800s.

Multi-decadal oscillations (about 20–80 years) were present during most of the 500-year record, but with different characteristic wavelengths. The 30-year running mean of the Meko et al. (2007) Lees Ferry reconstruction (Figure 2.9) shows that oscillations with a wavelength close to 30 years were prominent around 1200, around 1600, and over the historical period from the late 1800s to present. It also indicates that the 30-year average—a period often used in climatology to describe the average climate—is itself subject to substantial variability.

The key message of the reconstructed tree-ring record is that the variability of Colorado River hydroclimate is greater than one would infer from the observed record alone. A diverse array of decadal, multi-decadal, and century-scale flow sequences are present in the tree-ring record. As detailed in Chapter 10, the safest assumption is that any of these sequences could recur in the future due to natural variability alone.
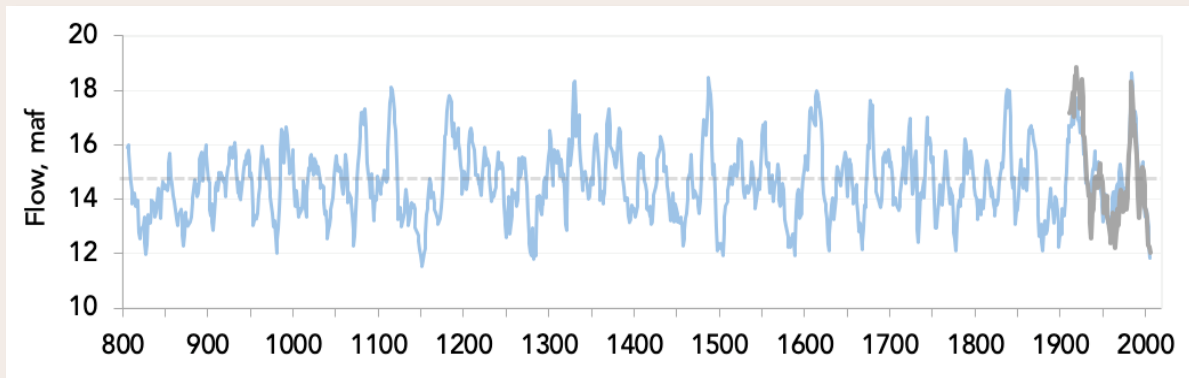
Figure 2.8

The 10-year running average of reconstructed Colorado River at Lees Ferry natural flow 762–2005 (blue) and the 10-year running average of observed natural flow 1906–2005 (gray). The long-term reconstructed mean of 14.7 maf is shown by the dashed line. (Data: Meko et al. 2007; treeflow.info)
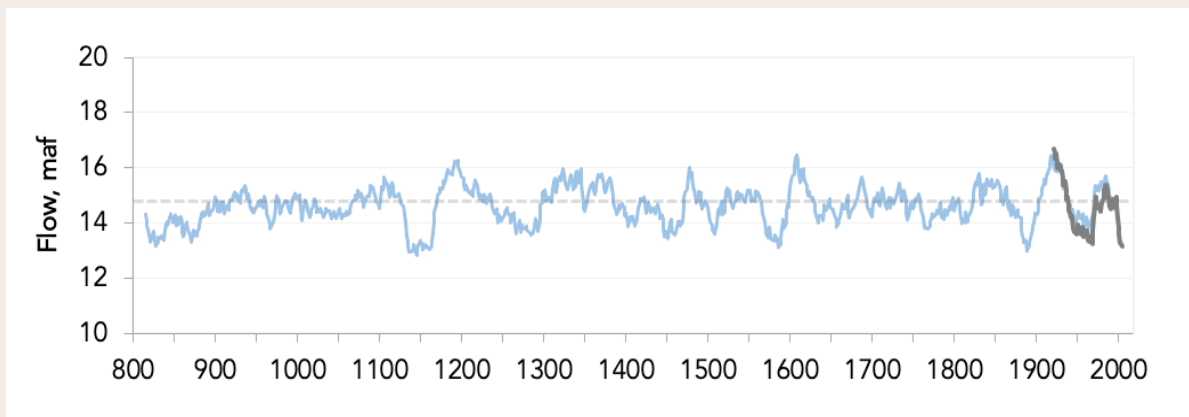
Figure 2.9

The 30-year running average of reconstructed Colorado River at Lees Ferry naturalized flow 762–2005 (blue) and the 30-year running average of observed flow (gray). The long-term reconstructed mean of 14.7 maf is shown by the dashed line. (Data: Meko et al. 2007; treeflow.info)

2.8   Mechanisms of hydroclimate variability and their predictive value

In general, the climate variability described in the previous section is the net effect of chaotic fluid motions in the Earth's atmosphere and oceans as they act to maintain global equilibrium in energy and moisture, or what is called "internal variability." The enormous heat storage capacity and slower movement of the oceans leads to patterns or modes of climate variability that play out over months to years, producing persistent and to some degree predictable influences on weather and climate over vast regions. This last point is especially important given the absence of consistent,

regular hydroclimatic cycles at interannual and longer time scales in the basin.

El Niño-Southern Oscillation (ENSO)

The El Niño-Southern Oscillation, or "ENSO," is the most important pattern of interannual global climate variability, and much of the skill in seasonal climate forecasting around the world is derived from it. The vast tropical Pacific Ocean absorbs tremendous amounts of solar energy that is redistributed northward and southward toward the poles. The key features of ENSO are changes in the sea-surface temperatures (SSTs) of the eastern tropical Pacific Ocean, the atmospheric pressure difference between eastern Pacific high pressure and western Pacific low pressure (the Southern Oscillation), and changes in the location of persistent bands of tropical thunderstorms. The Oceanic Niño Index (ONI) shows the irregular 2- to 7-year time scale of the oscillation between the two phases of ENSO: the El Niño (warm phase) events and La Niña (cold phase) events (Figure 2.10).

teleconnection

A physical linkage between a change in atmospheric/oceanic circulation in one region (e.g., ENSO) and a shift in weather or climate in a distant region (e.g., the Colorado River Basin).
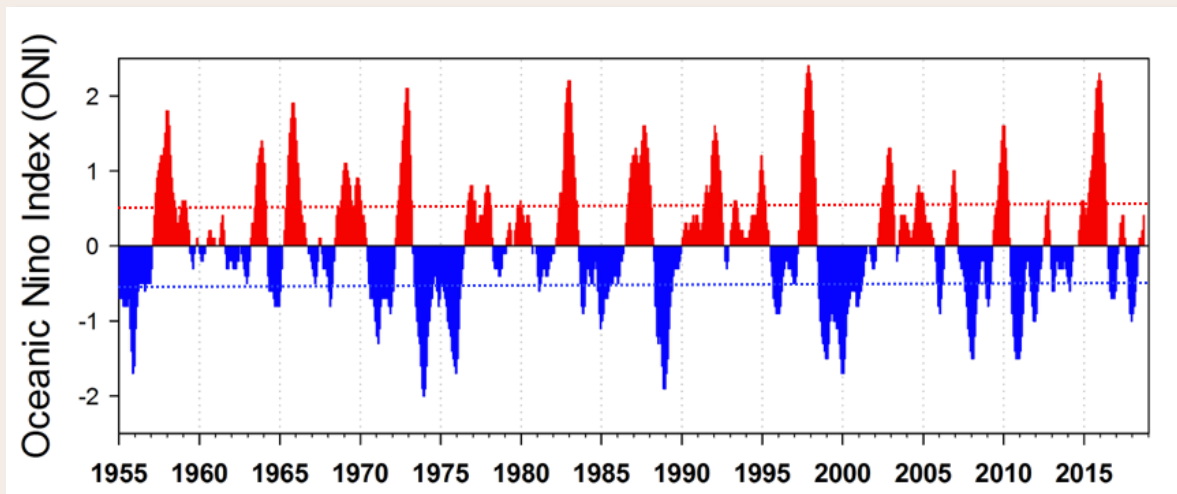
Figure 2.10

The monthly Oceanic Niño Index (ONI), 1955–October 2018. The ONI is a 3-month running average of sea-surface temperatures in the central tropical Pacific (Niño 3.4 region). Values greater than 0.5 (red dashed line) indicate El Niño conditions; values below -0.5 (blue dashed line) indicate La Niña conditions. (Source: NOAA Northwest Fisheries Science Center, https://www.nwfsc.noaa.gov/research/divisions/fe/estuarine/oeip/cb-mei.cfm)

Once an El Niño or La Niña event is established, often during summer, it tends to persist into the following calendar year. Thus, ENSO events impart some memory and seasonal predictability to the global climate system.

The massive transfers of energy accompanying ENSO influence the atmospheric circulation well beyond the tropics, including the position of

the jet stream and storm tracks over western North America (Figure 2.11). These "teleconnection" effects on the West were first described in the 1980s (Redmond and Koch 1991; Bradley et al. 1987). During El Niño events, the position of the cool-season storm track tends to shift southward, or split in two, such that the Southwest (i.e., the Lower Basin) receives higher than normal precipitation, while the Pacific Northwest is drier than normal. La Niña events see a strengthening of the normal winter pattern in which storm tracks are more northerly, and so the case is reversed: The Southwest tends to be drier than normal during La Niña, while the Pacific Northwest is wetter than normal (Cayan, Redmond, and Riddle 1999).
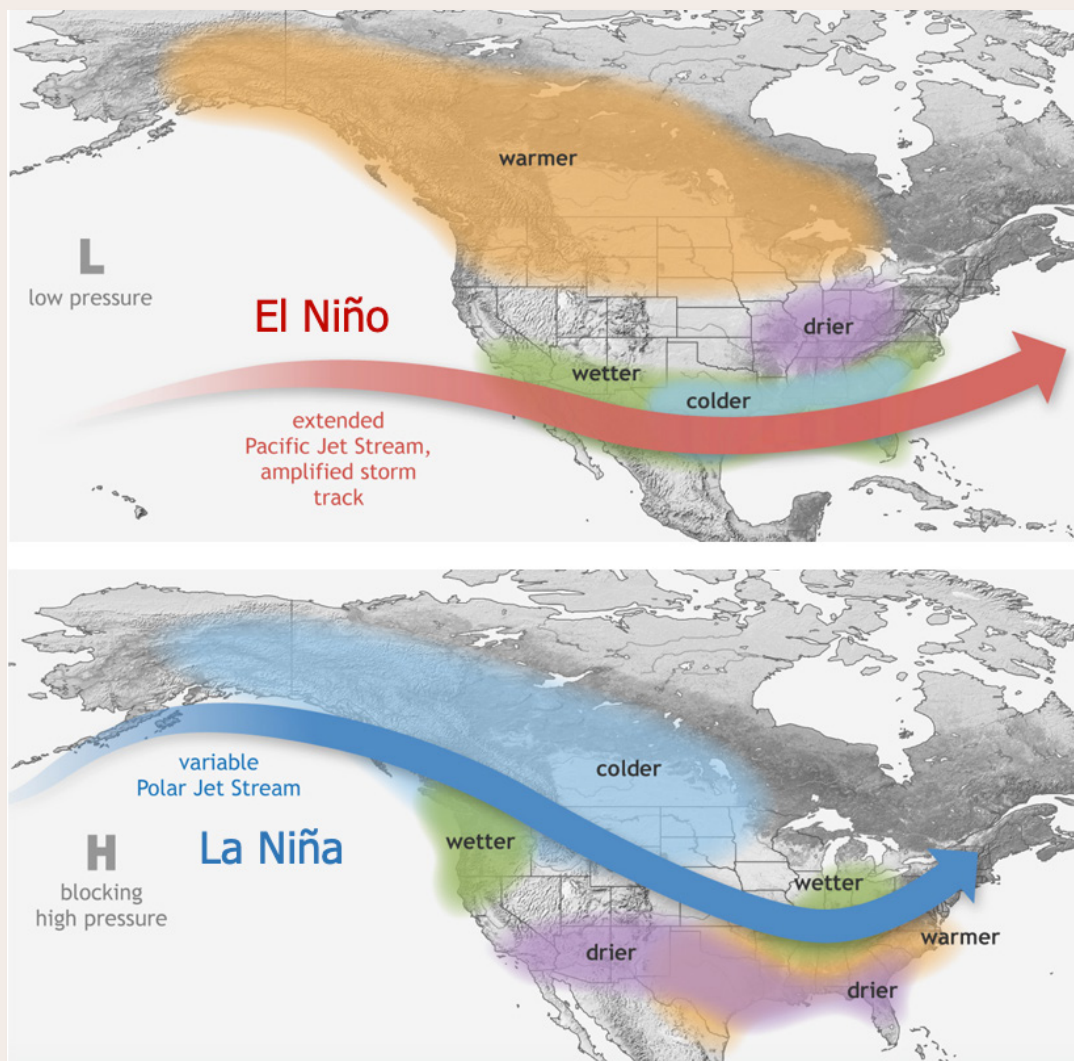
Figure 2.11

Typical changes in atmospheric circulation over North America associated with El Niño and La Niña events, and the corresponding regional climate anomalies that are likely to occur. (Source: adapted from NOAA, https://www.climate.gov/news-features/featured-images/how-el-ni%C3%B1o-and-la-ni%C3%B1a-affect-winter-jet-stream-and-us-climate)

In the past decade, a second "flavor" of El Niño event has been identified, with the maximum SST anomalies located in the Central Pacific (CP) in contrast with the Eastern Pacific (EP). In a CP El Niño, compared to traditional EP El Niño events, the winter drying influence on the Pacific Northwest is enhanced, but the winter wetting influence on the Southwest is similar (Yu and Zou 2013). It appears that CP El Niño events have become more common in recent decades (Freund et al. 2019).

For the Lower Basin, the ENSO influence on hydroclimate is strongest in the winter season, and ENSO state (observed or forecasted) is a better predictor of Lower Basin cool season (October–March) precipitation than of Upper Basin cool season precipitation (Figure 2.12). Note that while the correlations shown for the Lower Basin (r = 0.4 to 0.6) are statistically significant, they also indicate that most of the variability in cool-season precipitation is *not* statistically associated with ENSO. Also, the reliability of the ENSO signal in the Lower Basin is asymmetric: La Niña events are more likely to be dry than El Niño events are likely to be wet.

The Upper Basin lies across the transition region of the Southwest-Pacific Northwest ENSO dipole (Wise 2010), and so ENSO has less overall influence on Upper Basin cool-season precipitation and water-year streamflow than it does in the Lower Basin. Even so, there is some signal that can potentially be exploited for hydroclimate forecasting, especially in the northern and southern sub-basins of the Upper Basin (Figure 2.12).

The Upper Green River basin, and to a lesser extent the headwaters of the Yampa-White and Colorado rivers, tend to mirror the Pacific Northwest; i.e., wetter outcomes in La Niña. This mainly reflects a midwinter (December–February) tendency for the polar jet stream and storm track to be enhanced during La Niña, resulting in wetter conditions over the high elevations of southern Wyoming and northern Colorado, and conversely, more frequent blocking of westerly flow and storms in those areas during El Niño, resulting in drier conditions (Wolter, Dole, and Smith 1999). Further south in the Upper Basin, the San Juan River basin tends to mirror the Southwest and Lower Basin; i.e., wet in El Niño.

For Upper Basin-wide precipitation and streamflows (i.e., Lees Ferry), these opposing tendencies mostly cancel out, and it is hard to discern a clear tendency toward higher Lees Ferry flows in El Niño years and lower flows in La Niña years, even during strong events.
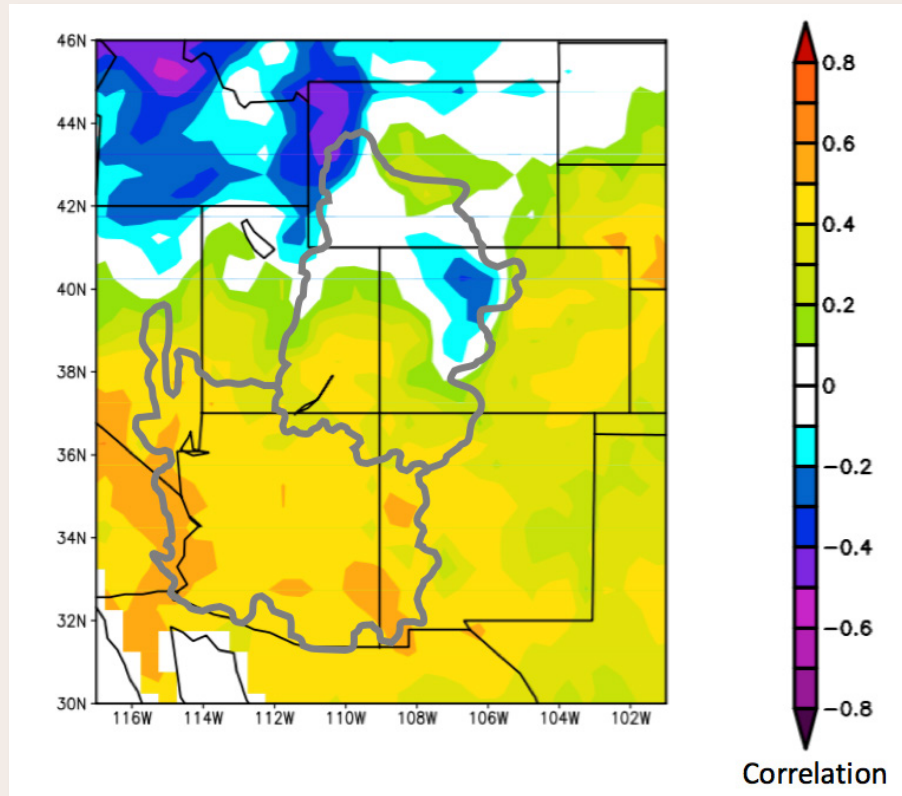
Correlation between October–March precipitation and August–January Niño 3.4 index from 1949–2014. Yellow and orange colors indicate areas that tend to be wetter during El Niño events and drier during La Niña events; blue and purple colors indicate areas that tend to be wetter during La Niña events and drier during El Niño events. (Source: NOAA ESRL Physical Sciences Division)

Figure 2.13 shows Lees Ferry water-year natural streamflows corresponding to El Niño (n = 12) and La Niña (n = 12) conditions in the beginning of the water year (i.e., fall) from 1980–2018. There are no meaningful differences in average or median flow between El Niño and La Niña cases, or between those and the ENSO-neutral cases (n = 14). The behavior at the lower tails of the distributions, however, appears more distinct: While there are no annual flows below 10 maf among the El Niño cases (0 of 12), 3 of 12 La Niña cases have flows below 10 maf, as do 4 of 14 ENSO-neutral cases.
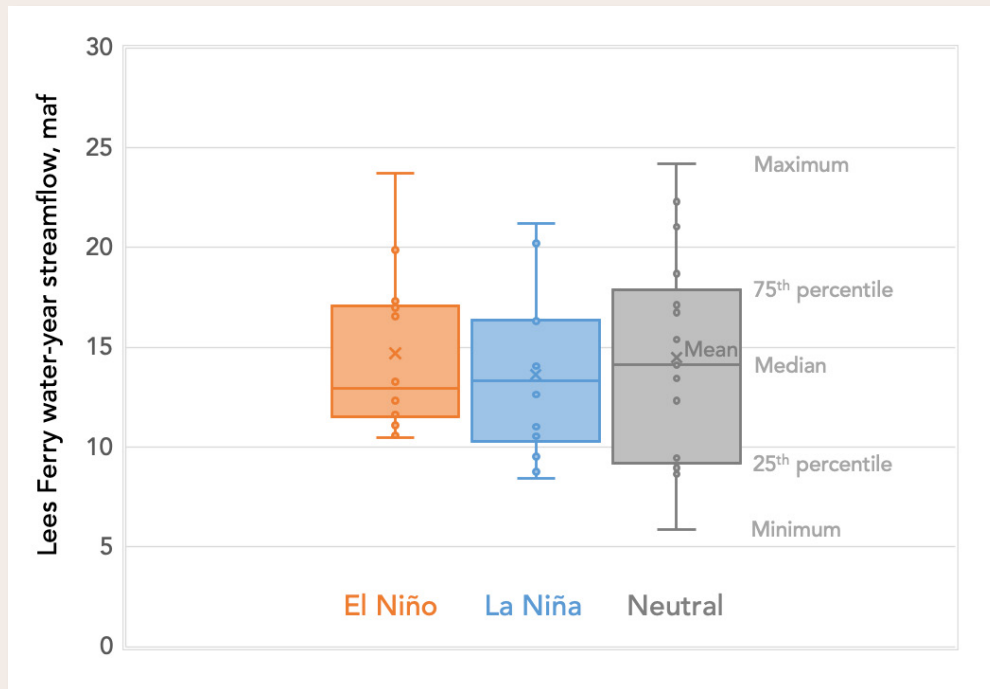
Upper Basin (Lees Ferry) water-year natural flows from 1980–2018, split into three ENSO categories: 12 fall El Niño cases, 12 fall La Niña cases, and 14 fall ENSO-neutral cases. El Niño conditions have been associated with higher average flow ("x" markers) than La Niña, but this difference is not statistically significant, nor are the differences from the average flow during ENSO-neutral years. (Data: Multivariate ENSO Index, K. Wolter; natural flows, Reclamation)

Decadal and multi-decadal oscillations

Pacific Decadal Oscillation (PDO)

In the north Pacific, to the north of the ENSO source region in the tropical Pacific, is the home of the Pacific Decadal Oscillation (PDO). The PDO was identified in the mid-1990s as the principal mode of sea-surface temperature variability in the northern Pacific. The PDO's warm phase has positive (warmer-than-normal, El Niño-like) anomalies in the eastern North Pacific and negative (cooler-than-normal, La Niña–like) anomalies in the central and western North Pacific (Mantua et al. 1997). The main oscillation from warm to cool and back is irregular but usually has a period of 10–40 years, with occasional shorter excursions. The PDO is not a single well-defined physical phenomenon like ENSO, and much of the variation in the PDO may actually be ENSO variability translating to the northern Pacific over longer time scales (Newman, Compo, and Alexander 2003; Newman et al. 2016; Chen and Wallace 2016). The ENSO dipole does appear to be strengthened when PDO is in the same phase as ENSO, so that the Southwest and the Lower Basin have had a stronger wet tendency during

warm PDO + warm ENSO (i.e., El Niño), and a stronger dry tendency during cold PDO + cold ENSO (La Niña) (Gershunov and Barnett 1998; Brown and Comrie 2004; Wise 2010). However, these climate influences of PDO do not appear to be stable over time, which argues against their use in hydroclimate forecasting (McAfee 2014; Wise 2015).

Quasi-Decadal Oscillation (QDO)

The Quasi-Decadal Oscillation (QDO), another Pacific atmosphere-ocean oscillation with similarities to ENSO and PDO, but at an intermediate frequency (9–12 years) and greater regularity, was identified in the early 2000s (Tourre et al. 2001). Like the PDO, it appears to modulate the activity of ENSO. A previously identified quasi-decadal periodicity in levels of the Great Salt Lake since the mid-1800s was found to be coherent with the QDO when a lag time representing hydrologic processes was included (Wang et al. 2011), enabling multi-year forecasts of Great Salt Lake levels, which have since been validated through one-half of a decadal cycle (Gillies et al. 2011; 2015). More recently, Wang et al. (2018), noting that the Upper Basin is adjacent to and atmospherically "downstream" of the watershed of the Great Salt Lake, and that the Upper Basin streamflow also has quasi-decadal periodicity, asserted that there is potential for decadal-scale Upper Basin prediction based on the QDO. However, as noted earlier and shown in Figure 2.7, the quasi-decadal periodicity in Upper Basin (Lees Ferry) streamflow is strongest over the 1980–2015 period, and relatively weak prior to 1980, and it is not clear whether there is a solid basis for using the quasi-decadal oscillation in basin hydroclimate forecasts.

Atlantic Multidecadal Oscillation (AMO)

The Atlantic Multidecadal Oscillation (AMO) (Schlesinger and Ramankutty 1994) is a slowly varying sea-surface temperature and pressure oscillation in the north Atlantic Ocean with an irregular 30–80-year cycle. A series of studies in the early 2000s (Gray et al. 2004; Hidalgo 2004; McCabe, Palecki, and Betancourt 2004) found that the positive (warm) phase of the AMO was statistically associated with increased risk of drought in the Upper Basin. A study using climate models found that the combination of negative PDO phase and positive AMO phase is the least favorable for moisture in the interior U.S. (Schubert et al. 2009).

The trouble with multi-decadal oscillations

Studies in the 2000s on the AMO, PDO and other oscillations raised hopes that observations and predictions of the AMO state, as well as PDO, could lead to better seasonal and longer hydroclimate forecasts for the basin (Reclamation 2007c). However, the physical mechanism by which the AMO actually affects conditions in the interior West is unclear, unlike with ENSO (Nowak et al. 2012). Like the PDO, the stability of the AMO's climate teleconnections over time is questionable. Also as with the PDO, there have been very few cycles of warm and cold phases during the observational

period (since about 1900) to compare with basin hydroclimate indices. Statistical relationships that have been found during the past century may not be representative of future relationships, given the limited number of cases to draw from (Switanek and Troch 2011).

The search for mechanisms of predictability continues

The identification of ENSO and PDO influence on western U.S. hydroclimate has spurred additional studies to identify other potential teleconnections, mainly between gridded Pacific Ocean SSTs and pressure fields and various hydroclimatic indices. By examining statistical relationships among hundreds of variables, these exploratory analyses are at high risk of finding relationships (i.e., teleconnections) that are statistically significant over the period of analysis, but are not rooted in a robust physical mechanism and therefore fail to show predictive skill beyond the period of analysis.

Recently, a new teleconnection was identified between sea-surface temperature and atmospheric pressure anomalies in the southwest Pacific Ocean near New Zealand in the late summer and fall, and winter (November–March) precipitation in the southwestern U.S., including the Lower Basin (Mamalakis et al. 2018). The authors' proposed New Zealand Index (NZI) had generally higher correlations with Southwest winter precipitation than did typical ENSO indicators over the 1950–2015 period. They also noted the strength of the NZI relationship has increased over the entire analysis period, almost doubling. This latter finding indicates volatility in the NZI-Southwest climate relationship and the potential for it to return to statistical non-significance in the future. Also, it is not clear that the NZI has a physical mechanism distinct from ENSO. It is possible that the NZI could be an adjunct to ENSO indicators in statistical forecasts of Southwest winter precipitation, but much more thorough exploration of the teleconnection, including its behavior prior to 1950 and its linkage with ENSO, is needed.

While the search for new teleconnections will undoubtedly continue in the research community, the inconvenient truth appears to be that most of the variability in basin hydroclimate is not associated with oscillations or discrete patterns that would potentially provide predictability on one or more time scales. This does not mean that the skill in seasonal precipitation forecasts cannot be improved (see Chapter 7), but that the skill may have a lower ceiling than both researchers and water managers would like.

2.9 A closer look at basin drought

Having described the overall hydroclimatic variability in the basin, and the key climatic mechanisms associated with that variability, it is important to take a closer look at the lower tail of the distribution of annual

hydroclimatic conditions (i.e., drought), which is the principal recurrent management challenge for water suppliers.

Hydrologic droughts in the basin are generally initiated by below-normal precipitation in the cool season (October–April) due to weather patterns that suppress storm tracks over the headwaters of the Upper Basin. The resulting reduced snowpack produces below normal spring-summer runoff, with an earlier peak. Due to early meltout and the low precipitation leading to below normal soil moisture, the land surface can dry out earlier in the warm season than usual, increasing evaporative demand and creating a feedback toward further warming and drying of the surface. Depletion of soil moisture in a dry year can lead to below normal runoff in the following year even if the precipitation in the second year is near normal (Das et al. 2011).

Analyses of hydrologic drought are complicated by the need to identify meaningful measures and thresholds for what constitutes drought conditions, and thus when droughts begin and end, and their severity over space and time. Which measures and thresholds are meaningful depends on the specific application context. This is especially true for the Colorado River system, in which total consumptive use plus other depletions typically exceeds supply, such that under even average hydrologic conditions the levels of Lake Mead and Lake Powell will tend to decline. The recent declines in mainstem reservoir storage reflect both direct drought impacts and the system imbalance between supply and depletions, and it is difficult to disentangle the two factors. To assess the nature of recent drought conditions, it may be more meaningful to look at natural inflows to the system, such as those estimated at the Lees Ferry gage, than at reservoir levels.

In the water supply analysis in Reclamation (2020) a "streamflow deficit" (i.e., drought) was defined as a two-year average flow less than 15 maf at Lees Ferry. The 2-year averaging acknowledges the buffering capacity of system reservoir storage. By this measure, the most severe drought in the observed record was from 2000–2005 (6 years), with a cumulative deficit of 24 maf, exceeding the 7-year droughts in the 1930s and 1960s, in which the deficits were about 18 maf. There was another 6-year drought from 2012–2017, with a cumulative deficit of 13 maf (Figure 2.14). Multi-year streamflow deficits of greater than 10 maf are clearly a recurrent feature of the basin's hydroclimate, but the period since 2000 appears highly unusual in that it includes two such droughts: the most severe (2000–2005) and the 5th most severe (2012–2017).
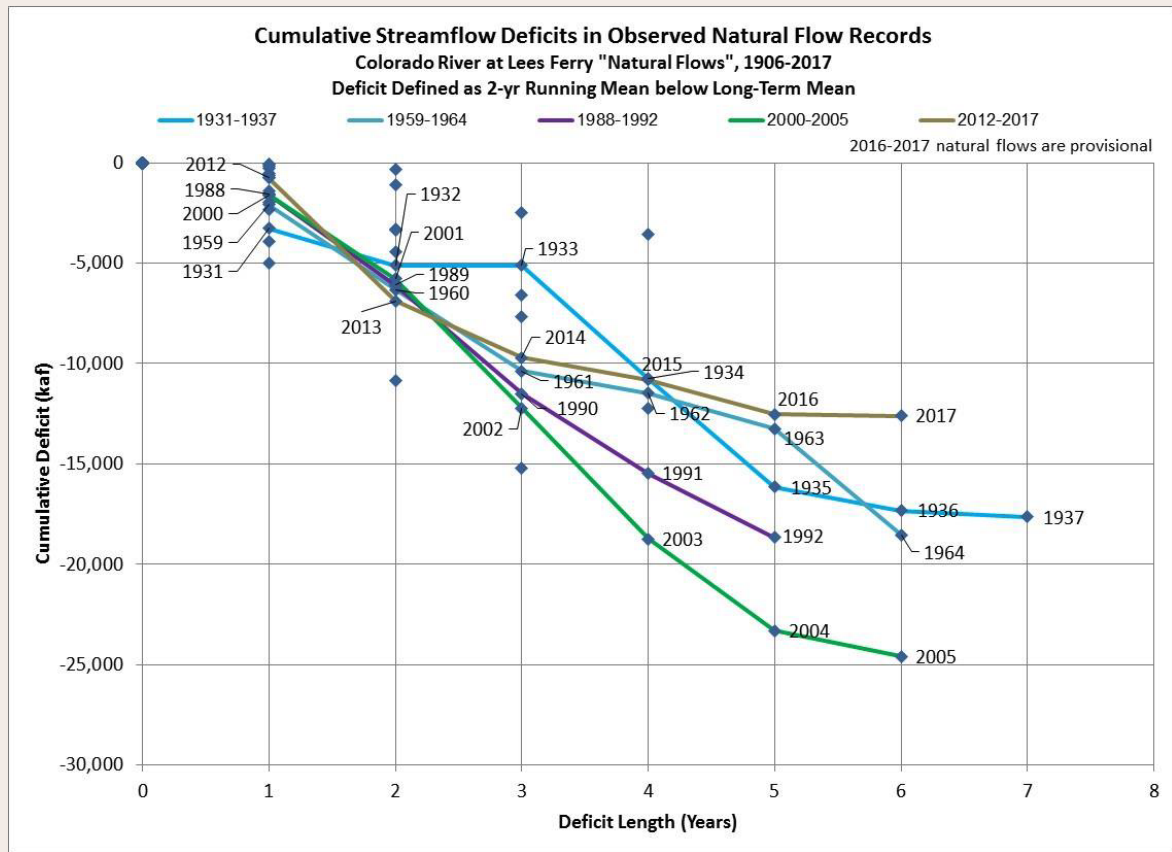
Figure 2.14

Cumulative streamflow deficits (defined as 2-year running mean below 15 maf) for the Colorado River at Lees Ferry, Arizona, with the five longest and most severe droughts (2000–2005, 2012–2017, 1988–1992, 1959–1965, 1931–1937) highlighted. (Source: Reclamation 2020)

Woodhouse (2012) analyzed the atmospheric and oceanic features associated with six multi-year Upper Basin droughts from the 1930s to the 2000s, using a different drought definition than shown in Figure 2.14. Her analysis showed that each extended drought evolves in a unique way. The onset and persistence of some droughts is linked to La Niña events, while in other cases, drought years coincide with El Niño events. Most critically, past multi-year droughts have persisted through a variety of modes of natural variability. A key feature for drought years *not* associated with La Niña events has been a high-pressure anomaly centered over the Pacific Northwest, which tends to deflect storm tracks away from the Upper Basin.

The water supply analysis in the "Colorado River Basin Water Supply and Demand Study" (hereinafter "Basin Study"; Reclamation 2012e) examined the streamflow reconstruction by Meko et al. (2007) and compared the distribution of the reconstructed streamflow deficits during the historical period (1906–2005) with the distribution of reconstructed streamflow deficits (droughts) over the entire reconstruction (762–2005). That analysis showed that most droughts are 3 years or shorter (Figure 2.15). The distribution of deficits over the 20th century is similar to the distribution over the entire >1200-year period, except at the tails; i.e., events of very long duration or high severity, or both. Over the full reconstruction period, droughts with estimated durations of greater than 5 years and estimated cumulative deficits of greater than 15 maf were much more frequent than in the 1906–2005 period.
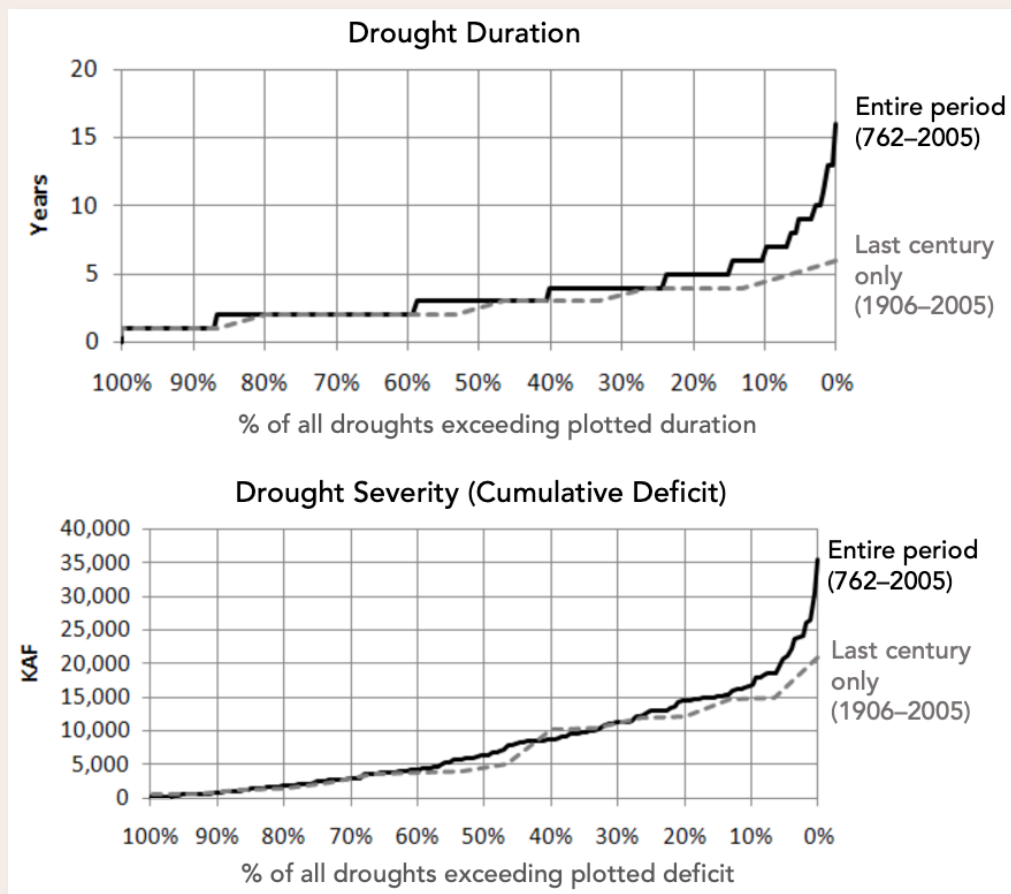
Figure 2.15

Drought characteristics over the most recent century (dashed gray line) from the Meko et al. (2007) tree-ring reconstruction of Lees Ferry natural flows, compared with the full reconstructed period (762–2005; solid black line). The full reconstruction contains extreme droughts with longer durations and larger cumulative deficits, as indicated by increasing divergences at lower exceedance probabilities (<10%). (Source: adapted from Reclamation 2012b)

2.10 Recent hydroclimate trends and likely causes

The most prominent hydroclimatic change in the basin over the past 40 years has been a substantial warming trend. Trends in precipitation are more difficult to discern. Changes in snowpack, runoff volume, and runoff timing have been observed and these can be linked, at least in part, to the warming trend. The recent trends in these and other variables for the Upper Basin specifically are summarized in Table 2.3.

Table 2.3

Summary of recent hydroclimate trends in the Upper Basin and the likely causes of those trends. See text in the sections below for references.

Variable	Trend since 1980s	Likely causes, in order of importance
Temperature	Increasing*	Anthropogenic climate change, natural variability
Precipitation	Decreasing	Natural variability, anthropogenic climate change
Snowpack water volume (April 1 SWE)	Decreasing*	Decreasing precipitation, warming temperatures
Timing of snowmelt and runoff	Earlier*	Warming temperatures, dust-on-snow, decreasing precipitation
Annual streamflow	Decreasing	Decreasing precipitation, warming temperatures

* Trend has been found to be statistically significant for part or all of the Upper Basin by one or more studies

Temperature

The most conspicuous feature of the observed record of annual temperatures for the basin is the warming trend in recent decades (Figure 2.16), as highlighted in many previous reports and studies (National Research Council 2007; Reclamation 2012e; Nowak et al. 2012). Since 1980, there has been a persistent and statistically significant warming trend of about +0.5°F per decade in both the Upper and Lower Basins, with a total of 2.0°F of warming during the 40-year period of 1980–2019. In the Upper and Lower Basins, and over the entire basin (Figure 2.16), 2009–2018 was the warmest 10-year period in the record, and 2017 was the warmest single year. Of the 20 warmest years on record, 17 have occurred since 1994. While the upward trend has included both warmer and cooler years, every year since 1994—including relatively cool 2019—has been warmer than the 1970–1999 average. The average temperature since 2000 has been 2.0°F warmer than the 20th-century average.
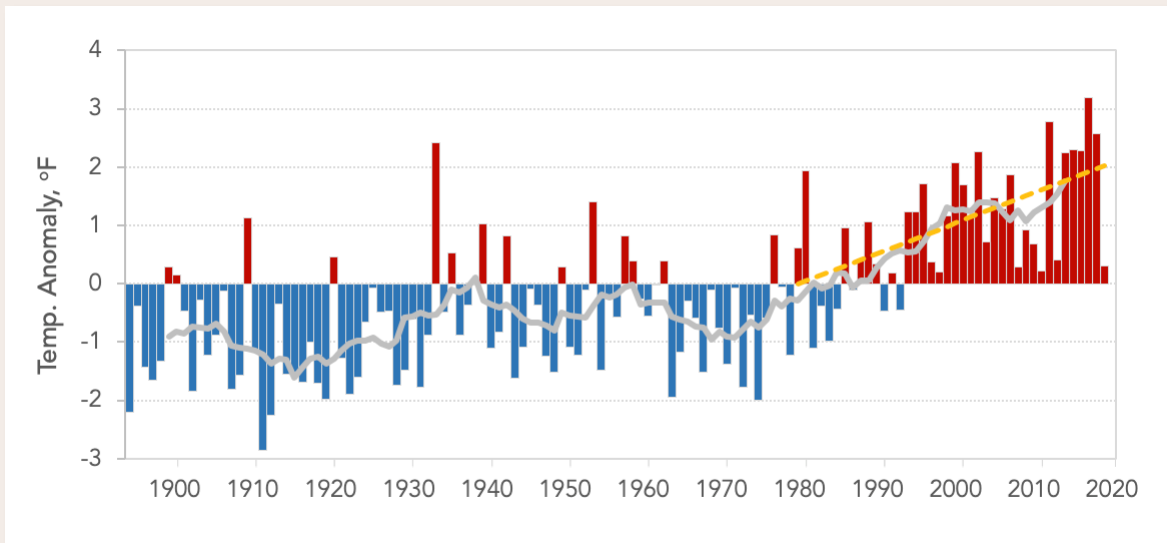
Figure 2.16

Annually averaged temperature for the Colorado River Basin, 1895–2019, shown as departures from a 1970–1999 average. The gray line is a 10-year running average plotted on the 6th year. A 40-year linear trend (dashed yellow line) shows 2.4°F of warming from 1980–2019. (Data: NOAA NCEI)

This warming has been observed in all seasons, with seasonal trends (+0.4°F to +0.7°F per decade) similar to those for annual temperatures. Daily maximum temperatures have warmed more (+0.65°F per decade) than the average temperatures (+0.5°F per decade) or the daily minimum temperatures (+0.4°F per decade). It is not clear whether the magnitude of warming has differed between lower and higher elevations within the basin (Lukas et al. 2014).

Paleoclimatic reconstructions of temperature for locations within, or regions that include, the Colorado River Basin all indicate that the period since 1950 has been warmer than any time in the past 600 years, and that more recent temperatures, since 2000, are warmer than at any time in the past 2000 years (Hoerling et al. 2013).

The warming trend for the basin since 1980 (+2.0°F) mirrors persistent warming trends seen over the same time period over the 11 western states (+1.7°F), the conterminous U.S. (+1.7°F), and the entire globe (+1.2°F). At the global scale, strong indications from multiple lines of evidence have led to the conclusion that it is extremely likely (>95% probability) that human influence through greenhouse gas emissions and other sources has been the dominant cause of the observed warming over the late 20th century and the 21st century (USGCRP 2017). Similarly, human influence has been detected in the observed warming trends for North America as a whole, and

for the northern and western regions of the U.S., including the Colorado River Basin (USGCRP 2017).

Precipitation

As shown previously (Figure 2.6), observed annual (water year) precipitation for the basin is far more variable on interannual time scales than temperature. For multi-decadal trends to statistically emerge from the background noise of this high variability, they would need to be large. While a straight-line fit to the 1980–2019 period for the Upper Basin does indicate lower average annual precipitation in more recent years, this declining trend is not statistically significant. The unusually high precipitation values in the 1980s means that any trend that starts in the vicinity of 1980 will tend downward. Importantly, the average annual precipitation over the past 20 years (2000–2019) does not stand out relative to periods of the same length earlier in the observed record. A declining but non-significant trend is also seen in Lower Basin annual precipitation over the 1980–2019 period. Looking at only cold-season (Oct–Mar) precipitation, the percentage declines over the 1980–2019 period in both the Upper and Lower Basins are greater than the declines for annual precipitation. But as with annual precipitation, the overall, below-average, cold-season precipitation from 2000–2019 is not an outlier in the context of the full observed record.

Detection and attribution analyses for recent multidecadal periods indicate that the generally lower precipitation seen in the southwestern U.S., including the Colorado River Basin, in recent decades was likely caused by natural variability, and not human-caused climate change (Barnett et al. 2008; Hoerling, Eischeid, and Perlwitz 2010; Lehner et al. 2018). New analyses using global climate models suggest that human-caused climate change is exerting a long-term tendency toward reduced precipitation in the region that includes the Colorado River Basin, though this tendency is small enough to be overwhelmed by natural variability, and is undetectable from the observed record of precipitation alone (Guo et al. 2019; Hoerling et al. 2019).

Snowpack

The peak water volume of the basin snowpack (e.g., April 1 SWE) is mainly determined by the amount of cold-season precipitation, but it can also reflect weather factors that lead to more or less snow loss (sublimation and melt) than usual during the cold season. Observations of SWE are available for portions of the basin since the 1930s and with much greater coverage over the basin starting in the late 1970s. These SWE records show interannual and decadal-scale variations in the regional snowpack that closely match the fluctuations in cold-season precipitation.

In the mid-2000s, several studies reported declining trends in April 1 SWE at most SNOTEL and snow course measurement sites throughout the

western U.S. (Hamlet et al. 2005; Mote et al. 2005; Regonda et al. 2005). These studies linked the declining SWE trends with warming spring temperatures throughout the West, with a key mechanism being an increasing fraction of cold-season precipitation falling as rain instead of snow as temperatures have increased (Knowles, Dettinger, and Cayan 2006). In the Colorado River Basin, declining SWE trends were generally weaker, or mixed with increasing trends, compared to other regions of the western U.S because winter temperatures are well below freezing, reducing the impact of this broader snow-to-rain shift (Hamlet et al. 2005; Knowles, Dettinger, and Cayan 2006). Later analyses specific to western Colorado also found declining trends in April 1 SWE, over the 1978–2007 period (Clow 2010), and over 30-, 50-, and 70-year periods ending in 2012 (Lukas et al. 2014). Clow (2010) partially attributed the decline in April 1 SWE to decreasing winter precipitation observed over the same period, also identifying a role for increasing spring temperatures.

Newer analyses have reinforced that the observed declining trends in April 1 SWE in the western U.S. are substantial and pervasive (Mote et al. 2018; Zeng, Broxton, and Dawson 2018; Fyfe et al. 2017). These analyses also report somewhat greater changes to snowpacks in the Colorado River Basin over the last several decades than was reported in the older studies. All of these studies indicate a role for warming temperatures in explaining the declining SWE, though they also suggest that recent precipitation trends have played an important role. A study that assessed the trends in April 1 SWE across the West from 1984-2018 assigned greater importance to warming, finding that the declining SWE trends in the Upper Basin over that period were of roughly the same magnitude that would be expected from warming alone (Siler, Proistosescu, and Po-Chedley 2019). Two studies that analyzed gridded spatially explicit SWE datasets (see Chapter 5) found larger SWE declines than one would infer from SNOTEL sites alone, indicating that lower-elevation snow below most of the SNOTEL network has experienced greater changes than higher-elevation snow (Fyfe et al. 2017; Zeng, Broxton, and Dawson 2018). Another recent study shows that these reductions in peak (April 1) SWE are one element of systemic changes to the seasonal snowpack accumulation and melt curves (e.g., Figure 2.4); across the western U.S., these curves are becoming significantly narrower and less skewed over time, indicating later onset of accumulation, earlier onset of melt, consequently slower melt, and shorter duration of snow cover (Evan 2018).

To summarize the studies of snowpack in the western U.S. and corresponding conclusions for the Colorado River Basin: (a) April 1 SWE has declined over the past 35–60 years across most of the basin headwaters, and some of these declining trends are statistically significant; (b) at least a portion of the April 1 SWE decline in the basin is attributable to warming temperatures since the late 1970s, with a contribution from the decline in

cool-season precipitation during the most recent decades, which itself is likely due to natural variability; (c) because of the relatively cold winter climate of the Upper Basin's headwaters, the snowpack is more resistant to warming-related impacts than most other regions of the West, and (d) within each sub-basin, lower elevations have generally seen larger reductions in April 1 SWE than higher elevations.

Timing of snowmelt and runoff

While the timing of peak spring runoff is not as important as the runoff quantity to overall basin water system outcomes due to the large system storage capacity, particular water uses can be sensitive to runoff timing, especially direct diversion for irrigation, and the variation and trends in the shape of the annual hydrograph can have implications for reservoir operations. The timing of snowmelt in the basin headwaters and peak runoff naturally varies from year to year, depending mainly on the size of the snowpack and the particular trajectory of the weather during the spring. Smaller snowpacks tend to become isothermal (i.e., reach 32°F throughout the snow column)—a precondition for rapid melt—earlier, and melt out earlier, than larger snowpacks. Persistent dry, sunny, spring weather—which is more likely to occur in low-snow years—will accelerate meltout, while frequent spring storms—more likely to occur in high snow years—will delay meltout. Snowpack size (e.g., April 1 SWE) and snowmelt and runoff timing are thus physically linked as well as observationally linked; a consistent shift in the timing of peak SWE and melt onset to dates earlier than April 1 will also register as a decline in April 1 SWE, even if peak seasonal SWE (SWE_{max}) does not decline.

Given the findings of widespread declines in April 1 SWE as described above, it is unsurprising that multiple studies since the early 2000s that have specifically examined the timing of snowmelt and runoff in parts or all of the western U.S. have found widespread trends toward earlier snowmelt and runoff over the past 3–6 decades (Stewart, Cayan, and Dettinger 2005; Regonda et al. 2005; Clow 2010; Fritze, Stewart, and Pebesma 2011; Hoerling et al. 2013; Pederson, Betancourt, and McCabe 2013). The Evan (2018) study described above also confirms the general shift toward earlier snowmelt. For the Upper Basin in particular, the more recent of these studies have detected progressively larger and more pervasive shifts toward earlier spring runoff onset and peak runoff. Clow (2010) found shifts toward earlier snowmelt and runoff timing in western Colorado of 1–4 weeks from 1978 to 2007. Similarly, Hoerling et al. (2013) found that for 13 of 17 gages in the Upper Basin, average runoff timing for 2001–2010 was earlier, by 1–3 weeks, than the average runoff timing for 1950–2000.

As with the trends in April 1 SWE, it is difficult to separate the likely causes of the shift toward earlier snowmelt and runoff. Warming winter-spring temperatures almost certainly have a role, but the decline in cold-season

precipitation since 2000 appears to be an important driver as well. Episodic dust-on-snow deposition also causes earlier snowmelt and runoff (Chapter 5; Painter et al. 2007; 2010; Deems et al. 2013). Snowpacks in the Upper Basin have become generally dustier in recent decades, with especially large effects on snowmelt and runoff timing in the San Juan Basin (Clow, Williams, and Schuster 2016; Painter et al. 2018).

Streamflow volumes and runoff efficiency

Among the indicators of hydroclimatic variability and change, annual streamflow volumes are the most directly relevant to basin water management and water use. Annual streamflow also integrates multiple processes and effects that play out over different temporal and spatial scales, complicating evaluation of the sources of variability and change.

As basin water managers and water users are well aware, the period since 2000 has seen overall below-average Upper Basin (Lees Ferry) flow volumes, with an average naturalized flow of 12.6 maf/year from 2000–2019, which is 15% below the long-term average of 14.8 maf (1906–2019). (Average flow from 1999–2018 was marginally lower than from 2000–2019.) The next lowest 20-year period of flow is 1950–1969, which averaged 13.0 maf/year. The cumulative streamflow deficit of roughly 47 maf since 2000 relative to the long-term average accounts for a large portion of the current drawdown of Lakes Powell and Mead. The declining trend in Lees Ferry natural flows from 1980–2019 is almost statistically significant (p = 0.06), and this trend is larger, compared to interannual variability, than the trend in Upper Basin water-year precipitation over the same period. However, even larger declining trends in Lees Ferry flows were observed over 40-year periods beginning in the 1910s and ending in the 1950s, so this recent decline is not unprecedented.

Unlike Upper Basin natural flows, the available flow data for the Lower Basin is primarily gaged flows, or the net gain in flow between gages (see Chapter 5), so the following trends may reflect impacts from human activities. The total inflows between Lees Ferry and Lake Mead show a downward trend similar to that for the Upper Basin, with an average of 1.02 maf/year from 2000–2016, 20% less than the long-term average of 1.23 maf/year (1906–2016). Within that overall number, the gaged inflows from the four tributaries show the following departures for 2000–2016 relative to the long-term mean: Paria River, -15%; Little Colorado River, -40%; Virgin River, -10%; and the Bill Williams River, -41%.

As discussed previously in this chapter, the variability in water-year precipitation is the most important driver of variability in annual streamflow. The period of reduced Upper Basin flow since the 2000s and the overall declining trend in flow since the late 1970s has coincided with a decline in water-year precipitation as described earlier. The consensus of

recent studies is that roughly half or more of the recent low-streamflow anomaly (since 2000) is due to variability and trends in precipitation (Nowak et al. 2012; Udall and Overpeck 2017; C. A. Woodhouse et al. 2016; McCabe et al. 2017; Barsugli and Livneh 2018; Xiao, Udall, and Lettenmaier 2018; Hoerling et al. 2019).

But it is also clear that warming temperatures can lead to long-term reductions in streamflow. Hydrologic modeling has been used to put a range of values to the general expectation that runoff in the Colorado River Basin decreases with increasing temperatures. An analysis by McCabe and Wolock (2007) using their relatively simple water-balance model for the Upper Basin indicated a 5% decline in Upper Basin runoff per 1°F of warming. Intercomparisons using more sophisticated hydrologic models (see Chapter 6) calibrated for the basin hydrology indicate a 1.5% to 6% decrease (model average: 3.5% decrease) in Upper Basin runoff per 1°F of regional warming (Vano, Das, and Lettenmaier 2012; Vano and Lettenmaier 2014). Based on this range of modeled temperature sensitivities of runoff, Udall and Overpeck (2017) concluded that approximately one-third (range: 17-50%) of the Lees Ferry streamflow departure from 2000–2014, relative to the 20th-century average, was due to the effects of the warming alone, with the remainder due to decreased precipitation during the 2000–2014 period.

Three more recent model-based studies, using different methodologies, came to conclusions at opposite ends of the range outlined by Udall and Overpeck (2017). Xiao, Udall, and Lettenmaier (2018), based on simulations of historical hydroclimate with the Variable Infiltration Capacity hydrologic model (see Chapter 6), concluded that a little more than one-half (54%) of the Lees Ferry streamflow departure from 2000–2014 was due to warming alone. Milly and Dunne (2020), using a different hydrologic model, also estimated that just over half of the 2000-2017 Lees Ferry streamflow departure was due to warming alone, and that the temperature sensitivity of runoff was about 5% per 1°F of regional warming. But based on simulations from three global climate models (GCMs) with embedded hydrology (or land surface) models, Hoerling et al. (2019) estimated that the temperature sensitivity of runoff was about 1.5% per 1°F of regional warming, and that about 20% of the Lees Ferry streamflow departure since 2000 was due to warming.

The warming effect on Upper Basin runoff has also been detected and quantified directly from the observational record, while taking into account the potentially confounding relationship between precipitation and temperature. Regression analysis by Nowak et al. (2012) indicated a 7.5% reduction in annual Upper Basin runoff for every 1°F warming, a larger reduction than shown by any of the hydrologic models. McCabe et al. (2017), using a similar regression analysis, concluded that the impact of warming temperatures on Upper Basin runoff was -7% for the period from the late

1980s through 2012, which implies a 4–5% reduction in annual runoff per 1°F warming, within the range found with the hydrologic models. Woodhouse et al. (2016) inferred an impact of warm-season temperatures on Upper Basin runoff in recent decades from the increasing differences between the precipitation anomaly and the runoff anomaly, but did not quantify the impact.

To summarize, compared with a decade ago, there is now substantial evidence from both hydrologic model experiments and analyses of the observed record that recent warming temperatures have already had a role in reducing Colorado River flows. Those studies also indicate that the magnitude of the incremental impact of climate warming on streamflow remains uncertain. This mirrors the consensus of participants at a recent workshop on understanding the causes of the historical changes in flow of the Colorado River (Barsugli and Livneh 2018). The workshop report also underscored that a key challenge in quantifying the role of temperature is the uncertainty in the observed records of temperature and especially precipitation, which is much more spatially and temporally variable than temperature. The most runoff-productive mountain areas have relatively sparse observations, and the different gridded climate datasets used to calibrate hydrologic models and in other analyses can have substantial differences over these mountain areas (see Chapter 4; Barsugli and Livneh 2018). For that matter, the record of naturalized runoff for the Upper Basin (Lees Ferry) used for many of these analyses has uncertainties that are not well quantified or broadly appreciated within the research and application communities (see Chapter 5).

Other recent studies, using both hydrologic models and field observations, have focused on the mechanisms by which warming acts to reduce Colorado River streamflows, including those mechanisms described earlier as impacting the snowpack. Following the seasonal sequence of events, these mechanisms include:

- Fall (and spring) precipitation increasingly comes as rain instead of snow, which reduces runoff efficiency (Berghuijs, Woods, and Hrachowitz 2014).
- Sublimation losses from snowpacks during the winter and spring are higher due to the warmer, "thirstier" atmosphere (Foster et al. 2016).
- Snowmelt initiates earlier in the spring, which leads to slower average melt rates (see Figure 2.4), which reduces runoff efficiency (Barnhart et al. 2016).
- The earlier meltout exposes soils earlier in the warm season, increasing the absorption of solar radiation at the land surface and leading to increased seasonal evaporation (Deems et al. 2013, Milly and Dunne 2020).

- The growing season for natural vegetation and crops starts earlier and lasts longer, leading to increased seasonal transpiration (Deems et al. 2013).
- Evapotranspiration rates generally increase with warmer temperatures (Foster et al. 2016; Milly and Dunne 2020).

The energy budget changes (i.e., increase in sublimation and evapotranspiration) appear to be a more important contributor to the overall temperature effect on runoff in the basin than the phase change in precipitation from snow to rain (Foster et al. 2016). This is consistent with other modeling analyses that have examined the seasonal dimension of temperature's effects; those studies have indicated that warming during the warm season (April–September) is much more effective at reducing runoff than warming of the same magnitude during the cold season (October–March) (Das et al. 2011; McCabe et al. 2017).

2.11   Challenges and opportunities

The most pressing challenges in our understanding of the historical and recent hydroclimate of the Colorado River Basin regard the recent changes in the key variables described in the previous section. Better quantification of these trends (*how much* things have changed), and more confident attributions of them to the respective causal factors (*why* things have changed), would facilitate greater inclusion of these changes in short-term and mid-term forecasting (Chapter 8) and long-term planning (Chapters 9-11).

Challenges
- There is still considerable uncertainty in the quantification of the relative roles of temperature, precipitation, antecedent soil moisture, dust-on-snow, and vegetation change in recent and ongoing variability and change in Upper Basin snowpack and streamflow.
- These factors have substantial spatial variability, but most studies have conducted analyses and presented findings only at the Upper Basin-wide scale (e.g. Lees Ferry).

Opportunities
- Conduct analyses of Upper Basin hydrologic change that are spatially disaggregated at least to the eight major sub-basins (Upper Green, Yampa-White, etc.), or focus only on the most productive headwaters areas, or both.
- Pursue the various pathways to improve hydrologic modeling presented in Chapter 6.
- Conduct intercomparisons of hydrologic models and statistical methods for assessing the factors behind hydrologic changes.

References

Abatzoglou, John T. 2013. "Development of Gridded Surface Meteorological Data for Ecological Applications and Modelling." *International Journal of Climatology* 33 (1): 121–31. https://doi.org/10.1002/joc.3413.

———. 2019. "Climatology Lab." Gridmet. 2019. http://www.climatologylab.org/gridmet.html.

Abatzoglou, John T., and Timothy J. Brown. 2012. "A Comparison of Statistical Downscaling Methods Suited for Wildfire Applications." International Journal of Climatology 32 (5): 772–80. https://doi.org/10.1002/joc.2312.

Adam, Jennifer C., and Dennis P. Lettenmaier. 2003. "Adjustment of Global Gridded Precipitation for Systematic Bias." Journal of Geophysical Research: Atmospheres 108 (D9): n/a-n/a. https://doi.org/10.1029/2002JD002499.

Adams, David K., and Andrew C. Comrie. 1997. "The North American Monsoon." Bulletin of the American Meteorological Society, 2197–2213. https://doi.org/10.1175/1520-0477(1997)078<2197:TNAM>2.0.CO;2.

Adams, Thomas E., III, and Randel Dymond. 2018. "Evaluation and Benchmarking of Operational Short-Range Ensemble Mean and Median Streamflow Forecasts for the Ohio River Basin." Journal of Hydrometeorology 19 (10): 1689–1706. https://doi.org/10.1175/JHM-D-18-0102.1.

Albano, Christine M., Michael D. Dettinger, Maureen I. McCarthy, Kevin D. Schaller, Toby L. Welborn, and Dale A. Cox. 2016. "Application of an Extreme Winter Storm Scenario to Identify Vulnerabilities, Mitigation Options, and Science Needs in the Sierra Nevada Mountains, USA." Natural Hazards 80 (2): 879–900. https://doi.org/10.1007/s11069-015-2003-4.

Albers, John R., and Matthew Newman. 2019. "A Priori Identification of Skillful Extratropical Subseasonal Forecasts." Geophysical Research Letters 46 (21): 12527–36. https://doi.org/10.1029/2019GL085270.

Alder, Jay R., and Steven W. Hostetler. 2019. "The Dependence of Hydroclimate Projections in Snow-Dominated Regions of the Western United States on the Choice of Statistically Downscaled Climate Data." Water Resources Research 55 (3): 2279–2300. https://doi.org/10.1029/2018WR023458.

Alder, Jay R., and Steven W. Hostetler. 2015. "Web Based Visualization of Large Climate Data Sets." Environmental Modelling & Software 68 (June): 175–80. https://doi.org/10.1016/j.envsoft.2015.02.016.

Allaby, Michael. 2008. A Dictionary of Earth Sciences. Oxford University Press. https://www.oxfordreference.com/view/10.1093/acref/9780199211944.001.0001/acref-9780199211944.

Allen, Richard G., L. S. Pereira, Dirk Raes, and Martin Smith. 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56. Rome: Food and Agriculture Organization of the United Nations.

Allen, Richard G., Masahiro Tasumi, and Ricardo Trezza. 2007. "Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC)—Model." Journal of Irrigation and Drainage Engineering 133 (4): 380–94. https://doi.org/10.1061/(ASCE)0733-9437(2007)133:4(380).

Alley, William M., and Leonard F. Konikow. 2015. "Bringing GRACE Down to Earth." Groundwater 53 (6): castle. https://doi.org/10.1111/gwat.12379.

Amatya, Devendra M., Suat Irmak, Prasanna Gowda, Ge Sun, Jami E. Nettles, and Kyle R. Douglas-Mankin. 2016. "Ecosystem Evapotranspiration: Challenges in Measurements, Estimates, and Modeling." Transactions of the ASABE 59 (2): 555–60. https://doi.org/10.13031/trans.59.11808.

Anderson, Brian Trail. 2011. "Spatial Distribution and Evolution of a Seasonal Snowpack in Complex Terrain: An Evaluation of the SNODAS Modeling Product." PhD Dissertation, Boise State University.

Anderson, Eric A. 1973. "National Weather Service River Forecast System-Snow Accumulation and Ablation Model." NWS HYDRO-17. NOAA Technical Memorandum.

Anderson, M. G., and T. P. Burt. 1985. Hydrological Forecasting. https://www.osti.gov/biblio/6271151.

Anderson, Martha C., Christopher Hain, Brian Wardlow, Agustin Pimstein, John R. Mecikalski, and William P. Kustas. 2011. "Evaluation of Drought Indices Based on Thermal Remote Sensing of Evapotranspiration over the Continental United States." Journal of Climate 24 (8): 2025–44. https://doi.org/10.1175/2010JCLI3812.1.

Anderson, Martha C., J. M. Norman, G. R. Diak, William P. Kustas, and John R. Mecikalski. 1997. "A Two-Source Time-Integrated Model for Estimating Surface Fluxes Using Thermal Infrared Remote Sensing." Remote Sensing of Environment 60 (2): 195–216. https://doi.org/10.1016/S0034-4257(96)00215-5.

Anderson, Richard M., Victor I. Koren, and Seann M. Reed. 2006. "Using SSURGO Data to Improve Sacramento Model a Priori Parameter Estimates." Journal of Hydrology 320 (1–2): 103–16. https://doi.org/10.1016/j.jhydrol.2005.07.020.

Anderson, SallyRose, Glenn Tootle, and Henri Grissino-Mayer. 2012. "Reconstructions of Soil Moisture for the Upper Colorado River Basin Using Tree-Ring Chronologies." JAWRA Journal of the American Water Resources Association 48 (4): 849–58. https://doi.org/10.1111/j.1752-1688.2012.00651.x.

Andreadis, Konstantinos M., Elizabeth A. Clark, Andrew W. Wood, Alan F. Hamlet, and Dennis P. Lettenmaier. 2005. "Twentieth-Century Drought in the Conterminous United States." Journal of Hydrometeorology 6 (6): 985–1001. https://doi.org/10.1175/JHM450.1.

Ault, Toby R., Julia E. Cole, Jonathan T. Overpeck, Gregory T. Pederson, and David M. Meko. 2014. "Assessing the Risk of Persistent Drought Using Climate Model Simulations and Paleoclimate Data." Journal of Climate 27 (20): 7529–49. https://doi.org/10.1175/JCLI-D-12-00282.1.

Ault, Toby R., Julia E. Cole, Jonathan T. Overpeck, Gregory T. Pederson, Scott St. George, Bette Otto-Bliesner, Connie A. Woodhouse, and Clara Deser. 2013. "The Continuum of Hydroclimate Variability in Western North America during the Last Millennium." Journal of Climate 26 (16): 5863–78. https://doi.org/10.1175/JCLI-D-11-00732.1.

Ault, Toby R., Justin S. Mankin, Benjamin I. Cook, and Jason E. Smerdon. 2016. "Relative Impacts of Mitigation, Temperature, and Precipitation on 21st-Century Megadrought Risk in the American Southwest." Science Advances 2 (10): e1600873. https://doi.org/10.1126/sciadv.1600873.

Ault, Toby R., and Scott St. George. 2018. "Unraveling the Mysteries of Megadrought." Physics Today 71 (8): 44–50. https://doi.org/10.1063/PT.3.3997.

Baker, Sarah A. 2019. "Development of Sub-Seasonal to Seasonal Watershed-Scale Hydroclimate Forecast Techniques to Support Water Management." Dissertation, Boulder, CO: University of Colorado. https://search.proquest.com/openview/86480abe8a4f1b7c3f0bccc9bf5142ac/1?pq-origsite=gscholar&cbl=18750&diss=y.

Baker, Sarah A., Andrew W. Wood, and Balaji Rajagopalan. 2019. "Developing Subseasonal to Seasonal Climate Forecast Products for Hydrology and Water Management." JAWRA Journal of the American Water Resources Association 55 (4): 1024–37. https://doi.org/10.1111/1752-1688.12746.

Bardsley, Tim, Andrew W. Wood, Michael T. Hobbins, T. Kirkham, L. Briefer, J. Niermeyer, and S. Burian. 2013. "Planning for an Uncertain Future: Climate Change Sensitivity Assessment toward Adaptation Planning for Public Water Supply." Earth Interactions 17: 1–26.

Barnett, Tim P., and David W. Pierce. 2009. "Sustainable Water Deliveries from the Colorado River in a Changing Climate." Proceedings of the National Academy of Sciences 106 (18): 7334–38. https://doi.org/10.1073/pnas.0812762106.

Barnett, Tim P., David W. Pierce, Hugo G. Hidalgo, Celine Bonfils, Benjamin D. Santer, Tapash Das, Govindasamy Bala, et al. 2008. "Human-Induced Changes in the Hydrology of the Western United States." Science 319 (5866): 1080–83. https://doi.org/10.1126/science.1152538.

Barnhart, Theodore B., Noah P. Molotch, Ben Livneh, Adrian A. Harpold, John F. Knowles, and Dominik Schneider. 2016. "Snowmelt Rate Dictates Streamflow." Geophysical Research Letters 43 (15): 8006–16. https://doi.org/10.1002/2016GL069690.

Barnston, Anthony G. 1994. "Linear Statistical Short-Term Climate Predictive Skill in the Northern Hemisphere." Journal of Climate 7: 1513–64. https://doi.org/10.1175/1520-0442(1994)007<1513:LSSTCP>2.0.CO;2.

Barnston, Anthony G., Michael K. Tippett, Michelle L. L'Heureux, Shuhua Li, and David G. DeWitt. 2012. "Skill of Real-Time Seasonal ENSO Model Predictions during 2002–11: Is Our Capability Increasing?" Bulletin of the American Meteorological Society 93 (5): 631–51. https://doi.org/10.1175/BAMS-D-11-00111.1.

Barnston, Anthony G., Michael K. Tippett, Meghana Ranganathan, and Michelle L. L'Heureux. 2017. "Deterministic Skill of ENSO Predictions from the North American Multimodel Ensemble." Climate Dynamics, March. https://doi.org/10.1007/s00382-017-3603-3.

Barrett, Andrew P. 2003. "National Operational Hydrologic Remote Sensing Center SNOw Data Assimilation System (SNODAS) Products at NSIDC." 11. Special Report. National Snow and Ice Data Center (NSIDC).

Barros, Ana Paula, and Dennis P. Lettenmaier. 1994. "Incorporation of an Evaporative Cooling Scheme into a Dynamic Model of Orographic Precipitation." Monthly Weather Review 122: 2777–83.

Barry, R.G., and R.J. Chorley. 2010. Atmosphere, Weather and Climate. Routledge. https://books.google.com/books?id=heM0uAAACAAJ.

Barsugli, Joseph J., Christopher J. Anderson, Joel B. Smith, and Jason M. Vogel. 2009. "Options for Improving Climate Modeling to Assist Water Utility Planning for Climate Change." Water Utility Climate Alliance.

Barsugli, Joseph J., and Ben Livneh. 2018. "A Workshop on Understanding the Causes of the Historical Changes in Flow of the Colorado River." Workshop Report. Boulder, CO: NOAA Earth Systems Research Laboratory.

Battaglin, William, Lauren Hay, and Steven L. Markstrom. 2011. "Simulating the Potential Effects of Climate Change in Two Colorado Basins and at Two Colorado Ski Areas." Earth Interactions 15 (22): 1–23. https://doi.org/10.1175/2011EI373.1.

Bauer, Peter, Alan Thorpe, and Gilbert Brunet. 2015. "The Quiet Revolution of Numerical Weather Prediction." Nature 525 (7567): 47–55. https://doi.org/10.1038/nature14956.

Becker, Emily, Huug M. Van den Dool, and Qin Zhang. 2014. "Predictability and Forecast Skill in NMME." Journal of Climate 27 (15): 5891–5906. https://doi.org/10.1175/JCLI-D-13-00597.1.

Beckers, J. V. L., A. H. Weerts, E. Tijdeman, and E. Welles. 2016. "ENSO-Conditioned Weather Resampling Method for Seasonal Ensemble Streamflow Prediction." Hydrol. Earth Syst. Sci. 20 (8): 3277–87. https://doi.org/10.5194/hess-20-3277-2016.

Behnke, Ruben, S. Vavrus, A. Allstadt, T. Albright, W. E. Thogmartin, and V. C. Radeloff. 2016. "Evaluation of Downscaled, Gridded Climate Data for the Conterminous United States." Ecological Applications 26 (5): 1338–51. https://doi.org/10.1002/15-1061.

Behnke, Ruben, Steve Vavrus, Andrew Allstadt, Thomas Albright, W. E. Thogmartin, and V. C. Radeloff. 2016. "Evaluation of Downscaled, Gridded Climate Data for the Conterminous United States." Ecological Applications 26 (5): 1338–51. https://doi.org/10.1002/15-1061.

Bellenger, H., E. Guilyardi, J. Leloup, M. Lengaigne, and J. Vialard. 2014. "ENSO Representation in Climate Models: From CMIP3 to CMIP5." Climate Dynamics 42 (7–8): 1999–2018. https://doi.org/10.1007/s00382-013-1783-z.

Bender, Jens, Thomas Wahl, and Jürgen Jensen. 2014. "Multivariate Design in the Presence of Non-Stationarity." Journal of Hydrology 514 (June): 123–30. https://doi.org/10.1016/j.jhydrol.2014.04.017.

Bender, Stacie, Paul Miller, Brent Bernard, and John Lhotak. 2014. "Use of Snow Data from Remote Sensing in Operational Streamflow Prediction." In , 11.

Bergeron, Jean M., Mélanie Trudel, and Robert Leconte. 2016. "Combined Assimilation of Streamflow and Snow Water Equivalent for Mid-Term Ensemble Streamflow Forecasts in Snow-Dominated Regions." Hydrology and Earth System Sciences 20 (10): 4375–89. https://doi.org/10.5194/hess-20-4375-2016.

Berghuijs, W. R., R. A. Woods, and M. Hrachowitz. 2014. "A Precipitation Shift from Snow towards Rain Leads to a Decrease in Streamflow." Nature Climate Change 4 (7): 583–86. https://doi.org/10.1038/nclimate2246.

Best, M. J., G. Abramowitz, H. R. Johnson, A. J. Pitman, G. Balsamo, A. Boone, M. Cuntz, et al. 2015. "The Plumbing of Land Surface Models: Benchmarking Model Performance." Journal of Hydrometeorology 16 (3): 1425–42. https://doi.org/10.1175/JHM-D-14-0158.1.

Beven, Keith J. 2002. "Towards an Alternative Blueprint for a Physically Based Digitally Simulated Hydrologic Response Modelling System." Hydrological Processes 16 (2): 189–206. https://doi.org/10.1002/hyp.343.

———. 2012. Rainfall-Runoff Modelling: The Primer. 2nd ed. Wiley-Blackwell.

Beven, Keith J., and Hannah L. Cloke. 2012. "Comment on 'Hyperresolution Global Land Surface Modeling: Meeting a Grand Challenge for Monitoring Earth's Terrestrial Water' by Eric F. Wood et Al." Water Resources Research 48 (1). https://doi.org/10.1029/2011WR010982.

Biddle, Suzanne Hardy. 2001. "Optimizing the TVA Reservoir System Using Riverware." In Bridging the Gap, 1–6. Proceedings. https://doi.org/10.1061/40569(2001)149.

Biondi, Franco, Alexander Gershunov, and Daniel R. Cayan. 2001. "North Pacific Decadal Climate Variability since 1661." Journal of Climate 14 (1): 5–10. https://doi.org/10.1175/1520-0442(2001)014<0005:NPDCVS>2.0.CO;2.

Bjerknes, J. 1966. "A Possible Response of the Atmospheric Hadley Circulation to Equatorial Anomalies of Ocean Temperature." Tellus 18 (4): 820–29. https://doi.org/10.1111/j.2153-3490.1966.tb00303.x.

———. 1969. "Atmospheric Teleconnections from the Equatorial Pacific." Monthly Weather Review 97: 163–72. https://doi.org/10.1175/1520-0493(1969)097<0163:ATFTEP>2.3.CO;2.

Blanford, H. F. 1884. "On the Connexion of the Himalaya Snowfall with Dry Winds and Seasons of Drought in India." Proceedings of the Royal Society of London 37: 21.

Blankenship, Clay B., Jonathan L. Case, William L. Crosson, and Bradley T. Zavodsky. 2018. "Correction of Forcing-Related Spatial Artifacts in a Land Surface Model by Satellite Soil Moisture Data Assimilation." IEEE Geoscience and Remote Sensing Letters 15 (4): 498–502. https://doi.org/10.1109/LGRS.2018.2805259.

Bolinger, Rebecca A., Christian D. Kummerow, and Nolan J. Doesken. 2014. "Attribution and Characteristics of Wet and Dry Seasons in the Upper Colorado River Basin." Journal of Climate 27 (23): 8661–73. https://doi.org/10.1175/JCLI-D-13-00618.1.

Bracken, Cameron W. 2011. "Seasonal to Inter-Annual Streamflow Simulation and Forecasting on the Upper Colorado River Basin and Implications for Water Resources Management." Boulder, CO: University of Colorado. https://www.colorado.edu/cadswes/sites/default/files/attached-files/bracken-ms_thesis-2011.pdf.

Bracken, Cameron W., Balaji Rajagopalan, and Connie A. Woodhouse. 2016. "A Bayesian Hierarchical Nonhomogeneous Hidden Markov Model for Multisite Streamflow Reconstructions." Water Resources Research 52 (10): 7837–50. https://doi.org/10.1002/2016WR018887.

Bradley, A. Allen, Mohamed Habib, and Stuart S. Schwartz. 2015. "Climate Index Weighting of Ensemble Streamflow Forecasts Using a Simple Bayesian Approach." Water Resources Research 51 (9): 7382–7400. https://doi.org/10.1002/2014WR016811.

Bradley, R. S., H. F. Diaz, G. N. Kiladis, and J. K. Eischeid. 1987. "ENSO Signal in Continental Temperature and Precipitation Records." Nature 327 (6122): 497–501. https://doi.org/10.1038/327497a0.

Braganza, Karl, Joëlle L. Gergis, Scott B. Power, James S. Risbey, and Anthony M. Fowler. 2009. "A Multiproxy Index of the El Niño–Southern Oscillation, A.D. 1525–1982." Journal of Geophysical Research 114 (D5). https://doi.org/10.1029/2008JD010896.

Brahney, J., A. P. Ballantyne, C. Sievers, and J. C. Neff. 2013. "Increasing Ca2+ Deposition in the Western US: The Role of Mineral Aerosols." Aeolian Research 10 (September): 77–87. https://doi.org/10.1016/j.aeolia.2013.04.003.

Bras, Rafael L., and Ignacio Rodríguez-Iturbe. 1985. Random Functions and Hydrology. Reading, Mass: Addison-Wesley.

Breheny, Patrick. 2012. "Kernel Density Estimation." Slides, University of Kentucky, Lexington, October. https://web.as.uky.edu/statistics/users/pbreheny/621/F12/notes/10-18.pdf.

Brekke, Levi D. 2009. "Long-Term Planning Hydrology Based on Various Blends of Instrumental Records, Paleoclimate, and Projected Climate Information." US Bureau of Reclamation. https://www.usbr.gov/research/projects/detail.cfm?id=6395.

———. 2011. "Addressing Climate Change in Long-Term Water Resources Planning and Management." CWTS-10-02. US Army Corps of Engineers Civil Works Technical Series. US Army Corps of Engineers. https://www.usbr.gov/climate/userneeds/docs/LTdoc.pdf.

Brekke, Levi D., Michael D. Dettinger, Edwin P. Maurer, and Michael Anderson. 2008. "Significance of Model Credibility in Estimating Climate Projection Distributions for Regional Hydroclimatological Risk Assessments." Climatic Change 89 (3–4): 371–94. https://doi.org/10.1007/s10584-007-9388-3.

Brekke, Levi D., Julie E. Kiang, J. Rolf Olsen, Roger S. Pulwarty, David A. Raff, D. Phil Turnipseed, Robert S. Webb, and Kathleen D. White. 2009. "Climate Change and Water Resources Management: A Federal Perspective." Circular 1331. Reston, Va: U.S. Geological Survey.

Brown, Casey, and Robert L. Wilby. 2012. "An Alternate Approach to Assessing Climate Risks." Eos, Transactions American Geophysical Union 93 (41): 401–2. https://doi.org/10.1029/2012EO410001.

Brown, David P., and Andrew C. Comrie. 2004. "A Winter Precipitation 'Dipole' in the Western United States Associated with Multidecadal ENSO Variability." Geophysical Research Letters 31 (9): n/a-n/a. https://doi.org/10.1029/2003GL018726.

Brown, Tim, John D. Horel, Gregory D. McCurdy, and Matthew G. Fearson. 2011. "Report to the NWCG: What Is the Appropriate RAWS Network?" Program for Climate, Ecosystem and Fire Applications (CEFA) Report 1101. National Wildfire Coordinating Group. https://www.nwcg.gov/publications/1003.

Bryant, Ann C., Thomas H. Painter, Jeffrey S. Deems, and Stacie M. Bender. 2013. "Impact of Dust Radiative Forcing in Snow on Accuracy of Operational Runoff Prediction in the Upper Colorado River Basin." Geophysical Research Letters 40 (15): 3945–49. https://doi.org/10.1002/grl.50773.

CADSWES. 2018. "RiverWare Technical Documentation Version 7.4, Objects." http://riverware.org/PDF/RiverWare/documentation/Objects.pdf.

California Dept. of Water Resources. 2016. "Description of Analytical Tools, Water Evaluation and Planning (WEAP)." https://water.ca.gov/LegacyFiles/waterplan/docs/tools/descriptions/WEAP-description.pdf.

———. 2019. "WRIMS: Water Resource Integrated Modeling System." 2019. http://water.ca.gov/Library/Modeling-and-Analysis/Modeling-Platforms/Water-Resource-Integrated-Modeling-System.

Carroll, Rosemary W. H., Lindsay A. Bearup, Wendy Brown, Wenming Dong, Markus Bill, and Kenneth H. Willlams. 2018. "Factors Controlling Seasonal Groundwater and Solute Flux from Snow-Dominated Basins." Hydrological Processes 32 (14): 2187–2202. https://doi.org/10.1002/hyp.13151.

Castle, Stephanie L., Brian F. Thomas, John T. Reager, Matthew Rodell, Sean C. Swenson, and James S. Famiglietti. 2014. "Groundwater Depletion during Drought Threatens Future Water Security of the Colorado River Basin." Geophysical Research Letters 41 (16): 5904–11. https://doi.org/10.1002/2014GL061055.

Cawthorne, Dylan. 2017. "2017 Colorado River Hydrology Research Symposium," 43.

Cayan, Daniel R., Michael D. Dettinger, David W. Pierce, Tapash Das, Noah Knowles, F. Martin Ralph, and Edwin Sumargo. 2016. "Natural Variability Anthropogenic Climate Change and Impacts on Water Availability and Flood Extremes in the Western United States." In Water Policy and Planning in a Variable and Changing Climate. Drought and Water Crises. CRC Press. https://doi.org/10.1201/b19534.

Cayan, Daniel R., Susan A. Kammerdiener, Michael D. Dettinger, Joseph M. Caprio, and David H. Peterson. 2001. "Changes in the Onset of Spring in the Western United States." Bulletin of the American Meteorological Society 82 (3): 399–416. https://doi.org/10.1175/1520-0477(2001)082<0399:CITOOS>2.3.CO;2.

Cayan, Daniel R., Kelly T. Redmond, and Laurence G. Riddle. 1999. "ENSO and Hydrologic Extremes in the Western United States." Journal of Climate 12 (9): 2881–93. https://doi.org/10.1175/1520-0442(1999)012<2881:EAHEIT>2.0.CO;2.

Chen, Xianyao, and John M. Wallace. 2016. "Orthogonal PDO and ENSO Indices." Journal of Climate 29 (10): 3883–92. https://doi.org/10.1175/JCLI-D-15-0684.1.

Christensen, Niklas S., and Dennis P. Lettenmaier. 2007. "A Multimodel Ensemble Approach to Assessment of Climate Change Impacts on the Hydrology and Water Resources of the Colorado River Basin." Hydrol. Earth Syst. Sci., 18.

Christensen, Niklas S., Andrew W. Wood, Nathalie Voisin, Dennis P. Lettenmaier, and Richard N. Palmer. 2004. "The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin." Climatic Change 62 (1–3): 337–63. https://doi.org/10.1023/B:CLIM.0000013684.13621.1f.

Clark, Martyn P., Marc F. P. Bierkens, Luis Samaniego, Ross A. Woods, Remko Uijlenhoet, Katrina E. Bennett, Valentijn R. N. Pauwels, Xitian Cai, Andrew W. Wood, and Christa D. Peters-Lidard. 2017. "The Evolution of Process-Based Hydrologic Models: Historical Challenges and the Collective Quest for Physical Realism." Hydrology and Earth System Sciences 21 (7): 3427–40. https://doi.org/10.5194/hess-21-3427-2017.

Clark, Martyn P., Subhrendu Gangopadhyay, Lauren E. Hay, Balaji Rajagopalan, and Robert Wilby. 2004. "The Schaake Shuffle: A Method for Reconstructing Space–Time Variability in Forecasted Precipitation and Temperature Fields." Journal of Hydrometeorology 5 (1): 243–62. https://doi.org/10.1175/1525-7541(2004)005<0243:TSSAMF>2.0.CO;2.

Clark, Martyn P., and Lauren E. Hay. 2004. "Use of Medium-Range Numerical Weather Prediction Model Output to Produce Forecasts of Streamflow." Journal of Hydrometeorology 5 (15): 32. https://doi.org/doi:10.1175/1525-7541(2004)005<0015:UOMNWP>2.0.CO;2.

Clark, Martyn P., Bart Nijssen, Jessica D. Lundquist, Dmitri Kavetski, David E. Rupp, Ross A. Woods, Jim E. Freer, et al. 2015. "A Unified Approach for Process-Based Hydrologic Modeling: 1. Modeling Concept." Water Resources Research 51 (4): 2498–2514. https://doi.org/10.1002/2015WR017198.

Clark, Martyn P., and Andrew G. Slater. 2006. "Probabilistic Quantitative Precipitation Estimation in Complex Terrain." Journal of Hydrometeorology 7 (1): 3–22. https://doi.org/10.1175/JHM474.1.

Clark, Martyn P., Robert L. Wilby, Ethan D. Gutmann, Julie A. Vano, Subhrendu Gangopadhyay, Andrew W. Wood, Hayley J. Fowler, Christel Prudhomme, Jeffrey R. Arnold, and Levi D. Brekke. 2016. "Characterizing Uncertainty of the Hydrologic Impacts of Climate Change." Current Climate Change Reports 2 (2): 55–64. https://doi.org/10.1007/s40641-016-0034-x.

Clayton, Jordan, Steven Quiring, Tyson Ochsner, Michael Cosh, C. Baker, Trent Ford, John Bolten, and Molly Woloszyn. 2019. "Building a One-Stop Shop for Soil Moisture Information." Eos 100 (June). https://doi.org/10.1029/2019EO123631.

CLIMAS and WWA. n.d. "TreeFlow – Streamflow Reconstructions from Tree Rings." TreeFlow. Accessed June 27, 2019. https://www.treeflow.info/.

Cloke, Hannah L., and Florian Pappenberger. 2009. "Ensemble Flood Forecasting: A Review." Journal of Hydrology 375 (3–4): 613–26. https://doi.org/10.1016/j.jhydrol.2009.06.005.

Clow, David W. 2010. "Changes in the Timing of Snowmelt and Streamflow in Colorado: A Response to Recent Warming." Journal of Climate 23 (9): 2293–2306. https://doi.org/10.1175/2009JCLI2951.1.

Clow, David W., Leora Nanus, Kristine L. Verdin, and Jeffrey Schmidt. 2012. "Evaluation of SNODAS Snow Depth and Snow Water Equivalent Estimates for the Colorado Rocky Mountains, USA: EVALUATION OF SNODAS." Hydrological Processes 26 (17): 2583–91. https://doi.org/10.1002/hyp.9385.

Clow, David W., Mark W. Williams, and Paul F. Schuster. 2016. "Increasing Aeolian Dust Deposition to Snowpacks in the Rocky Mountains Inferred from Snowpack, Wet Deposition, and Aerosol Chemistry." Atmospheric Environment 146 (December): 183–94. https://doi.org/10.1016/j.atmosenv.2016.06.076.

Coats, Sloan, Jason E. Smerdon, Benjamin I. Cook, and Richard Seager. 2015. "Are Simulated Megadroughts in the North American Southwest Forced?" Journal of Climate 28 (1): 124–42. https://doi.org/10.1175/JCLI-D-14-00071.1.

Coats, Sloan, Jason E. Smerdon, Benjamin I. Cook, Richard Seager, Edward R. Cook, and K. J. Anchukaitis. 2016. "Internal Ocean-Atmosphere Variability Drives Megadroughts in Western North America." Geophysical Research Letters 43 (18): 9886–94. https://doi.org/10.1002/2016GL070105.

"CoCoRaHS: Community Collaborative Rain, Hail & Snow Network." n.d. Accessed November 13, 2019. https://www.cocorahs.org/.

Cohn, Timothy, Julie Kiang, and Robert Mason. 2013. "Estimating Discharge Measurement Uncertainty Using the Interpolated Variance Estimator." Journal of Hydraulic Engineering 139 (5): 502–10. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000695.

Colorado State University. 2017. "MODSIM-DSS." 2017. http://modsim.engr.colostate.edu/.

Colorado State University. 2019. "CoAgMET." CoAgMET Colorado's Mesonet. 2019. https://coagmet.colostate.edu/.

Colorado Water Conservation Board. 2012. "Colorado River Water Availability Study." Colorado Water Conservation Board. http://cwcbweblink.state.co.us/WebLink/ElectronicFile.aspx?docid=158319&searchid=78f0eafa-0b8f-4d8a-9ff3-faf67cc82f52&dbid=0.

Cook, Benjamin I., Toby R. Ault, and Jason E. Smerdon. 2015. "Unprecedented 21st Century Drought Risk in the American Southwest and Central Plains." Science Advances 1 (1): e1400082. https://doi.org/10.1126/sciadv.1400082.

Cook, Benjamin I., Richard Seager, and Ron L. Miller. 2011. "On the Causes and Dynamics of the Early Twentieth-Century North American Pluvial." Journal of Climate 24 (19): 5043–60. https://doi.org/10.1175/2011JCLI4201.1.

Cook, Edward R. 2004. "Long-Term Aridity Changes in the Western United States." Science 306 (5698): 1015–18. https://doi.org/10.1126/science.1102586.

Cook, Edward R., and Leonardas Kairiūkštis, eds. 1990. Methods of Dendrochronology: Applications in the Environmental Science. Dordrecht, Netherlands ; Boston : [S.l.]: Kluwer Academic Publishers ; International Institute for Applied Systems Analysis.

Cook, Edward R., Richard Seager, Mark A. Cane, and David W. Stahle. 2007. "North American Drought: Reconstructions, Causes, and Consequences." Earth-Science Reviews 81 (1–2): 93–134. https://doi.org/10.1016/j.earscirev.2006.12.002.

Cook, Edward R., Richard Seager, Richard R. Heim, Russell S. Vose, Celine Herweijer, and Connie Woodhouse. 2010. "Megadroughts in North America: Placing IPCC Projections of Hydroclimatic Change in a Long-Term Palaeoclimate Context." Journal of Quaternary Science 25 (1): 48–61. https://doi.org/10.1002/jqs.1303.

Cosgrove, Brian A. 2003. "Real-Time and Retrospective Forcing in the North American Land Data Assimilation System (NLDAS) Project." Journal of Geophysical Research 108 (D22). https://doi.org/10.1029/2002JD003118.

Cowan, Michael S., R. Wayne Cheney, and Jeffrey C. Addiego. 1981. "An Executive Summary of the Colorado River Simulation System." Denver, Colorado: Reclamation.

CWCB. 2012. "Colorado River Water Availability Study." Colorado Water Conservation Board. https://dnrweblink.state.co.us/cwcb/0/doc/158319/Electronic.aspx?searchid=78f0eafa-0b8f-4d8a-9ff3-faf67cc82f52.

Daly, Christopher. 2006. "Guidelines for Assessing the Suitability of Spatial Climate Data Sets." International Journal of Climatology 26 (6): 707–21. https://doi.org/10.1002/joc.1322.

Daly, Christopher, Wayne P. Gibson, George H. Taylor, Gregory L. Johnson, and Phillip Pasteris. 2002. "A Knowledge-Based Approach to the Statistical Mapping of Climate." Climate Research 22: 99–113. https://doi.org/10.3354/cr022099.

Daly, Christopher, Michael Halbleib, Joseph I. Smith, Wayne P. Gibson, Matthew K. Doggett, George H. Taylor, Jan Curtis, and Phillip P. Pasteris. 2008. "Physiographically Sensitive Mapping of Climatological Temperature and Precipitation across the Conterminous United States." International Journal of Climatology 28 (15): 2031–64. https://doi.org/10.1002/joc.1688.

Daly, Christopher, Ronald P. Neilson, and Donald L. Phillips. 1994. "A Statistical-Topographic Model for Mapping Climatological Precipitation over Mountainout Terrain." Journal of Applied Meteorology 33: 140–58.

Daly, Christopher, Joseph I. Smith, and Keith V. Olson. 2015. "Mapping Atmospheric Moisture Climatologies across the Conterminous United States." Edited by Robert Guralnick. PLOS ONE 10 (10): e0141140. https://doi.org/10.1371/journal.pone.0141140.

Daly, Christopher, George Taylor, and Wayne Gibson. 1997. "The PRISM Approach to Mapping Precipitation and Temperature." In Proceedings,10th AMS Conference on Applied Climatology, 20–23.

D'Arrigo, Rosanne, R. Villalba, and G. Wiles. 2001. "Tree-Ring Estimates of Pacific Decadal Climate Variability." Climate Dynamics 18 (3–4): 219–24. https://doi.org/10.1007/s003820100177.

Das, Tapash, David W. Pierce, Daniel R. Cayan, Julie A. Vano, and Dennis P. Lettenmaier. 2011. "The Importance of Warm Season Warming to Western U.S. Streamflow Changes." Geophysical Research Letters 38 (23): n/a-n/a. https://doi.org/10.1029/2011GL049660.

Davis, Gary. 2007. "History of the NOAA Satellite Program." Journal of Applied Remote Sensing 1 (1): 012504. https://doi.org/10.1117/1.2642347.

Dawson, Nicholas, Patrick Broxton, and Xubin Zeng. 2018. "Evaluation of Remotely Sensed Snow Water Equivalent and Snow Cover Extent over the Contiguous United States." Journal of Hydrometeorology 19 (11): 1777–91. https://doi.org/10.1175/JHM-D-18-0007.1.

Day, Gerald N. 1985. "Extended Streamflow Forecasting Using NWSRFS." Journal of Water Resources Planning and Management 111 (2): 157–70. https://doi.org/10.1061/(ASCE)0733-9496(1985)111:2(157).

DeChant, Caleb M., and Hamid Moradkhani. 2011a. "Radiance Data Assimilation for Operational Snow and Streamflow Forecasting." Advances in Water Resources 34 (3): 351–64. https://doi.org/10.1016/j.advwatres.2010.12.009.

———. 2011b. "Improving the Characterization of Initial Condition for Ensemble Streamflow Prediction Using Data Assimilation." Hydrology and Earth System Sciences 15 (11): 3399–3410. https://doi.org/10.5194/hess-15-3399-2011.

Deems, Jeffrey S., and Alan F. Hamlet. 2010. "Historical Meteorological Driving Data Set," 13.

Deems, Jeffrey S., Thomas H. Painter, Joseph J. Barsugli, Jayne Belnap, and Bradley Udall. 2013. "Combined Impacts of Current and Future Dust Deposition and Regional Warming on Colorado River Basin Snow Dynamics and Hydrology." Hydrology and Earth System Sciences 17 (11): 4401–13. https://doi.org/10.5194/hess-17-4401-2013.

DelSole, Timothy, and Jagadish Shukla. 2009. "Artificial Skill Due to Predictor Screening." Journal of Climate 22 (2): 331–45. https://doi.org/10.1175/2008JCLI2414.1.

Demargne, Julie, Mary Mullusky, Larry Lowe, James Coe, Kevin Werner, Brenda Alcorn, Lisa Holts, et al. 2009. "Towards Standard Verification Strategies For Operational Hydrologic Forecasting: Report of the NWS Hydrologic Forecast Verification Team." Silver Spring, Maryland. https://www.nws.noaa.gov/oh/rfcdev/docs/NWS-Hydrologic-Forecast-Verification-Team_Final-report_Sep09.pdf.

Demargne, Julie, Limin Wu, Satish K. Regonda, James D. Brown, Haksu Lee, Minxue He, Dong-Jun Seo, et al. 2014. "The Science of NOAA's Operational Hydrologic Ensemble Forecast Service." Bulletin of the American Meteorological Society 95 (1): 79–98. https://doi.org/10.1175/BAMS-D-12-00081.1.

Deser, Clara, Reto Knutti, Susan Solomon, and Adam S. Phillips. 2012. "Communication of the Role of Natural Variability in Future North American Climate." Nature Climate Change 2 (11): 775–79. https://doi.org/10.1038/nclimate1562.

Deser, Clara, Adam Phillips, Vincent Bourdette, and Haiyan Teng. 2012. "Uncertainty in Climate Change Projections: The Role of Internal Variability." Climate Dynamics 38 (3–4): 527–46. https://doi.org/10.1007/s00382-010-0977-x.

DHI. 2019. "MIKE HYDRO Basin." February 2019. https://www.mikepoweredbydhi.com/products/mike-hydro-basin.

Diamond, Howard J., Thomas R. Karl, Michael A. Palecki, C. Bruce Baker, Jesse E. Bell, Ronald D. Leeper, David R. Easterling, et al. 2013. "U.S. Climate Reference Network After One Decade of Operations," 14.

Dirmeyer, Paul A., and Subhadeep Halder. 2016. "Sensitivity of Numerical Weather Forecasts to Initial Soil Moisture Variations in CFSv2." Weather and Forecasting 31 (6): 1973–83. https://doi.org/10.1175/WAF-D-16-0049.1.

Doesken, Nolan J., and Henry W. Reges. 2010. "The Value of the Citizen Weather Observer." Weatherwise 63 (6): 30–37.

Dorigo, Wouter, Peter Oevelen, Wolfgang Wagner, Matthias Drusch, Susanne Mecklenburg, Alan Robock, and Thomas Jackson. 2011. "A New International Network for in Situ Soil Moisture Data." Eos, Transactions American Geophysical Union 92 (17): 141–42. https://doi.org/10.1029/2011EO170001.

Duan, Qingyun, Soroosh Sorooshian, and Vijai K. Gupta. 1994. "Optimal Use of the SCE-UA Global Optimization Method for Calibrating Watershed Models." Journal of Hydrology 158 (3): 265–84. https://doi.org/10.1016/0022-1694(94)90057-4.

Duniway, Michael C., Alix A. Pfennigwerth, Stephen E. Fick, Travis W. Nauman, Jayne Belnap, and Nichole N. Barger. 2019. "Wind Erosion and Dust from US Drylands: A Review of Causes, Consequences, and Solutions in a Changing World." Ecosphere 10 (3): e02650. https://doi.org/10.1002/ecs2.2650.

Durre, Imke, Matthew J. Menne, Byron E. Gleason, Tamara G. Houston, and Russell S. Vose. 2010. "Comprehensive Automated Quality Assurance of Daily Surface Observations." Journal of Applied Meteorology and Climatology 49 (8): 1615–33. https://doi.org/10.1175/2010JAMC2375.1.

Emerton, Rebecca E., Ervin Zsoter, Louise Arnal, Hannah L. Cloke, Davide Muraro, Christel Prudhomme, Elisabeth M. Stephens, Peter Salamon, and Florian Pappenberger. 2018. "Developing a Global Operational Seasonal Hydro-Meteorological Forecasting System: GloFAS-Seasonal v1.0." Geoscientific Model Development 11 (8): 3327–46. https://doi.org/10.5194/gmd-11-3327-2018.

Erkyihun, Solomon Tassew, Balaji Rajagopalan, Edith Zagona, Upmanu Lall, and Kenneth Nowak. 2016. "Wavelet-Based Time Series Bootstrap Model for Multidecadal Streamflow Simulation Using Climate Indicators." Water Resources Research 52 (5): 4061–77. https://doi.org/10.1002/2016WR018696.

Evan, Amato T. 2018. "A New Method to Characterize Changes in the Seasonal Cycle of Snowpack." Journal of Applied Meteorology and Climatology, December. https://doi.org/10.1175/JAMC-D-18-0150.1.

Eyring, Veronika, Peter M. Cox, Gregory M. Flato, Peter J. Gleckler, Gab Abramowitz, Peter Caldwell, William D. Collins, et al. 2019. "Taking Climate Model Evaluation to the next Level." Nature Climate Change 9 (2): 102–10. https://doi.org/10.1038/s41558-018-0355-y.

Fan, Y., Martyn P. Clark, D. M. Lawrence, S. Swenson, L. E. Band, S. L. Brantley, P. D. Brooks, et al. 2019. "Hillslope Hydrology in Global Change Research and Earth System Modeling." Water Resources Research 55 (2): 1737–72. https://doi.org/10.1029/2018WR023903.

Federal Aviation Administration (FAA). 2019. "Surface Weather Observation Stations (ASOS/AWOS)." Surface Weather Observation Stations (ASOS/AWOS). 2019. https://www.faa.gov/air_traffic/weather/asos/.

Ficklin, Darren L., Iris T. Stewart, and Edwin P. Maurer. 2013. "Climate Change Impacts on Streamflow and Subbasin-Scale Hydrology in the Upper Colorado River Basin." Edited by Vishal Shah. PLoS ONE 8 (8): e71297. https://doi.org/10.1371/journal.pone.0071297.

Finch, J. W. 2001. "A Comparison between Measured and Modelled Open Water Evaporation from a Reservoir in South-East England." Hydrological Processes 15 (14): 2771–78. https://doi.org/10.1002/hyp.267.

Flato, Gregory M., J. Marotzke, B. Abiodun, P. Braconnot, S. C. Chou, W. Collins, P. Cox, et al. 2013. "Evaluation of Climate Models." In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Doschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, 741–882. Cambridge, UK: Cambridge University Press. https://doi.org/10.1017/CBO9781107415324.020.

Fleming, Sean W., and Angus G. Goodbody. 2019. "A Machine Learning Metasystem for Robust Probabilistic Nonlinear Regression-Based Forecasting of Seasonal Water Availability in the US West." IEEE Access 7: 119943–64. https://doi.org/10.1109/ACCESS.2019.2936989.

Flossmann, Andrea I., Michael Manton, Ali Abshaev, Roelof Bruintjes, Masataka Murakami, Thara Prabhakaran, and Zhanyu Yao. 2019. "Review of Advances in Precipitation Enhancement Research." Bulletin of the American Meteorological Society 100 (8): 1465–80. https://doi.org/10.1175/BAMS-D-18-0160.1.

Foster, Lauren M., Lindsay A. Bearup, Noah P. Molotch, Paul Brooks, and Reed M. Maxwell. 2016. "Energy Budget Increases Reduce Mean Streamflow More than Snow–Rain Transitions: Using Integrated Modeling to Isolate Climate Change Impacts on Rocky Mountain Hydrology." Environmental Research Letters 11 (4): 044015. https://doi.org/10.1088/1748-9326/11/4/044015.

Franz, Kristie J., Terrie S. Hogue, and Soroosh Sorooshian. 2008. "Operational Snow Modeling: Addressing the Challenges of an Energy Balance Model for National Weather Service Forecasts." Journal of Hydrology 360: 48–66.

French, Jeffrey R., Katja Friedrich, Sarah A. Tessendorf, Robert M. Rauber, Bart Geerts, Roy M. Rasmussen, Lulin Xue, Melvin L. Kunkel, and Derek R. Blestrud. 2018. "Precipitation Formation from Orographic Cloud Seeding." Proceedings of the National Academy of Sciences 115 (6): 1168–73. https://doi.org/10.1073/pnas.1716995115.

Freund, Mandy B., Benjamin J. Henley, David J. Karoly, Helen V. McGregor, Nerilie J. Abram, and Dietmar Dommenget. 2019. "Higher Frequency of Central Pacific El Niño Events in Recent Decades Relative to Past Centuries." Nature Geoscience 12 (6): 450–55. https://doi.org/10.1038/s41561-019-0353-3.

Frevert, Donald K., and R. Wayne Cheney. 1988. "Alternative Methods of Generating Hydrologic Data for Reservoir Optimization." In Computerized Decision Support Systems for Water Managers. New York, NY: American Society of Civil Engineers.

Friedrich, Katja, Robert L. Grossman, Justin Huntington, Peter D. Blanken, John Lenters, Kathleen D. Holman, David Gochis, et al. 2018. "Reservoir Evaporation in the Western United States: Current Science, Challenges, and Future Needs." Bulletin of the American Meteorological Society 99 (1): 167–87. https://doi.org/10.1175/BAMS-D-15-00224.1.

Fritts, Harold C. 1976. Tree Rings and Climate. London ; New York: Academic Press.

Fritts, Harold C., J. Guiot, and G. A. Gordon. 1990. "Verification. in Methods of Dendrochronology: Applications in the Environmental Sciences." In Methods of Dendrochronology: Applications in the Environmental Sciences. Edited by E. R. Cook and L. A. Kairiukstis, 178–185. Dordrecht: Kluwer Academic Publishers.

Fritze, Holger, Iris T. Stewart, and Edzer Pebesma. 2011. "Shifts in Western North American Snowmelt Runoff Regimes for the Recent Warm Decades." Journal of Hydrometeorology 12 (5): 989–1006. https://doi.org/10.1175/2011JHM1360.1.

Fyfe, John C., Chris Derksen, Lawrence Mudryk, Gregory M. Flato, Benjamin D. Santer, Neil C. Swart, Noah P. Molotch, et al. 2017. "Large Near-Term Projected Snowpack Loss over the Western United States." Nature Communications 8 (April): 14996. https://doi.org/10.1038/ncomms14996.

Gangopadhyay, Subhrendu, Benjamin L. Harding, Balaji Rajagopalan, Jeffrey J. Lukas, and Terrance J. Fulp. 2009. "A Nonparametric Approach for Paleohydrologic Reconstruction of Annual Streamflow Ensembles." Water Resources Research 45 (6). https://doi.org/10.1029/2008WR007201.

Gangopadhyay, Subhrendu, Gregory J. McCabe, and Connie A. Woodhouse. 2015. "Beyond Annual Streamflow Reconstructions for the Upper Colorado River Basin: A Paleo-Water-Balance Approach." Water Resources Research 51 (12): 9763–74. https://doi.org/10.1002/2015WR017283.

Gao, Bo-cai. 1996. "NDWI—A Normalized Difference Water Index for Remote Sensing of Vegetation Liquid Water from Space." Remote Sensing of Environment 58 (3): 257–66. https://doi.org/10.1016/S0034-4257(96)00067-3.

Gao, Yanhong, Julie A. Vano, Chunmei Zhu, and Dennis P. Lettenmaier. 2011. "Evaluating Climate Change over the Colorado River Basin Using Regional Climate Models." Journal of Geophysical Research 116 (D13). https://doi.org/10.1029/2010JD015278.

Garbrecht, Jurgen D., and Thomas C. Piechota. 2005. Climate Variations, Climate Change, and Water Resources Engineering. American Society of Civil Engineers. https://doi.org/10.1061/9780784408247.

Garen, David C. 1992. "Improved Techniques in Regression-Based Streamflow Volume Forecasting." Journal of Water Resources Planning and Management 118 (6): 654–70. https://doi.org/10.1061/(ASCE)0733-9496(1992)118:6(654).

Garen, David C., and Thomas C. Pagano. 2007. "Statistical Techniques Used in the VIPER Water Supply Forecasting Software." Technical Note TN-210-SSWSF-2. Technical Note. Natural Resource Conservation Service. https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=34239.wba.

Garfin, Gregg, Angela Jardine, Robert Merideth, Mary Black, and Sarah LeRoy, eds. 2013. Assessment of Climate Change in the Southwest United States: A Report Prepared for the National Climate Assessment. Washington, DC: Island Press/Center for Resource Economics. https://doi.org/10.5822/978-1-61091-484-0.

Gates, W. Lawrence, James S. Boyle, Curt Covey, Clyde G. Dease, Charles M. Doutriaux, Robert S. Drach, Michael Fiorino, et al. 1992. "An Overview of the Results of the Atmospheric Model Intercomparison Project (AMIP I)." Bulletin of the American Meteorological Society 73: 1962–70. https://doi.org/10.1175/1520-0477(1999)080<0029:AOOTRO>2.0.CO;2.

Gedalof, Ze'ev, Nathan J. Mantua, and David L. Peterson. 2002. "A Multi-Century Perspective of Variability in the Pacific Decadal Oscillation: New Insights from Tree Rings and Coral." Geophysical Research Letters 29 (24): 57-1-57–4. https://doi.org/10.1029/2002GL015824.

Geerts, Bart, Qun Miao, Yang Yang, Roy Rasmussen, and Daniel Breed. 2010. "An Airborne Profiling Radar Study of the Impact of Glaciogenic Cloud Seeding on Snowfall from Winter Orographic Clouds." Journal of the Atmospheric Sciences 67 (10): 3286–3302. https://doi.org/10.1175/2010JAS3496.1.

Geerts, Bart, Binod Pokharel, Katja Friedrich, Dan Breed, Roy Rasmussen, Yang Yang, Qun Miao, Samuel Haimov, Bruce Boe, and Evan Kalina. 2013. "The AgI Seeding Cloud Impact Investigation (ASCII) Campaign 2012: Overview and Preliminary Results." Journal of Weather Modification 45: 20.

Georgakakos, Konstantine P., N. E. Graham, F.-Y. Cheng, C. Spencer, E. Shamir, A. P. Georgakakos, H. Yao, and M. Kistenmacher. 2012. "Value of Adaptive Water Resources Management in Northern California under Climatic Variability and Change: Dynamic Hydroclimatology." Journal of Hydrology 412–413 (January): 47–65. https://doi.org/10.1016/j.jhydrol.2011.04.032.

Gergis, Joëlle, Karl Braganza, Anthony Fowler, Scott Mooney, and James Risbey. 2006. "Reconstructing El Niño–Southern Oscillation (ENSO) from High-Resolution Palaeoarchives." Journal of Quaternary Science 21 (7): 707–22. https://doi.org/10.1002/jqs.1070.

Gershunov, Alexander, and Tim P. Barnett. 1998. "Interdecadal Modulation of ENSO Teleconnections I." Bulletin of the American Meteorological Society 79 (12): 12.

Gillies, Robert R., Oi-Yu Chung, Shih-Yu Wang, R. Justin DeRose, and Yan Sun. 2015. "Added Value from 576 Years of Tree-Ring Records in the Prediction of the Great Salt Lake Level." Journal of Hydrology 529 (October): 962–68. https://doi.org/10.1016/j.jhydrol.2015.08.058.

Gillies, Robert R., Oi-Yu Chung, Shih-Yu Wang, and Piotr Kokoszka. 2011. "Incorporation of Pacific SSTs in a Time Series Model toward a Longer-Term Forecast for the Great Salt Lake Elevation." Journal of Hydrometeorology 12 (3): 474–80. https://doi.org/10.1175/2010JHM1352.1.

Giorgi, Filippo, and Linda O. Mearns. 1991. "Approaches to the Simulation of Regional Climate Change: A Review." Reviews of Geophysics 29 (2): 191. https://doi.org/10.1029/90RG02636.

Gleckler, P. J., K. E. Taylor, and C. Doutriaux. 2008. "Performance Metrics for Climate Models." Journal of Geophysical Research 113 (D6). https://doi.org/10.1029/2007JD008972.

Gobena, A. K., and T. Y. Gan. 2010. "Incorporation of Seasonal Climate Forecasts in the Ensemble Streamflow Prediction System." Journal of Hydrology 385 (1): 336–52. https://doi.org/10.1016/j.jhydrol.2010.03.002.

Gochis, David J., W. Yu, and D. N. Yates. 2015. "The WRF-Hydro Model Technical Description and User's Guide, Version 3.0." http://www.ral.ucar.edu/projects/wrf_hydro/.

Gold, David. 2017. "An Introduction to Copulas." Water Programming: A Collaborative Research Blog (blog). November 11, 2017. https://waterprogramming.wordpress.com/2017/11/11/an-introduction-to-copulas/.

Gonzalez, Patrick, G. M. Garfin, D. D. Breshears, K. M. Brooks, H. E. Brown, E. H. Elias, A. Gunasekara, et al. 2018. "Fourth National Climate Assessment-Chapter 25: Southwest." https://nca2018.globalchange.govhttps://nca2018.globalchange.gov/chapter/25.

Goodison, B. E., P. Y. T. Louie, and D. Yang. 1998. "WMO Solid Precipitation Measurement Intercomparison--Final Report," 318.

Grantz, Katrina, Balaji Rajagopalan, Martyn P. Clark, and Edith Zagona. 2005. "A Technique for Incorporating Large-Scale Climate Information in Basin-Scale Ensemble Streamflow Forecasts." Water Resources Research 41 (10). https://doi.org/10.1029/2004WR003467.

———. 2007. "Seasonal Shifts in the North American Monsoon." Journal of Climate 20 (9): 1923–35. https://doi.org/10.1175/JCLI4091.1.

Gray, Stephen T., Lisa J. Graumlich, Julio L. Betancourt, and Gregory T. Pederson. 2004. "A Tree-Ring Based Reconstruction of the Atlantic Multidecadal Oscillation since 1567 A.D." Geophysical Research Letters 31 (12): n/a-n/a. https://doi.org/10.1029/2004GL019932.

Gray, Stephen T., and Gregory J. McCabe. 2010. "A Combined Water Balance and Tree Ring Approach to Understanding the Potential Hydrologic Effects of Climate Change in the Central Rocky Mountain Region." Water Resources Research 46 (5). https://doi.org/10.1029/2008WR007650.

Grayson, Rodger B., Ian D. Moore, and Thomas A. McMahon. 1992a. "Physically Based Hydrologic Modeling: 1. A Terrain-Based Model for Investigative Purposes." Water Resources Research 28 (10): 2639–58. https://doi.org/10.1029/92WR01258.

———. 1992b. "Physically Based Hydrologic Modeling: 2. Is the Concept Realistic?" Water Resources Research 28 (10): 2659–66. https://doi.org/10.1029/92WR01259.

Groisman, Pavel Ya, and David R. Easterling. 1994. "Variability and Trends of Total Precipitation and Snowfall over the United States and Canada." Journal of Climate 7: 184–204.

Grygier, J. C., and Jery R. Stedinger. 1990. "SPIGOT, A Synthetic Streamflow Generation Software Package." Ithaca, NY: School of Civil and Environmental Engineering, Cornell University.

Guan, Bin, Noah P. Molotch, Duane E. Waliser, Steven M. Jepsen, Thomas H. Painter, and Jeff Dozier. 2013. "Snow Water Equivalent in the Sierra Nevada: Blending Snow Sensor Observations with Snowmelt Model Simulations." Water Resources Research 49 (8): 5029–46. https://doi.org/10.1002/wrcr.20387.

Guan, Bin, Duane E. Waliser, Noah P. Molotch, Eric J. Fetzer, and Paul J. Neiman. 2012. "Does the Madden–Julian Oscillation Influence Wintertime Atmospheric Rivers and Snowpack in the Sierra Nevada?" Monthly Weather Review 140 (2): 325–42. https://doi.org/10.1175/MWR-D-11-00087.1.

Guentchev, Galina, Joseph J. Barsugli, and Jon Eischeid. 2010. "Homogeneity of Gridded Precipitation Datasets for the Colorado River Basin." Journal of Applied Meteorology and Climatology 49 (12): 2404–15. https://doi.org/10.1175/2010JAMC2484.1.

Guo, Ruixia, Clara Deser, Laurent Terray, and Flavio Lehner. 2019. "Human Influence on Winter Precipitation Trends (1921–2015) over North America and Eurasia Revealed by Dynamical Adjustment." Geophysical Research Letters 46 (6): 3426–34. https://doi.org/10.1029/2018GL081316.

Gutmann, Ethan D., Idar Barstad, Martyn P. Clark, Jeffrey Arnold, and Roy Rasmussen. 2016. "The Intermediate Complexity Atmospheric Research Model (ICAR)." Journal of Hydrometeorology 17 (3): 957–73. https://doi.org/10.1175/JHM-D-15-0155.1.

Gutmann, Ethan D., Tom Pruitt, Martyn P. Clark, Levi Brekke, Jeffrey R. Arnold, David A. Raff, and Roy M. Rasmussen. 2014. "An Intercomparison of Statistical Downscaling Methods Used for Water Resource Assessments in the United States." Water Resources Research 50 (9): 7167–86. https://doi.org/10.1002/2014WR015559.

Gutmann, Ethan D., Roy M. Rasmussen, Changhai Liu, Kyoko Ikeda, David J. Gochis, Martyn P. Clark, Jimy Dudhia, and Gregory Thompson. 2012. "A Comparison of Statistical and Dynamical Downscaling of Winter Precipitation over Complex Terrain." Journal of Climate 25 (1): 262–81. https://doi.org/10.1175/2011JCLI4109.1.

Haarsma, Reindert J., Malcolm J. Roberts, Pier Luigi Vidale, Catherine A. Senior, Alessio Bellucci, Qing Bao, Ping Chang, et al. 2016. "High Resolution Model Intercomparison Project (HighResMIP v1.0) for CMIP6." Geoscientific Model Development 9 (11): 4185–4208. https://doi.org/10.5194/gmd-9-4185-2016.

Haas, Amy. 2018. "Seventieth Annual Report of the Upper Colorado River Commission." Annual report 70. Salt Lake City, UT: Upper Colorado River Commission. http://www.ucrcommission.com/RepDoc/UCRCAnnualReports/70_UCRC_Annual_Report.pdf.

Hagedorn, Renate, Francisco J. Doblas-Reyes, and T. N. Palmer. 2005. "The Rationale behind the Success of Multi-Model Ensembles in Seasonal Forecasting – I. Basic Concept." Tellus A 57 (3): 219–33. https://doi.org/10.1111/j.1600-0870.2005.00103.x.

Hamel, Jama L. n.d. "AgriMet Quality Procedures.Doc."

Hamilton, A. S., and R. D. Moore. 2012. "Quantifying Uncertainty in Streamflow Records." Canadian Water Resources Journal / Revue Canadienne Des Ressources Hydriques 37 (1): 3–21. https://doi.org/10.4296/cwrj3701865.

Hamlet, Alan F., and Dennis P. Lettenmaier. 1999. "Columbia River Streamflow Forecasting Based on ENSO and PDO Climate Signals." Journal of Water Resources Planning and Management 125 (6): 333–41. https://doi.org/10.1061/(ASCE)0733-9496(1999)125:6(333).

———. 2005. "Production of Temporally Consistent Gridded Precipitation and Temperature Fields for the Continental United States." Journal of Hydrometeorology 6 (3): 330–36. https://doi.org/10.1175/JHM420.1.

Hamlet, Alan F., Philip W. Mote, Martyn P. Clark, and Dennis P. Lettenmaier. 2005. "Effects of Temperature and Precipitation Variability on Snowpack Trends in the Western United States." Journal of Climate 18 (21): 4545–61. https://doi.org/10.1175/JCLI3538.1.

Hanson, Clayton L., Gregory L. Johnson, and Albert Rango. 1999. "Comparison of Precipitation Catch between Nine Measuring Systems." Journal of Hydrologic Engineering 4 (1): 70–76. https://doi.org/10.1061/(ASCE)1084-0699(1999)4:1(70).

Hao, Z., and V. P. Singh. 2012. "Entropy-Copula Method for Single-Site Monthly Streamflow Simulation." Water Resources Research 48 (6). https://doi.org/10.1029/2011WR011419.

Harding, Benjamin L., Andrew W. Wood, and James R. Prairie. 2012. "The Implications of Climate Change Scenario Selection for Future Streamflow Projection in the Upper Colorado River Basin." Hydrology and Earth System Sciences 16 (11): 3989–4007. https://doi.org/10.5194/hess-16-3989-2012.

Harding, Benjamin L. 2015. "Colorado River Water Availability Study, Phase II, Updating Climate Impacted Hydrology."

Harpold, Adrian A., Kent Sutcliffe, Jordan Clayton, Angus Goodbody, and Shareily Vazquez. 2017. "Does Including Soil Moisture Observations Improve Operational Streamflow Forecasts in Snow-Dominated Watersheds?" JAWRA Journal of the American Water Resources Association 53 (1): 179–96. https://doi.org/10.1111/1752-1688.12490.

Harrison, Brent, and Roger Bales. 2015. "Skill Assessment of Water Supply Outlooks in the Colorado River Basin." Hydrology 2 (3): 112–31. https://doi.org/10.3390/hydrology2030112.

Harwell, Glenn R. 2012. "Estimation of Evaporation from Open Water—A Review of Selected Studies, Summary of U.S. Army Corps of Engineers Data Collection and Methods, and Evaluation of Two Methods for Estimation of Evaporation from Five Reservoirs in Texas." Scientific Investigations Report 2012–5202. U.S. Geological Survey.

Hausfather, Zeke. 2019. "CMIP6-the next Generation of Climate Models Explained." Carbon Brief. 2019. https://www.carbonbrief.org/cmip6-the-next-generation-of-climate-models-explained.

Hausfather, Zeke, Matthew J. Menne, Claude N. Williams, Troy Masters, Ronald Broberg, and David Jones. 2013. "Quantifying the Effect of Urbanization on U.S. Historical Climatology Network Temperature Record." Journal of Geophysical Research: Atmospheres 118 (2): 481–94. https://doi.org/10.1029/2012JD018509.

Hausfather, Zeke, and Glen P. Peters. 2020. "Emissions – the 'Business as Usual' Story Is Misleading." Nature 577 (7792): 618–20. https://doi.org/10.1038/d41586-020-00177-3.

Hawkins, Ed, and Rowan Sutton. 2009. "The Potential to Narrow Uncertainty in Regional Climate Predictions." Bulletin of the American Meteorological Society 90 (8): 1095–1108. https://doi.org/10.1175/2009BAMS2607.1.

Hedrick, A., H.-P. Marshall, A. Winstral, K. Elder, S. Yueh, and D. Cline. 2015. "Independent Evaluation of the Snodas Snow Depth Product Using Regional-Scale Lidar-Derived Measurements." The Cryosphere 9 (1): 13–23. https://doi.org/10.5194/tc-9-13-2015.

Helms, Douglas, Steven E. Phillips, and Paul F. Reich. 2008. The History of Snow Survey and Water Supply Forecasting-Interviews with U.S. Department of Agriculture Pioneers. USDA NRCS Historical Notes 8. US Department of Agriculture. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1043910.pdf.

Henn, Brian, Andrew J. Newman, Ben Livneh, Christopher Daly, and Jessica D. Lundquist. 2018. "An Assessment of Differences in Gridded Precipitation Datasets in Complex Terrain." Journal of Hydrology 556 (January): 1205–19. https://doi.org/10.1016/j.jhydrol.2017.03.008.

Hereford, Richard, and Robert H. Webb. 1992. "Historic Variation of Warm-Season Rainfall, Southern Colorado Plateau, Southwestern U.S.A." Climatic Change 22 (3): 239–56. https://doi.org/10.1007/BF00143030.

Herman Jonathan D., Zeff Harrison B., Lamontagne Jonathan R., Reed Patrick M., and Characklis Gregory W. 2016. "Synthetic Drought Scenario Generation to Support Bottom-Up Water Supply Vulnerability Assessments." Journal of Water Resources Planning and Management 142 (11): 04016050. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000701.

Herweijer, Celine, Richard Seager, Edward R. Cook, and Julien Emile-Geay. 2007. "North American Droughts of the Last Millennium from a Gridded Network of Tree-Ring Data." Journal of Climate 20 (7): 1353–76. https://doi.org/10.1175/JCLI4042.1.

Hidalgo, Hugo G., Thomas C. Piechota, and John A. Dracup. 2000. "Alternative Principal Components Regression Procedures for Dendrohydrologic Reconstructions." Water Resources Research 36 (11): 3241–49.

Hidalgo, Hugo G. 2004. "Climate Precursors of Multidecadal Drought Variability in the Western United States." Water Resources Research 40 (12). https://doi.org/10.1029/2004WR003350.

Hidalgo, Hugo G., Michael D. Dettinger, and Daniel R. Cayan. 2008. "Downscaling with Constructed Analogues: Daily Precipitation and Temperature Fields Over the United States." California Energy Commission.

Hidalgo, Hugo G., and John A. Dracup. 2003. "ENSO and PDO Effects on Hydroclimatic Variability in the Upper Colorado River Basin." Journal of Hydrometeorology 4: 5–23.

Higgins, R. Wayne, H-K. Kim, and D. Unger. 2004. "Long-Lead Seasonal Temperature and Precipitation Prediction Using Tropical Pacific SST Consolidation Forecasts." Journal of Climate 17: 3398–3414. https://doi.org/10.1175/1520-0442(2004)017<3398:LSTAPP>2.0.CO;2.

Higgins, R. Wayne, Wei Shi, E. Yarosh, and R. Joyce. 2000. "Improved United States Precipitation Quality Control System and Analysis. NCEP/Climate Prediction Center ATLAS No. 7." U. S. DEPARTMENT OF COMMERCE National Oceanic and Atmospheric Administration National Weather Service. https://www.cpc.ncep.noaa.gov/products/outreach/research_papers/ncep_cpc_atlas/7/.

Hobbins, Michael T., and Justin L. Huntington. 2017. Evapotranspiration and Evaporative Demand, Chapter 42: Handbook of Applied Hydrology. Edited by V. P. Singh and Ven Te Chow. Second edition. New York: Mcgraw-Hill Education.

Hobbins, Michael T., Daniel McEvoy, and Christopher Hain. 2017. "Evapotranspiration, Evaporative Demand, and Drought." In Drought and Water Crises, by Donald Wilhite and Roger Pulwarty, 259–88. CRC Press. https://doi.org/10.1201/9781315265551-15.

Hobbins, Michael T., Andrew W. Wood, Daniel J. McEvoy, Justin L. Huntington, Charles Morton, Martha C. Anderson, and Christopher Hain. 2016. "The Evaporative Demand Drought Index. Part I: Linking Drought Evolution to Variations in Evaporative Demand." Journal of Hydrometeorology 17 (6): 1745–61. https://doi.org/10.1175/JHM-D-15-0121.1.

Hobbins, Michael T., Andrew W. Wood, David Streubel, and Kevin Werner. 2012. "What Drives the Variability of Evaporative Demand across the Conterminous United States?" Journal of Hydrometeorology 13 (4): 1195–1214. https://doi.org/10.1175/JHM-D-11-0101.1.

Hoerling, Martin P., Joseph J. Barsugli, B. Livneh, J. Eischeid, X. Quan, and A. Badger. 2019. "Causes for the Century-Long Decline in Colorado River Flow." Journal of Climate, August, JCLI-D-19-0207.1. https://doi.org/10.1175/JCLI-D-19-0207.1.

Hoerling, Martin P., Michael Dettinger, Klaus Wolter, Jeffrey J. Lukas, Jon Eischeid, Rama Nemani, Brant Liebmann, Kenneth E. Kunkel, and Arun Kumar. 2013. "Present Weather and Climate: Evolving Conditions." In Assessment of Climate Change in the Southwest United States: A Report Prepared for the National Climate Assessment, edited by Gregg Garfin, Angela Jardine, Robert Merideth, Mary Black, and Sarah LeRoy, 74–100. Washington, DC: Island Press/Center for Resource Economics. https://doi.org/10.5822/978-1-61091-484-0_5.

Hoerling, Martin P., Jon Eischeid, and Judith Perlwitz. 2010. "Regional Precipitation Trends: Distinguishing Natural Variability from Anthropogenic Forcing." Journal of Climate 23 (8): 2131–45. https://doi.org/10.1175/2009JCLI3420.1.

Hood, Eran, Mark Williams, and Don Cline. 1999. "Sublimation from a Seasonal Snowpack at a Continental, Mid-Latitude Alpine Site." Hydrological Processes 13 (12–13): 1781–97. https://doi.org/10.1002/(SICI)1099-1085(199909)13:12/13<1781::AID-HYP860>3.0.CO;2-C.

Huang, Chengcheng, Andrew J. Newman, Martyn P. Clark, Andrew W. Wood, and Xiaogu Zheng. 2017. "Evaluation of Snow Data Assimilation Using the Ensemble Kalman Filter for Seasonal Streamflow Prediction in the Western United States." Hydrol. Earth Syst. Sci. 21 (1): 635–50. https://doi.org/10.5194/hess-21-635-2017.

Huang, Jin, Huug M. Van den Dool, and Anthony G. Barnston. 1996. "Long-Lead Seasonal Temperature Prediction Using Optimal Climate Normals." Journal of Climate 9: 809–17. https://doi.org/10.1175/1520-0442(1996)009<0809:LLSTPU>2.0.CO;2.

Huang, Jin, Huug M. Van den Dool, and Konstantine P. Georgarakos. 1995. "Analysis of Model-Calculated Soil Moisture over the United States (1931–1993) and Applications to Long-Range Temperature Forecasts." Journal of Climate. https://doi.org/10.1175/1520-0442(1996)009<1350:AOMCSM>2.0.CO;2.

Hubbard, K. G., X. Lin, and E. A. Walter-Shea. 2001. "The Effectiveness of the ASOS, MMTS, Gill, and CRS Air Temperature Radiation Shields*." Journal of Atmospheric and Oceanic Technology 18 (6): 851–64. https://doi.org/10.1175/1520-0426(2001)018<0851:TEOTAM>2.0.CO;2.

Hudson, Debbie. 2017. "Ensemble Verification Metrics." presented at the ECMWF Annual Seminar 2017, Reading, UK.

Hultstrand, Douglas M., and Steven R. Fassnacht. 2018. "The Sensitivity of Snowpack Sublimation Estimates to Instrument and Measurement Uncertainty Perturbed in a Monte Carlo Framework." Frontiers of Earth Science 12 (4): 728–38. https://doi.org/10.1007/s11707-018-0721-0.

Hurrell, James W., M. M. Holland, P. R. Gent, S. Ghan, Jennifer E. Kay, and P. J. Kushner. 2013. "The Community Earth System Model," 22.

Ikeda, Kyoko, Roy Rasmussen, Changhai Liu, David Gochis, David Yates, Fei Chen, Mukul Tewari, et al. 2010. "Simulation of Seasonal Snowfall over Colorado." Atmospheric Research 97 (4): 462–77. https://doi.org/10.1016/j.atmosres.2010.04.010.

International Boundary and Water Commission. 2012. "Minute No. 319. Interim International Cooperative Measures in the Colorado River Basin Through 2017 and Extension of Minute 318 Cooperative Measures to Address the Continued Effects of the April 2010 Earthquake in the Mexicali Valley, Baja California." https://www.ibwc.gov/Files/Minutes/Minute_319.pdf.

———. 2017. "Minute No. 323. Extension of Cooperative Measures and Adoption of a Binational Water Scarcity Contingency Plan in the Colorado River Basin." https://www.ibwc.gov/Files/Minutes/Min323.pdf.

Interstate Council on Water Policy. 2012. "Colorado River Water Science Stakeholders' Roundtable--A Meeing for USGS Cooperative Water Program Partners." Pdf presented at the Colorado River Water Science Stakeholders' Roundtable--A meeing for USGS Cooperative Water Program Partners, Salt Lake City, UT, February 8. https://water.usgs.gov/coop/meeting.book.01262012.pdf.

Iowa State University. n.d. "ASOS Network Quick Links." Iowa Environmental Mesonet Networks. https://mesonet.agron.iastate.edu/ASOS/.

———. n.d. "AWOS Quick Links." Iowa Environmental Mesonet Networks. https://mesonet.agron.iastate.edu/AWOS/.

———. n.d. "NWS COOP Quick Links." Iowa Environmental Mesonet Networks. https://mesonet.agron.iastate.edu/COOP/.

———. n.d. "SCAN Network." Iowa Environmental Mesonet Networks. https://mesonet.agron.iastate.edu/scan/.

Jana, Srijita, Balaji Rajagopalan, Michael A. Alexander, and Andrea J. Ray. 2018. "Understanding the Dominant Sources and Tracks of Moisture for Summer Rainfall in the Southwest United States." Journal of Geophysical Research: Atmospheres 123 (10): 4850–70. https://doi.org/10.1029/2017JD027652.

Jensen, Marvin E., Avry Dotan, and Roland Sanford. 2005. "Penman-Monteith Estimates of Reservoir Evaporation." In Impacts of Global Climate Change, 1–24. Anchorage, Alaska, United States: American Society of Civil Engineers. https://doi.org/10.1061/40792(173)548.

Johnson, Jennifer. 2014. "MODSIM versus RiverWare: A Comparative Analysis of Two River Reservoir Modeling Tools." 2014.3669. US Bureau of Reclamation. https://www.usbr.gov/research/projects/download_product.cfm?id=1360.

Julander, Randall P., and Michael Bricco. 2006. "An Examination of External Influences Imbedded in the Historical Snow Data of Utah." In Proceedings of the Western Snow Conference, 17. Utah State University.

Julander, Randall P., and Jordan A. Clayton. 2018. "Determining the Proportion of Streamflow That Is Generated by Cold Season Processes versus Summer Rainfall in Utah, USA." Journal of Hydrology: Regional Studies 17 (June): 36–46. https://doi.org/10.1016/j.ejrh.2018.04.005.

Kain, John S., Stephen M. Goss, and Michael E. Baldwin. 2000. "The Melting Effect as a Factor in Precipitation-Type Forecasting." Weather and Forecasting 15 (6): 700–714. https://doi.org/10.1175/1520-0434(2000)015<0700:TMEAAF>2.0.CO;2.

Kalnay, Eugenia, Masao Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, et al. 1996. "The NCEP/NCAR 40-Year Reanalysis Project." Bulletin of the American Meteorological Society 77 (3): 437–71. https://doi.org/10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2.

Kapnick, Sarah B., Xiaosong Yang, Gabriel A. Vecchi, Thomas L. Delworth, Rich Gudgel, Sergey Malyshev, P. C. D. Milly, Elena Shevliakova, Seth Underwood, and Steven A. Margulis. 2018. "Potential for Western US Seasonal Snowpack Prediction." Proceedings of the National Academy of Sciences 115 (6): 1180–85. https://doi.org/10.1073/pnas.1716760115.

Karl, Thomas R., H. F. Diaz, and George Kukla. 1988. "Urbanization: Its Detection and Effect in the United States Climate Record." Journal of Climate 1: 1099–1123.

Karl, Thomas R., Claude N. Williams, Pamela J. Young, and Wayne M. Wendland. 1986. "A Model to Estimate the Time of Observation Bias Associated with Monthly Mean, Maximum, Minimum, and Mean Temperatures for the United States." Journal of Climate and Applied Meteorology 25: 145–60.

Kay, Jennifer E., C. Deser, A. Phillips, A. Mai, C. Hannay, G. Strand, J. M. Arblaster, et al. 2015. "The Community Earth System Model (CESM) Large Ensemble Project: A Community Resource for Studying Climate Change in the Presence of Internal Climate Variability." Bulletin of the American Meteorological Society 96 (8): 1333–49. https://doi.org/10.1175/BAMS-D-13-00255.1.

Kendall, Donald R., and John A. Dracup. 1991. "A Comparison of Index-Sequential and AR(1) Generated Hydrologic Sequences." Journal of Hydrology 122 (1): 335–52. https://doi.org/10.1016/0022-1694(91)90187-M.

Kenney, Douglas S., Christopher Goemans, Roberta Klein, Jessica Lowrey, and Kevin Reidy. 2008. "Residential Water Demand Management: Lessons from Aurora, Colorado." JAWRA Journal of the American Water Resources Association 44 (1): 192–207. https://doi.org/10.1111/j.1752-1688.2007.00147.x.

Khaliq, M. N., T. B. M. J. Ouarda, J. -C. Ondo, P. Gachon, and B. Bobée. 2006. "Frequency Analysis of a Sequence of Dependent and/or Non-Stationary Hydro-Meteorological Observations: A Review." Journal of Hydrology 329 (3): 534–52. https://doi.org/10.1016/j.jhydrol.2006.03.004.

Kiang, Julie E., Chris Gazoorian, Hilary McMillan, Gemma Coxon, Jérôme Le Coz, Ida K. Westerberg, Arnaud Belleville, et al. 2018. "A Comparison of Methods for Streamflow Uncertainty Estimation." Water Resources Research 54 (10): 7149–76. https://doi.org/10.1029/2018WR022708.

Kiang, Julie E., David W. Stewart, Stacey A. Archfield, Emily B. Osborne, and Ken Eng. 2013. "A National Streamflow Network Gap Analysis." Scientific Investigations Report 2013–5013. Scientific Investigations Report. U.S. Geological Survey. https://pubs.usgs.gov/sir/2013/5013/pdf/sir2013-5013.pdf.

Kidston, Joseph, Adam A. Scaife, Steven C. Hardiman, Daniel M. Mitchell, Neal Butchart, Mark P. Baldwin, and Lesley J. Gray. 2015. "Stratospheric Influence on Tropospheric Jet Streams, Storm Tracks and Surface Weather." Nature Geoscience 8 (6): 433–40. https://doi.org/10.1038/ngeo2424.

Kirtman, Ben P., Dughong Min, Johnna M. Infanti, James L. Kinter, Daniel A. Paolino, Qin Zhang, Huug M. Van den Dool, et al. 2014. "The North American Multimodel Ensemble: Phase-1 Seasonal-to-Interannual Prediction; Phase-2 toward Developing Intraseasonal Prediction." Bulletin of the American Meteorological Society 95 (4): 585–601. https://doi.org/10.1175/BAMS-D-12-00050.1.

Klotzbach, Philip J. 2014. "The Madden–Julian Oscillation's Impacts on Worldwide Tropical Cyclone Activity." Journal of Climate 27 (6): 2317–30. https://doi.org/10.1175/JCLI-D-13-00483.1.

Knaff, John A., and Christopher W. Landsea. 1997. "An El Niño Southern Oscillation CLImatology and PERsistence (CLIPER) Forecasting Scheme." Weather and Forecasting 12 (3): 633–52. https://doi.org/10.1175/1520-0434(1997)012<0633:AENOSO>2.0.CO;2 Cite this publication.

Knowles, Noah, Michael D. Dettinger, and Daniel R. Cayan. 2006. "Trends in Snowfall versus Rainfall in the Western United States." Journal of Climate 19 (18): 4545–59. https://doi.org/10.1175/JCLI3850.1.

Knutti, Reto. 2010. "The End of Model Democracy?: An Editorial Comment." Climatic Change 102 (3–4): 395–404. https://doi.org/10.1007/s10584-010-9800-2.

Knutti, Reto, Reinhard Furrer, Claudia Tebaldi, Jan Cermak, and Gerald A. Meehl. 2010. "Challenges in Combining Projections from Multiple Climate Models." Journal of Climate 23 (10): 2739–58. https://doi.org/10.1175/2009JCLI3361.1.

Knutti, Reto, David Masson, and Andrew Gettelman. 2013. "Climate Model Genealogy: Generation CMIP5 and How We Got There." Geophysical Research Letters 40 (6): 1194–99. https://doi.org/10.1002/grl.50256.

Koren, Victor, Michael Smith, and Qingyun Duan. 2003. "Use of a Priori Parameter Estimates in the Derivation of Spatially Consistent Parameter Sets of Rainfall-Runoff Models." In Calibration of Watershed Models, 239–54. American Geophysical Union (AGU). https://doi.org/10.1002/9781118665671.ch18.

Koster, Randal D., S. P. P. Mahanama, T. J. Yamada, Gianpaolo Balsamo, A. A. Berg, M. Boisserie, P. A. Dirmeyer, et al. 2011. "The Second Phase of the Global Land–Atmosphere Coupling Experiment: Soil Moisture Contributions to Subseasonal Forecast Skill." Journal of Hydrometeorology 12 (5): 805–22. https://doi.org/10.1175/2011JHM1365.1.

Kuhn, Eric, and John Fleck. 2019. Science Be Dammed. Tucson: University of Arizona Press.

Kuiper, Dana, Rose Loehr, Maggie Dunklee, Laurel Grimsted, and Tony Tolsdorf. 2014. "Chapter 6. Data Management." In Part 622 Snow Survey and Water Supply Forecasting National Engineering Handbook. USDA Natural Resources Conservation Service.

Kumar, Sanjiv, Matthew Newman, Yan Wang, and Ben Livneh. 2019. "Potential Reemergence of Seasonal Soil Moisture Anomalies in North America." Journal of Climate 32 (10): 2707–34. https://doi.org/10.1175/JCLI-D-18-0540.1.

Kumar, Sujay V., Benjamin F. Zaitchik, Christa D. Peters-Lidard, Matthew Rodell, Rolf Reichle, Bailing Li, Michael Jasinski, et al. 2016. "Assimilation of Gridded GRACE Terrestrial Water Storage Estimates in the North American Land Data Assimilation System." Journal of Hydrometeorology 17 (7): 1951–72. https://doi.org/10.1175/JHM-D-15-0157.1.

Labadie, John W., Fontane Darrell G., Tabios Guillermo Q., and Chou Nine Fang. 1987. "Stochastic Analysis of Dependable Hydropower Capacity." Journal of Water Resources Planning and Management 113 (3): 422–37. https://doi.org/10.1061/(ASCE)0733-9496(1987)113:3(422).

Lall, Upmanu. 1995. "Recent Advances in Nonparametric Function Estimation: Hydrologic Applications." Reviews of Geophysics 33 (S2): 1093–1102. https://doi.org/10.1029/95RG00343.

Lall, Upmanu, and Ashish Sharma. 1996. "A Nearest Neighbor Bootstrap For Resampling Hydrologic Time Series." Water Resources Research 32 (3): 679–93. https://doi.org/10.1029/95WR02966.

Lamb, Kenneth W. 2010. "Improving Ensemble Streamflow Prediction Using Interdecadal/Interannual Climate Variability." UNLV Theses, Dissertations, Professional Papers, and Capstones, December, 718.

Lane, William L., and Donald K. Frevert. 1988. "Applied Stochastic Techniques: LAST Computer Package : User Manual." Manual. Denver, Colorado: Division of Planning Technical Services, Engineering and Research Center, Bureau of Reclamation, U.S. Dept. of the Interior.

Langousis, Andreas, and Vassilios Kaleris. 2014. "Statistical Framework to Simulate Daily Rainfall Series Conditional on Upper-Air Predictor Variables." Water Resources Research 50 (5): 3907–32. https://doi.org/10.1002/2013WR014936.

Lanzante, John R., Keith W. Dixon, Mary Jo Nath, Carolyn E. Whitlock, and Dennis Adams-Smith. 2018. "Some Pitfalls in Statistical Downscaling of Future Climate." Bulletin of the American Meteorological Society 99 (4): 791–803. https://doi.org/10.1175/BAMS-D-17-0046.1.

Lareau, Neil P., and John D. Horel. 2012. "The Climatology of Synoptic-Scale Ascent over Western North America: A Perspective on Storm Tracks." Monthly Weather Review 140 (6): 1761–78. https://doi.org/10.1175/MWR-D-11-00203.1.

Lee, Taesam S., Jose D. Salas, J. Keedy, D. Frevert, and T. Fulp. 2007. "Stochastic Modeling and Simulation of the Colorado River Flows." In World Environmental and Water Resources Congress 2007, 1–10. Tampa, Florida, United States: American Society of Civil Engineers. https://doi.org/10.1061/40927(243)423.

Lee, Taesam S., and Jose D. Salas. 2006. "Record Extension of Monthly Flows for the Colorado River System." US Bureau of Reclamation. https://www.usbr.gov/lc/region/g4000/NaturalFlow/Final.RecordExtensionReport.2006.pdf.

———. 2011. "Copula-Based Stochastic Simulation of Hydrological Data Applied to Nile River Flows." Hydrology Research 42 (4): 318–30. https://doi.org/10.2166/nh.2011.085.

Leeper, Ronald D., Jared Rennie, and Michael A. Palecki. 2015. "Observational Perspectives from U.S. Climate Reference Network (USCRN) and Cooperative Observer Program (COOP) Network: Temperature and Precipitation Comparison." Journal of Atmospheric and Oceanic Technology 32 (4): 703–21. https://doi.org/10.1175/JTECH-D-14-00172.1.

Lehner, Flavio, Clara Deser, Isla R. Simpson, and Laurent Terray. 2018. "Attributing the U.S. Southwest's Recent Shift Into Drier Conditions." Geophysical Research Letters 45 (12): 6251–61. https://doi.org/10.1029/2018GL078312.

Lehner, Flavio, Andrew W. Wood, J. A. Vano, D. M. Lawrence, Martyn P. Clark, and Justin S. Mankin. 2019. "The Potential to Reduce Uncertainty in Regional Runoff Projections from Climate Models." Nature Climate Change 9: 926–33. https://doi.org/10.1038/s41558-019-0639-x.

Lehner, Flavio, Andrew W. Wood, Dagmar Llewellyn, Douglas B. Blatchford, Angus G. Goodbody, and Florian Pappenberger. 2017. "Mitigating the Impacts of Climate Nonstationarity on Seasonal Streamflow Predictability in the U.S. Southwest." Geophysical Research Letters 44 (24): 12,208-12,217. https://doi.org/10.1002/2017GL076043.

Lenaerts, Jan T. M., Brooke Medley, Michiel R. van den Broeke, and Bert Wouters. 2019. "Observing and Modeling Ice Sheet Surface Mass Balance." Reviews of Geophysics 57 (2): 376–420. https://doi.org/10.1029/2018RG000622.

Letcher, Theodore W., and Justin R. Minder. 2015. "Characterization of the Simulated Regional Snow Albedo Feedback Using a Regional Climate Model over Complex Terrain." Journal of Climate 28 (19): 7576–95. https://doi.org/10.1175/JCLI-D-15-0166.1.

Leung, L. Ruby, Ying-Hwa Kuo, and Joe Tribbia. 2006. "Research Needs and Directions of Regional Climate Modeling Using WRF and CCSM." Bulletin of the American Meteorological Society 87 (12): 1747–52. https://doi.org/10.1175/BAMS-87-12-1747.

Li, Dongyue, Melissa L. Wrzesien, Michael Durand, Jennifer Adam, and Dennis P. Lettenmaier. 2017. "How Much Runoff Originates as Snow in the Western United States, and How Will That Change in the Future?" Geophysical Research Letters 44 (12): 6163–72. https://doi.org/10.1002/2017GL073551.

Li, Haibin, Justin Sheffield, and Eric F. Wood. 2010. "Bias Correction of Monthly Precipitation and Temperature Fields from Intergovernmental Panel on Climate Change AR4 Models Using Equidistant Quantile Matching." Journal of Geophysical Research 115 (D10): D10101. https://doi.org/10.1029/2009JD012882.

Liang, Xu, Dennis P. Lettenmaier, Eric F. Wood, and Stephen J. Burges. 1994. "A Simple Hydrologically Based Model of Land Surface Water and Energy Fluxes for General Circulation Models." Journal of Geophysical Research: Atmospheres 99 (D7): 14415–28. https://doi.org/10.1029/94JD00483.

Lin, X., and K. G. Hubbard. 2004. "Sensor and Electronic Biases/Errors in Air Temperature Measurements in Common Weather Station Networks*." Journal of Atmospheric and Oceanic Technology 21 (7): 1025–32. https://doi.org/10.1175/1520-0426(2004)021<1025:SAEEIA>2.0.CO;2.

Linacre, Edward. 1992. Climate Data and Resources: A Reference and Guide.

Liston, Glen E., and Kelly Elder. 2006. "A Distributed Snow-Evolution Modeling System (SnowModel)." Journal of Hydrometeorology 7 (6): 1259–76. https://doi.org/10.1175/JHM548.1.

Liu, Changhai, Kyoko Ikeda, Roy Rasmussen, Mike Barlage, Andrew J. Newman, Andreas F. Prein, Fei Chen, et al. 2017. "Continental-Scale Convection-Permitting Modeling of the Current and Future Climate of North America." Climate Dynamics 49 (1–2): 71–95. https://doi.org/10.1007/s00382-016-3327-9.

Liu, Yuqiong, A. H. Weerts, Martyn P. Clark, H.-J. Hendricks Franssen, S. Kumar, H. Moradkhani, D.-J. Seo, et al. 2012. "Advancing Data Assimilation in Operational Hydrologic Forecasting: Progresses, Challenges, and Emerging Opportunities." Hydrology and Earth System Sciences 16 (10): 3863–87. https://doi.org/10.5194/hess-16-3863-2012.

Livezey, Robert E., and Marina M. Timofeyeva. 2008. "The First Decade of Long-Lead U.S. Seasonal Forecasts: Insights from a Skill Analysis." Bulletin of the American Meteorological Society 89 (6): 843–54. https://doi.org/10.1175/2008BAMS2488.1.

Livneh, Ben. n.d. "Data Sets: Daily Observational Hydrometeorology Data Set: CONUS Extent with Canadian Extent of the Columbia River Basin." Water and Climate Research Group. https://ciresgroups.colorado.edu/livneh/data/.

———. n.d. "Data Sets: Daily Observational Hydrometeorology Data Set: North American Extent." Water and Climate Research Group. https://ciresgroups.colorado.edu/livneh/data/.

Livneh, Ben, Andrew M. Badger, and Jeffrey J. Lukas. 2017. "Assessing the Robustness of Snow-Based Drought Indicators in the Upper Colorado River Basin under Future Climate Change." In World Environmental and Water Resources Congress 2017, 511–25. Sacramento, California: American Society of Civil Engineers. https://doi.org/10.1061/9780784480618.051.

Livneh, Ben, Theodore J. Bohn, David W. Pierce, Francisco Munoz-Arriola, Bart Nijssen, Russell Vose, Daniel R. Cayan, and Levi Brekke. 2015. "A Spatially Comprehensive, Hydrometeorological Data Set for Mexico, the U.S., and Southern Canada 1950–2013." Scientific Data 2 (August): 150042. https://doi.org/10.1038/sdata.2015.42.

Livneh, Ben, Eric A. Rosenberg, Chiyu Lin, Bart Nijssen, Vimal Mishra, Kostas M. Andreadis, Edwin P. Maurer, and Dennis P. Lettenmaier. 2013. "A Long-Term Hydrologically Based Dataset of Land Surface Fluxes and States for the Conterminous United States: Update and Extensions." Journal of Climate 26 (23): 9384–92. https://doi.org/10.1175/JCLI-D-12-00508.1.

Loucks, Daniel P., and Eelco van Beek. 2017. Water Resource Systems Planning and Management. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-44234-1.

Lukas, Jeffrey J., Joseph J. Barsugli, Nolan J. Doesken, Imtiaz Rangwala, and Klaus Wolter. 2014. "Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation." Western Water Assessment, University of Colorado Boulder. https://wwa.colorado.edu/climate/co2014report/Climate_Change_CO_Report_2014_FINAL.pdf.

Lukas, Jeffrey J., Elizabeth McNie, Tim Bardsley, Jeffrey S. Deems, and Noah Molotch. 2016. "Snowpack Monitoring for Streamflow Forecasting and Drought Planning." Western Water Assessement.

Lukas, Jeffrey J., Lisa Wade, and Balaji Rajagopalan. 2013. "Paleohydrology of the Lower Colorado River Basin."

Lundquist, Jessica D., Mimi Hughes, Brian Henn, Ethan D. Gutmann, Ben Livneh, Jeff Dozier, and Paul Neiman. 2015. "High-Elevation Precipitation Patterns: Using Snow Measurements to Assess Daily Gridded Datasets across the Sierra Nevada, California." Journal of Hydrometeorology 16 (4): 1773–92. https://doi.org/10.1175/JHM-D-15-0019.1.

Luo, Lifeng, and Eric F. Wood. 2008. "Use of Bayesian Merging Techniques in a Multimodel Seasonal Hydrologic Ensemble Prediction System for the Eastern United States." Journal of Hydrometeorology 9 (5): 866–84. https://doi.org/10.1175/2008JHM980.1.

Lute, A. C., John T. Abatzoglou, and Katherine C. Hegewisch. 2015. "Projected Changes in Snowfall Extremes and Interannual Variability of Snowfall in the Western United States." Water Resources Research 51 (2): 960–72. https://doi.org/10.1002/2014WR016267.

Lynker. 2019. "CRAM Water Resources Modeling Tool." https://www.lynker.com/wp-content/uploads/CRAM-Model-Lynker.pdf.

Ma, Chenchen. 2017. "Evaluating and Correcting Sensor Change Artifacts in the SNOTEL Temperature Records, Southern Rocky Mountains, Colorado." Ft. Collins, CO: Colorado State University.

MacDonald, Glen M., and Roslyn A. Case. 2005. "Variations in the Pacific Decadal Oscillation over the Past Millennium." Geophysical Research Letters 32 (8). https://doi.org/10.1029/2005GL022478.

MacDonald, Glen M., and Abbie H. Tingstad. 2007. "Recent and Multicentennial Precipitation Variability and Drought Occurrence in the Uinta Mountains Region, Utah." Arctic, Antarctic, and Alpine Research 39 (4): 549–55. https://doi.org/10.1657/1523-0430(06-070)[MACDONALD]2.0.CO;2.

Mahoney, Kelly, Michael Alexander, James D. Scott, and Joseph J. Barsugli. 2013. "High-Resolution Downscaled Simulations of Warm-Season Extreme Precipitation Events in the Colorado Front Range under Past and Future Climates." Journal of Climate 26 (21): 8671–89. https://doi.org/10.1175/JCLI-D-12-00744.1.

Maloney, Eric D., and Dennis L. Hartmann. 2000. "Modulation of Eastern North Pacific Hurricanes by the Madden–Julian Oscillation." Journal of Climate 13: 10.

Mamalakis, Antonios, Jin-Yi Yu, James T. Randerson, Amir AghaKouchak, and Efi Foufoula-Georgiou. 2018. "A New Interhemispheric Teleconnection Increases Predictability of Winter Precipitation in Southwestern US." Nature Communications 9 (1). https://doi.org/10.1038/s41467-018-04722-7.

Mantua, Nathan J., Michael Dettinger, Thomas C. Pagano, and Pedro Restrepo. 2008. "A Description and Evaluation of Hydrologic and Climate Forecast and Data Products That Support Decision-Making for Water Resource Managers." Asheville, NC. https://pdfs.semanticscholar.org/ad74/f7701476a309e366190b246936fe0e150a7d.pdf?_ga=2.174838242.1797202885.1563210564-120100695.1562772778.

Mantua, Nathan J., Steven R. Hare, Yuan Zhang, John M. Wallace, and Robert C. Francis. 1997. "A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production." Bulletin of the American Meteorological Society 78 (6): 1069–79. https://doi.org/10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2.

Maraun, Douglas. 2016. "Bias Correcting Climate Change Simulations - a Critical Review." Current Climate Change Reports 2 (4): 211–20. https://doi.org/10.1007/s40641-016-0050-x.

Maraun, Douglas, Theodore G. Shepherd, Martin Widmann, Giuseppe Zappa, Daniel Walton, José M. Gutiérrez, Stefan Hagemann, et al. 2017. "Towards Process-Informed Bias Correction of Climate Change Simulations." Nature Climate Change 7 (11): 764–73. https://doi.org/10.1038/nclimate3418.

Marco, J. B., R. Harboe, and J. D. Salas. 1993. Stochastic Hydrology and Its Use in Water Resources Systems Simulation and Optimization. Vol. 237. NATO ASI Series, E. Kluwer Academic Publishers.

Mariotti, Annarita, Cory Baggett, Elizabeth A. Barnes, Emily Becker, Amy Butler, Dan C. Collins, Paul A. Dirmeyer, et al. 2020. "Windows of Opportunity for Skillful Forecasts Subseasonal to Seasonal and Beyond." Bulletin of the American Meteorological Society, January, BAMS-D-18-0326.1. https://doi.org/10.1175/BAMS-D-18-0326.1.

Mariotti, Annarita, Paolo M. Ruti, and Michel Rixen. 2018. "Progress in Subseasonal to Seasonal Prediction through a Joint Weather and Climate Community Effort." Npj Climate and Atmospheric Science 1 (1). https://doi.org/10.1038/s41612-018-0014-z.

Matott, L. Shawn, Beth Hymiak, Camden Reslink, Christine Baxter, and Shirmin Aziz. 2013. "Telescoping Strategies for Improved Parameter Estimation of Environmental Simulation Models." Computers & Geosciences 60 (October): 156–67. https://doi.org/10.1016/j.cageo.2013.07.023.

Maurer, Edwin P., and David W. Pierce. 2014. "Bias Correction Can Modify Climate Model Simulated Precipitation Changes without Adverse Effect on the Ensemble Mean." Hydrology and Earth System Sciences 18 (3): 915–25. https://doi.org/10.5194/hess-18-915-2014.

Maurer, Edwin P., Andrew W. Wood, Jennifer C. Adam, Dennis P. Lettenmaier, and Bart Nijssen. 2002. "A Long-Term Hydrologically Based Dataset of Land Surface Fluxes and States for the Conterminous United States." Journal of Climate 15 (22): 3237–51. https://doi.org/10.1175/1520-0442(2002)015<3237:ALTHBD>2.0.CO;2.

Maxwell, Reed M., Laura E. Condon, Stefan J. Kollet, Kate Maher, Roy Haggerty, and Mary Michael Forrester. 2016. "The Imprint of Climate and Geology on the Residence Times of Groundwater." Geophysical Research Letters 43 (2): 701–8. https://doi.org/10.1002/2015GL066916.

Maxwell, Reed M., and Norman L. Miller. 2005. "Development of a Coupled Land Surface and Groundwater Model." Journal of Hydrometeorology 6 (3): 233–47. https://doi.org/10.1175/JHM422.1.

McAfee, Stephanie A. 2014. "Consistency and the Lack Thereof in Pacific Decadal Oscillation Impacts on North American Winter Climate." Journal of Climate 27 (19): 7410–31. https://doi.org/10.1175/JCLI-D-14-00143.1.

McAfee, Stephanie A., Galina Guentchev, and Jon Eischeid. 2014. "Reconciling Precipitation Trends in Alaska: 2. Gridded Data Analyses." Journal of Geophysical Research: Atmospheres 119 (24): 13,820-13,837. https://doi.org/10.1002/2014JD022461.

McAfee, Stephanie A., Gregory J. McCabe, Stephen T. Gray, and Gregory T. Pederson. 2019. "Changing Station Coverage Impacts Temperature Trends in the Upper Colorado River Basin." International Journal of Climatology 39 (3): 1517–38. https://doi.org/10.1002/joc.5898.

McAfee, Stephanie A., Joellen L. Russell, and Paul J. Goodman. 2011. "Evaluating IPCC AR4 Cool-Season Precipitation Simulations and Projections for Impacts Assessment over North America." Climate Dynamics 37 (11–12): 2271–87. https://doi.org/10.1007/s00382-011-1136-8.

McCabe, Gregory J., and Steven L. Markstrom. 2007. "A Monthly Water-Balance Model Driven By a Graphical User Interface." Open-File Report 2007–1088. U.S. Geological Survey.

McCabe, Gregory J., Michael A. Palecki, and Julio L. Betancourt. 2004. "Pacific and Atlantic Ocean Influences on Multidecadal Drought Frequency in the United States." Proceedings of the National Academy of Sciences 101 (12): 4136–41. https://doi.org/10.1073/pnas.0306738101.

McCabe, Gregory J., and David M. Wolock. 2007. "Warming May Create Substantial Water Supply Shortages in the Colorado River Basin." Geophysical Research Letters 34 (22). https://doi.org/10.1029/2007GL031764.

———. 2011. "Independent Effects of Temperature and Precipitation on Modeled Runoff in the Conterminous United States." Water Resources Research 47 (11). https://doi.org/10.1029/2011WR010630.

———. 2019. "Hydroclimatology of the Mississippi River Basin." JAWRA Journal of the American Water Resources Association 55 (4): 1053–64. https://doi.org/10.1111/1752-1688.12749.

McCabe, Gregory J., David M. Wolock, Gregory T. Pederson, Connie A. Woodhouse, and Stephanie A. McAfee. 2017. "Evidence That Recent Warming Is Reducing Upper Colorado River Flows." Earth Interactions 21 (10): 1–14. https://doi.org/10.1175/EI-D-17-0007.1.

McGuire, Marketa, Andrew W. Wood, Alan F. Hamlet, and Dennis P. Lettenmaier. 2006. "Use of Satellite Data for Streamflow and Reservoir Storage Forecasts in the Snake River Basin." Journal of Water Resources Planning and Management 132 (2): 97–110. https://doi.org/10.1061/(ASCE)0733-9496(2006)132:2(97).

McKinnon, Karen A., Andrew Poppick, Etienne Dunn-Sigouin, and Clara Deser. 2017. "An 'Observational Large Ensemble' to Compare Observed and Modeled Temperature Trend Uncertainty Due to Internal Variability." Journal of Climate 30 (19): 7585–98. https://doi.org/10.1175/JCLI-D-16-0905.1.

McMahon, Thomas A., Richard M. Vogel, Murray C. Peel, and Geoffrey G.S. Pegram. 2007. "Global Streamflows – Part 1: Characteristics of Annual Streamflows." Journal of Hydrology 347 (3–4): 243–59. https://doi.org/10.1016/j.jhydrol.2007.09.002.

McMillan, Hilary, Tobias Krueger, and Jim Freer. 2012. "Benchmarking Observational Uncertainties for Hydrology: Rainfall, River Discharge and Water Quality." Hydrological Processes 26 (26): 4078–4111. https://doi.org/10.1002/hyp.9384.

McMillan, Hilary, Jan Seibert, Asgeir Petersen-Overleir, Michel Lang, Paul White, Ton Snelder, Kit Rutherford, Tobias Krueger, Robert Mason, and Julie Kiang. 2017. "How Uncertainty Analysis of Streamflow Data Can Reduce Costs and Promote Robust Decisions in Water Management Applications." Water Resources Research 53 (7): 5220–28. https://doi.org/10.1002/2016WR020328.

Mearns, Linda, S. Sain, L. R. Leung, M. S. Bukovsky, S. McGinnis, S. Biner, D. Caya, et al. 2013. "Climate Change Projections of the North American Regional Climate Change Assessment Program (NARCCAP)." Climatic Change 120 (4): 965–75. https://doi.org/10.1007/s10584-013-0831-3.

Mearns, Linda, Seth McGinnis, Daniel Korytina, Raymond Arritt, Sébastien Biner, Melissa Bukovsky, Hsin-I Chang, et al. 2017. "The NA-CORDEX Dataset." UCAR/NCAR. https://doi.org/10.5065/d6sj1jch.

Meko, David M., Charles W. Stockton, and W. R. Boggess. 1995. "The Tree-Ring Record of Severe Sustained Drought." Journal of the American Water Resources Association 31 (5): 789–801. https://doi.org/10.1111/j.1752-1688.1995.tb03401.x.

Meko, David M., and Connie A. Woodhouse. 2011. "Dendroclimatology, Dendrohydrology, and Water Resources Management." In Tree Rings and Climate: Progress and Prospects. Springer.

Meko, David M., Connie A. Woodhouse, Christopher A. Baisan, Troy Knight, Jeffrey J. Lukas, Malcolm K. Hughes, and Matthew W. Salzer. 2007. "Medieval Drought in the Upper Colorado River Basin." Geophysical Research Letters 34 (10). https://doi.org/10.1029/2007GL029988.

Meko, David M., Connie A. Woodhouse, and E.R. Bigio. 2017. "Final Report: Southern California Tree-Ring Study." California Department of Water Resources. https://data.ca.gov/dataset/paleo-dendrochronological-tree-ring-hyrdoclimatic-reconstructions-northern-and-southern-14.

Meko, David M., Connie A. Woodhouse, and K. Morino. 2012. "Dendrochronology and Links to Streamflow." Journal of Hydrology 412–413 (January): 200–209. https://doi.org/10.1016/j.jhydrol.2010.11.041.

Mendoza, Pablo A., Martyn P. Clark, Michael Barlage, Balaji Rajagopalan, Luis Samaniego, Gab Abramowitz, and Hoshin Vijai Gupta. 2015. "Are We Unnecessarily Constraining the Agility of Complex Process-based Models?" Water Resources Research 51 (1): 716–28.

Mendoza, Pablo A., Andrew W. Wood, Elizabeth Clark, Eric Rothwell, Martyn P. Clark, Bart Nijssen, Levi D. Brekke, and Jeffrey R. Arnold. 2017. "An Intercomparison of Approaches for Improving Operational Seasonal Streamflow Forecasts." Hydrology and Earth System Sciences 21 (7): 3915–35. https://doi.org/10.5194/hess-21-3915-2017.

Menne, Matthew J., Imke Durre, Russell S. Vose, Byron E. Gleason, and Tamara G. Houston. 2012. "An Overview of the Global Historical Climatology Network-Daily Database." Journal of Atmospheric and Oceanic Technology 29 (7): 897–910. https://doi.org/10.1175/JTECH-D-11-00103.1.

Menne, Matthew J., and Claude N. Williams. 2009. "Homogenization of Temperature Series via Pairwise Comparisons." Journal of Climate 22 (7): 1700–1717. https://doi.org/10.1175/2008JCLI2263.1.

Menne, Matthew J., Claude N. Williams, and Russell S. Vose. 2009. "The U.S. Historical Climatology Network Monthly Temperature Data, Version 2." Bulletin of the American Meteorological Society 90 (7): 993–1008. https://doi.org/10.1175/2008BAMS2613.1.

Mesinger, Fedor, Geoff DiMego, Eugenia Kalnay, Kenneth Mitchell, Perry C. Shafran, Wesley Ebisuzaki, Dušan Jović, et al. 2006. "North American Regional Reanalysis." Bulletin of the American Meteorological Society 87 (3): 343–60. https://doi.org/10.1175/BAMS-87-3-343.

Michaelsen, Joel. 1987. "Cross-Validation in Statistical Climate Forecast Models." Journal of Climate and Applied Meteorology 26: 1589–1600.

Michaelsen, Joel, H. A. Loaiciga, L. Haston, and S. Garver. 1990. "Estimating Drought Probabilities in California Using Tree Rings. California Department of Water Resources Report B- 57105." University of California, Santa Barbara CA.

Miller, Matthew P., Susan G. Buto, David D. Susong, and Christine A. Rumsey. 2016. "The Importance of Base Flow in Sustaining Surface Water Flow in the Upper Colorado River Basin." Water Resources Research 52 (5): 3547–62. https://doi.org/10.1002/2015WR017963.

Miller, W. Paul, R. Alan Butler, Thomas Piechota, James Prairie, Katrina Grantz, and Gina DeRosa. 2012. "Water Management Decisions Using Multiple Hydrologic Models within the San Juan River Basin under Changing Climate Conditions." Journal of Water Resources Planning and Management 138 (5): 412–20. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000237.

Miller, W. Paul, Gina M. DeRosa, Subhrendu Gangopadhyay, and Juan B. Valdés. 2013. "Predicting Regime Shifts in Flow of the Gunnison River under Changing Climate Conditions: Regime Shifts Over the Gunnison River Basin." Water Resources Research 49 (5): 2966–74. https://doi.org/10.1002/wrcr.20215.

Miller, W. Paul, Thomas Piechota, Subhrendu Gangopadhyay, and Tom Pruitt. 2011. "Development of Streamflow Projections Under Changing Climate Conditions Over Colorado River Basin Headwaters." Hydrol. Earth Syst. Sci., 21.

Milly, P. C. D., Julio Betancourt, Malin Falkenmark, Robert M. Hirsch, Zbigniew W. Kundzewicz, Dennis P. Lettenmaier, and Ronald J. Stouffer. 2008. "Stationarity Is Dead: Whither Water Management?" Science 319 (5863): 573–74. https://doi.org/10.1126/science.1151915.

Milly, P. C. D., Julio Betancourt, Malin Falkenmark, Robert M. Hirsch, Zbigniew W. Kundzewicz, Dennis P. Lettenmaier, Ronald J. Stouffer, Michael D. Dettinger, and Valentina Krysanova. 2015. "On Critiques of 'Stationarity Is Dead: Whither Water Management?'" Water Resources Research 51 (9): 7785–89. https://doi.org/10.1002/2015WR017408.

Milly, P. C. D., and K. A. Dunne. 2020. "Colorado River Flow Dwindles as Warming-Driven Loss of Reflective Snow Energizes Evaporation." Science, February. https://doi.org/10.1126/science.aay9187.

Milly, P. C. D., K. A. Dunne, and A. V. Vecchia. 2005. "Global Pattern of Trends in Streamflow and Water Availability in a Changing Climate." Nature 438 (7066): 347–50. https://doi.org/10.1038/nature04312.

Mitchell, Kenneth E. 2004. "The Multi-Institution North American Land Data Assimilation System (NLDAS): Utilizing Multiple GCIP Products and Partners in a Continental Distributed Hydrological Modeling System." Journal of Geophysical Research 109 (D7). https://doi.org/10.1029/2003JD003823.

Mizukami, Naoki, Martyn P. Clark, Ethan D. Gutmann, Pablo A. Mendoza, Andrew J. Newman, Bart Nijssen, Ben Livneh, Lauren E. Hay, Jeffrey R. Arnold, and Levi D. Brekke. 2016. "Implications of the Methodological Choices for Hydrologic Portrayals of Climate Change over the Contiguous United States: Statistically Downscaled Forcing Data and Hydrologic Models." Journal of Hydrometeorology 17 (1): 73–98. https://doi.org/10.1175/JHM-D-14-0187.1.

Mizukami, Naoki, Martyn P. Clark, Andrew J. Newman, Andrew W. Wood, Ethan D. Gutmann, Bart Nijssen, Oldrich Rakovec, and Luis Samaniego. 2017. "Towards Seamless Large-Domain Parameter Estimation for Hydrologic Models." Water Resources Research 53 (9): 8020–40. https://doi.org/10.1002/2017WR020401.

Mizukami, Naoki, Martyn P. Clark, K. Sampson, B. Nijssen, Yixin Mao, Hilary McMillan, R. J. Viger, et al. 2016. "MizuRoute Version 1: A River Network Routing Tool for a Continental Domain Water Resources Applications." Geoscientific Model Development 9 (6): 2223–38.

Mo, Kingtse C. 2003. "Ensemble Canonical Correlation Prediction of Surface Temperature over the United States." Journal of Climate 16 (11): 1665–83. https://doi.org/10.1175/1520-0442(2003)016<1665:ECCPOS>2.0.CO;2.

Mo, Kingtse C., and Dennis P. Lettenmaier. 2014. "Hydrologic Prediction over the Conterminous United States Using the National Multi-Model Ensemble." Journal of Hydrometeorology 15 (4): 1457–72. https://doi.org/10.1175/JHM-D-13-0197.1.

Mo, Kingtse C., Jae-Kyung E. Schemm, and Soo-Hyun Yoo. 2009. "Influence of ENSO and the Atlantic Multidecadal Oscillation on Drought over the United States." Journal of Climate 22 (22): 5962–82. https://doi.org/10.1175/2009JCLI2966.1.

Monteith, J. L. 1965. "Evaporation and Environment." Symposia of the Society for Experimental Biology 19: 205–34.

Moradkhani, Hamid, and Matthew Meier. 2010. "Long-Lead Water Supply Forecast Using Large-Scale Climate Predictors and Independent Component Analysis." Journal of Hydrologic Engineering 15 (10): 744–62. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000246.

Moreo, Michael T., and Amy Swancar. 2013. "Evaporation from Lake Mead, Nevada and Arizona, March 2010 through February 2012." Scientific Investigations Report 2013–5229. Scientific Investigations Report. U.S. Geological Survey. https://pubs.usgs.gov/sir/2013/5229/.

Mote, Philip W., Levi Brekke, Philip B. Duffy, and Ed Maurer. 2011. "Guidelines for Constructing Climate Scenarios." Eos, Transactions American Geophysical Union 92 (31): 257–58. https://doi.org/10.1029/2011EO310001.

Mote, Philip W., Alan F. Hamlet, Martyn P. Clark, and Dennis P. Lettenmaier. 2005. "Declining Mountain Snowpack in Western North America." Bulletin of the American Meteorological Society 86 (1): 39–50. https://doi.org/10.1175/BAMS-86-1-39.

Mote, Philip W., Sihan Li, Dennis P. Lettenmaier, Mu Xiao, and Ruth Engel. 2018. "Dramatic Declines in Snowpack in the Western US." Npj Climate and Atmospheric Science 1 (1). https://doi.org/10.1038/s41612-018-0012-1.

Mundhenk, Bryan D., Elizabeth A. Barnes, Eric D. Maloney, and Cory F. Baggett. 2018. "Skillful Empirical Subseasonal Prediction of Landfalling Atmospheric River Activity Using the Madden–Julian Oscillation and Quasi-Biennial Oscillation." Npj Climate and Atmospheric Science 1 (1): 20177. https://doi.org/10.1038/s41612-017-0008-2.

Munson, Seth M., Jayne Belnap, and Gregory S. Okin. 2011. "Responses of Wind Erosion to Climate-Induced Vegetation Changes on the Colorado Plateau." Proceedings of the National Academy of Sciences 108 (10): 3854–59. https://doi.org/10.1073/pnas.1014947108.

Naghettini, Mauro. 2016. Fundamentals of Statistical Hydrology. New York, NY: Springer Science+Business Media. https://doi-org.colorado.idm.oclc.org/10.1007/978-3-319-43561-9.

Najafi, Mohammad Reza, and Hamid Moradkhani. 2015. "Ensemble Combination of Seasonal Streamflow Forecasts." Journal of Hydrologic Engineering 21 (1): 04015043. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001250.

NASA. 2019. "Rising to New Challenges for California's Snow Forecasting Program."

Nash, Linda L., and Peter H. Gleick. 1991. "Sensitivity of Streamflow in the Colorado Basin to Climatic Changes." Journal of Hydrology 125 (3–4): 221–41. https://doi.org/10.1016/0022-1694(91)90030-L.

Nathanson, Milton. 1978. "Updating the Hoover Dam Documents, 1978." Reclamation. http://www.riversimulator.org/Resources/LawOfTheRiver/HooverDamDocs/UpdatingHoover1978.pdf.

National Academies, Board on Atmospheric Sciences and Climate, Ocean Studies Board, Division on Earth and Life Studies, and National Academies of Sciences, Engineering, and Medicine. 2016. Next Generation Earth System Prediction: Strategies for Subseasonal to Seasonal Forecasts. Washington, D.C.: National Academies Press. https://doi.org/10.17226/21873.

National Interagency Fire Center. n.d. "Remote Automatic Weather Stations (RAWS)." Remote Automatic Weather Stations. https://raws.nifc.gov/.

National Oceanic and Atmospheric Administration. 2019. "Cooperative Observer Network." Cooperative Observer Network. 2019. https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/cooperative-observer-network-coop.

———. n.d. "Automated Surface Observing System (ASOS)." Automated Surface Observing System. https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/automated-surface-observing-system-asos.

———. n.d. "Automated Weather Observing System (AWOS)." Automated Weather Observing System. https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/automated-weather-observing-system-awos.

———. n.d. "CLIMGRID." Readme File for CLIMGRID. https://data.noaa.gov/dataset/dataset/gridded-5km-ghcn-daily-temperature-and-precipitation-dataset-version-1/resource/72ce7666-9b67-4f58-b433-d9db15320702.

National Research Council. 2003. Critical Issues in Weather Modification Research. Washington, D.C.: National Academies Press. https://doi.org/10.17226/10829.

———. 2004. Assessing the National Streamflow Information Program. https://doi.org/10.17226/10967.

———. 2007. Colorado River Basin Water Management: Evaluating and Adjusting to Hydroclimatic Variability. Washington, D.C.: National Academies Press. https://doi.org/10.17226/11857.

National Weather Service. n.d. "Automated Surface Observing Systems." ASOS National Program Automated Surface Observing Systems. https://www.weather.gov/asos/asostech.

———. n.d. "Cooperative Observer Program (COOP)." Cooperative Observer Program. https://www.weather.gov/coop/overview.

National Wildfire Coordinating Group. 2014. "Interagency Wildland Fire Weather Station Standards & Guidelines," 50.

Natural Resource Conservation Service. n.d. "Automated Soil Climate Monitoring." Automated Soil Climate Monitoring. https://www.wcc.nrcs.usda.gov/about/mon_scan.html.

———. n.d. "Snow Telemetry (SNOTEL) and Snow Course Data and Products." Snow Telemetry and Snow Course Data and Products. https://www.wcc.nrcs.usda.gov/snow/.

NCAR, Weather Modification Incorporated, University of Wyoming, Heritage Environmental Consultants, Desert Research Institute (DRI), and University of Alabama. 2014. "The Wyoming Weather Modification Project Pilot Program: Level II Study. Draft Executive Summary." Wyoming Water Development Commission. http://wwdc.state.wy.us/weathermod/WYWeatherModPilotProgramExecSummary.html.

Nearing, Grey S., Benjamin L. Ruddell, Martyn P. Clark, Bart Nijssen, and Christa Peters-Lidard. 2018. "Benchmarking and Process Diagnostics of Land Models." Journal of Hydrometeorology 19 (11): 1835–52. https://doi.org/10.1175/JHM-D-17-0209.1.

Neff, J. C., A. P. Ballantyne, G. L. Farmer, N. M. Mahowald, J. L. Conroy, C. C. Landry, J. T. Overpeck, T. H. Painter, C. R. Lawrence, and R. L. Reynolds. 2008. "Increasing Eolian Dust Deposition in the Western United States Linked to Human Activity." Nature Geoscience 1 (3): 189–95. https://doi.org/10.1038/ngeo133.

Newman, Andrew J., Martyn P. Clark, Jason Craig, Bart Nijssen, Andrew W. Wood, Ethan D. Gutmann, Naoki Mizukami, Levi Brekke, and Jeff R. Arnold. 2015. "Gridded Ensemble Precipitation and Temperature Estimates for the Contiguous United States." Journal of Hydrometeorology 16 (6): 2481–2500. https://doi.org/10.1175/JHM-D-15-0026.1.

Newman, Andrew J., Martyn P. Clark, Ryan J. Longman, and Thomas W. Giambelluca. 2019. "Methodological Intercomparisons of Station-Based Gridded Meteorological Products: Utility, Limitations, and Paths Forward." Journal of Hydrometeorology 20 (3): 531–47. https://doi.org/10.1175/JHM-D-18-0114.1.

Newman, Matthew, Michael A. Alexander, Toby R. Ault, Kim M. Cobb, Clara Deser, Emanuele Di Lorenzo, Nathan J. Mantua, et al. 2016. "The Pacific Decadal Oscillation, Revisited." Journal of Climate 29 (12): 4399–4427. https://doi.org/10.1175/JCLI-D-15-0508.1.

Newman, Matthew, Gilbert P. Compo, and Michael A. Alexander. 2003. "ENSO-Forced Variability of the Pacific Decadal Oscillation." Journal of Climate 16 (23): 3853–57. https://doi.org/10.1175/1520-0442(2003)016<3853:EVOTPD>2.0.CO;2.

Niu, Guo-Yue, Zong-Liang Yang, Kenneth E. Mitchell, Fei Chen, Michael B. Ek, Michael Barlage, Anil Kumar, et al. 2011. "The Community Noah Land Surface Model with Multiparameterization Options (Noah-MP): 1. Model Description and Evaluation with Local-Scale Measurements." Journal of Geophysical Research: Atmospheres 116 (D12). https://doi.org/10.1029/2010JD015139.

NOAA Earth System Research Laboratory. n.d. "Livneh Daily CONUS Near-Surface Gridded Meteorological and Derived Hydrometeorological Data." Livneh Daily CONUS Near-Surface Gridded Meteorological and Derived Hydrometeorological Data. https://www.esrl.noaa.gov/psd/data/gridded/data.livneh.html.

NOAA National Centers for Environmental Information. n.d. "U.S. Climate Reference Network." Accessed November 17, 2019. https://www.ncdc.noaa.gov/crn/.

NOAA National Environmental, Satellite, Data, and Information Service. 2007. "United States Climate Reference Network Functional Requirements Document." US Department of Commerce. NOAA-CRN/OSD-2003-0009R1UD0.

Nowak, Kenneth, Martin P. Hoerling, Balaji Rajagopalan, and Edith Zagona. 2012. "Colorado River Basin Hydroclimatic Variability." Journal of Climate 25 (12): 4389–4403. https://doi.org/10.1175/JCLI-D-11-00406.1.

Nowak, Kenneth, James Prairie, Balaji Rajagopalan, and Upmanu Lall. 2010. "A Nonparametric Stochastic Approach for Multisite Disaggregation of Annual to Daily Streamflow." Water Resources Research 46 (8). https://doi.org/10.1029/2009WR008530.

NRCS. n.d. "NRCS (Natural Resources Conservation Service) Interactive Map 4.0." Accessed June 21, 2019. https://www.wcc.nrcs.usda.gov/webmap_beta/index.html.

Oaida, Catalina M., John T. Reager, Konstantinos M. Andreadis, Cédric H. David, Steve R. Levoe, Thomas H. Painter, Kat J. Bormann, Amy R. Trangsrud, Manuela Girotto, and James S. Famiglietti. 2019. "A High-Resolution Data Assimilation Framework for Snow Water Equivalent Estimation across the Western United States and Validation with the Airborne Snow Observatory." Journal of Hydrometeorology 20 (3): 357–78. https://doi.org/10.1175/JHM-D-18-0009.1.

Okumura, Yuko M., Pedro DiNezio, and Clara Deser. 2017. "Evolving Impacts of Multiyear La Niña Events on Atmospheric Circulation and U.S. Drought." Geophysical Research Letters 44 (22): 11,614-11,623. https://doi.org/10.1002/2017GL075034.

O'Lenic, Edward A., David A. Unger, Michael S. Halpert, and Kenneth S. Pelman. 2008. "Developments in Operational Long-Range Climate Prediction at CPC." Weather and Forecasting 23 (3): 496–515. https://doi.org/10.1175/2007WAF2007042.1.

O'Neill, Brian C., Claudia Tebaldi, Detlef P. van Vuuren, Veronika Eyring, Pierre Friedlingstein, George Hurtt, Reto Knutti, et al. 2016. "The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6." Geoscientific Model Development 9 (9): 3461–82. https://doi.org/10.5194/gmd-9-3461-2016.

Ostler, Don A. 2017. "Sixty-Ninth Annual Report of the Upper Colorado River Commission." Annual report 69. Salt Lake City, UT: Upper Colorado River Commission. http://www.ucrcommission.com/RepDoc/UCRCAnnualReports/69_UCRC_Annual_Report.pdf.

Ouarda, Taha B. M. J., John W. Labadie, and Darrell G. Fontane. 1997. "Indexed Sequential Hydrologic Modeling for Hyropower Capacity Estimation." Journal of the American Water Resources Association 33 (6): 1337–49. https://doi.org/10.1111/j.1752-1688.1997.tb03557.x.

Oyler, Jared W. n.d. "TopoWx." ScriMHub. http://www.scrimhub.org/resources/topowx/.

Oyler, Jared W., Ashley Ballantyne, Kelsey Jencso, Michael Sweet, and Steven W. Running. 2015. "Creating a Topoclimatic Daily Air Temperature Dataset for the Conterminous United States Using Homogenized Station Data and Remotely Sensed Land Skin Temperature." International Journal of Climatology 35 (9): 2258–79. https://doi.org/10.1002/joc.4127.

Oyler, Jared W., Solomon Z. Dobrowski, Ashley P. Ballantyne, Anna E. Klene, and Steven W. Running. 2015. "Artificial Amplification of Warming Trends across the Mountains of the Western United States." Geophysical Research Letters 42 (1): 153–61. https://doi.org/10.1002/2014GL062803.

Oyler, Jared W., Solomon Z. Dobrowski, Zachary A. Holden, and Steven W. Running. 2016. "Remotely Sensed Land Skin Temperature as a Spatial Predictor of Air Temperature across the Conterminous United States." Journal of Applied Meteorology and Climatology 55 (7): 1441–57. https://doi.org/10.1175/JAMC-D-15-0276.1.

Ozdogan, Mutlu, Yang Yang, George Allez, and Chelsea Cervantes. 2010. "Remote Sensing of Irrigated Agriculture: Opportunities and Challenges." Remote Sensing 2 (9): 2274–2304. https://doi.org/10.3390/rs2092274.

Pagano, Thomas C., and David C. Garen. 2005. "A Recent Increase in Western U.S. Streamflow Variability and Persistence." Journal of Hydrometeorology 6 (2): 173–79. https://doi.org/10.1175/JHM410.1.

Pagano, Thomas C., David C. Garen, Tom R. Perkins, and Phillip A. Pasteris. 2009. "Daily Updating of Operational Statistical Seasonal Water Supply Forecasts for the Western U.S.1." JAWRA Journal of the American Water Resources Association 45 (3): 767–78. https://doi.org/10.1111/j.1752-1688.2009.00321.x.

Pagano, Thomas C., David Garen, and Soroosh Sorooshian. 2004. "Evaluation of Official Western U.S. Seasonal Water Supply Outlooks, 1922–2002." Journal of Hydrometeorology 5: 14.

Pagano, Thomas C., Andrew W. Wood, Kevin Werner, and Rashawn Tama-Sweet. 2014. "Western U.S. Water Supply Forecasting: A Tradition Evolves." Eos, Transactions American Geophysical Union 95 (3): 28–29. https://doi.org/10.1002/2014EO030007.

Painter, Thomas H., Andrew P. Barrett, Christopher C. Landry, Jason C. Neff, Maureen P. Cassidy, Corey R. Lawrence, Kathleen E. McBride, and G. Lang Farmer. 2007. "Impact of Disturbed Desert Soils on Duration of Mountain Snow Cover." Geophysical Research Letters 34 (12). https://doi.org/10.1029/2007GL030284.

Painter, Thomas H., Daniel F. Berisford, Joseph W. Boardman, Kathryn J. Bormann, Jeffrey S. Deems, Frank Gehrke, Andrew Hedrick, et al. 2016. "The Airborne Snow Observatory: Fusion of Scanning Lidar, Imaging Spectrometer, and Physically-Based Modeling for Mapping Snow Water Equivalent and Snow Albedo." Remote Sensing of Environment 184 (October): 139–52. https://doi.org/10.1016/j.rse.2016.06.018.

Painter, Thomas H., Ann C. Bryant, and S. McKenzie Skiles. 2012. "Radiative Forcing of Dust in Mountain Snow from MODIS Surface Reflectance Data." Geophysical Research Letters 39 (L17502).

Painter, Thomas H., Jeffrey S. Deems, Jayne Belnap, Alan F. Hamlet, Christopher C. Landry, and Bradley Udall. 2010. "Response of Colorado River Runoff to Dust Radiative Forcing in Snow." Proceedings of the National Academy of Sciences 107 (40): 17125–30. https://doi.org/10.1073/pnas.0913139107.

Painter, Thomas H., Karl Rittger, Ceretha McKenzie, Peter Slaughter, Robert E. Davis, and Jeff Dozier. 2009. "Retrieval of Subpixel Snow Covered Area, Grain Size, and Albedo from MODIS." Remote Sensing of Environment 113 (4): 868–79. https://doi.org/10.1016/j.rse.2009.01.001.

Painter, Thomas H., S. McKenzie Skiles, Jeffrey S. Deems, W. Tyler Brandt, and Jeff Dozier. 2018. "Variation in Rising Limb of Colorado River Snowmelt Runoff Hydrograph Controlled by Dust Radiative Forcing in Snow." Geophysical Research Letters 45 (2): 797–808. https://doi.org/10.1002/2017GL075826.

Painter, Thomas H., S. McKenzie Skiles, Jeffrey S. Deems, Ann C. Bryant, and Christopher C. Landry. 2012. "Dust Radiative Forcing in Snow of the Upper Colorado River Basin: 1. A 6 Year Record of Energy Balance, Radiation, and Dust Concentrations." Water Resources Research 48 (7). https://doi.org/10.1029/2012WR011985.

Panofsky, Hans A., and G. Brier. 1968. Some Applications of Statistics to Meteorology. Earth and Mineral Sciences Continuing Education, College of Earth and Mineral Sciences.

Pederson, Gregory T., Julio L. Betancourt, and Gregory J. McCabe. 2013. "Regional Patterns and Proximal Causes of the Recent Snowpack Decline in the Rocky Mountains, U.S." Geophysical Research Letters 40 (9): 1811–16. https://doi.org/10.1002/grl.50424.

Pederson, Gregory T., Stephen T. Gray, Connie A. Woodhouse, Julio L. Betancourt, Daniel B. Fagre, Jeremy S. Littell, Emma Watson, Brian H. Luckman, and Lisa J. Graumlich. 2011. "The Unusual Nature of Recent Snowpack Declines in the North American Cordillera." Science 333 (6040): 332–35. https://doi.org/10.1126/science.1201570.

Pegion, Kathy, Ben P. Kirtman, Emily Becker, Dan C. Collins, Emerson LaJoie, Robert Burgman, Ray Bell, et al. 2019. "The Subseasonal Experiment (SubX): A Multi-Model Subseasonal Prediction Experiment." Bulletin of the American Meteorological Society, July, BAMS-D-18-0270.1. https://doi.org/10.1175/BAMS-D-18-0270.1.

Pendergrass, Angeline G., Reto Knutti, Flavio Lehner, Clara Deser, and Benjamin M. Sanderson. 2017. "Precipitation Variability Increases in a Warmer Climate." Scientific Reports 7 (1). https://doi.org/10.1038/s41598-017-17966-y.

Penman, H. L. 1948. "Natural Evaporation from Open Water, Bare Soil and Grass." Proceedings of the Royal Society A 193 (1032). https://doi.org/10.1098/rspa.1948.0037.

Peterson, Thomas C., David R. Easterling, Thomas R. Karl, Pavel Groisman, Neville Nicholls, Neil Plummer, Simon Torok, et al. 1998. "Homogeneity Adjustments of in Situ Atmospheric Climate Data: A Review." International Journal of Climatology 18 (13): 1493–1517. https://doi.org/10.1002/(SICI)1097-0088(19981115)18:13<1493::AID-JOC329>3.0.CO;2-T.

Peterson, Thomas C., Russell Vose, Richard Schmoyer, and Vyachevslav Razuvaëv. 1998. "Global Historical Climatology Network (GHCN) Quality Control of Monthly Temperature Data." International Journal of Climatology 18 (11): 1169–79. https://doi.org/10.1002/(SICI)1097-0088(199809)18:11<1169::AID-JOC309>3.0.CO;2-U.

Phillips, Morgan. 2013. "Estimates of Sublimation in the Upper Colorado River Basin." Master's, Colorado State University.

Piechota, Thomas C., Francis H. S. Chiew, John A. Dracup, and Thomas A. McMahon. 1998. "Seasonal Streamflow Forecasting in Eastern Australia and the El Niño–Southern Oscillation." Water Resources Research 34 (11): 3035–44. https://doi.org/10.1029/98WR02406.

Pierce, David W., Tim P. Barnett, Hugo G. Hidalgo, Tapash Das, Céline Bonfils, Benjamin D. Santer, Govindasamy Bala, et al. 2008. "Attribution of Declining Western U.S. Snowpack to Human Effects." Journal of Climate 21 (23): 6425–44. https://doi.org/10.1175/2008JCLI2405.1.

Pierce, David W., Tim P. Barnett, B. D. Santer, and P. J. Gleckler. 2009. "Selecting Global Climate Models for Regional Climate Change Studies." Proceedings of the National Academy of Sciences 106 (21): 8441–46. https://doi.org/10.1073/pnas.0900094106.

Pierce, David W., Daniel R. Cayan, Edwin P. Maurer, John T. Abatzoglou, and Katherine C. Hegewisch. 2015. "Improved Bias Correction Techniques for Hydrological Simulations of Climate Change." Journal of Hydrometeorology 16 (6): 2421–42. https://doi.org/10.1175/JHM-D-14-0236.1.

Pierce, David W., Daniel R. Cayan, and Bridget L. Thrasher. 2014. "Statistical Downscaling Using Localized Constructed Analogs (LOCA)." Journal of Hydrometeorology 15 (6): 2558–85. https://doi.org/10.1175/JHM-D-14-0082.1.

Pierce, David W., Julie F. Kalansky, and Daniel R. Cayan. 2018. "Climate, Drought, and Sea Level Scenarios for California's Fourth Climate Change Assessment."

"Plans & Reports | Upper Colorado Region | Bureau of Reclamation." n.d. Accessed December 12, 2019. https://www.usbr.gov/uc/envdocs/plans.html#CCULR.

Powell, Anthony. 2015. "Utilizing Probabilistic Forecasts for Colorado River Reservoir Operations Using a Mid-Term Probabilistic Operations Model for Decision Making and Risk Management." In Reno, NV, 11. Reno, NV: Advisory Committee on Water Information.

Powell Consortium. 1995. "Severe Sustained Drought, Managing the Colorado River System in Time of Water Shortage."

Prairie, James, and Russell Callejo. 2005. "Natural Flow and Salt Computation Methods, Calendar Years 1971-1995." US Bureau of Reclamation.

Prairie, James, Kenneth Nowak, Balaji Rajagopalan, Upmanu Lall, and Terrance Fulp. 2008. "A Stochastic Nonparametric Approach for Streamflow Generation Combining Observational and Paleoreconstructed Data: An Approach for Streamflow Generation." Water Resources Research 44 (6). https://doi.org/10.1029/2007WR006684.

Prairie, James, Balaji Rajagopalan, Terry J. Fulp, and Edith A. Zagona. 2006. "Modified K-NN Model for Stochastic Streamflow Simulation." Journal of Hydrologic Engineering 11 (4): 371–78. https://doi.org/10.1061/(ASCE)1084-0699(2006)11:4(371).

Prairie, James, Balaji Rajagopalan, Upmanu Lall, and Terrance Fulp. 2007. "A Stochastic Nonparametric Technique for Space-Time Disaggregation of Streamflows." Water Resources Research 43 (3). https://doi.org/10.1029/2005WR004721.

Prein, Andreas F., Wolfgang Langhans, Giorgia Fosser, Andrew Ferrone, Nikolina Ban, Klaus Goergen, Michael Keller, et al. 2015. "A Review on Regional Convection-permitting Climate Modeling: Demonstrations, Prospects, and Challenges." Reviews of Geophysics 53 (2): 323–61. https://doi.org/10.1002/2014RG000475.

PRISM. 2016. "Descriptions of PRISM Spatial Climate Datasets for the Conterminous United States." http://www.prism.oregonstate.edu/documents/PRISM_datasets.pdf.

Quayle, Robert Q., David R. Easterling, Thomas R. Karl, and Pamela J. Hughes. 1991. "Effects of Recent Thermomenter Changes in the Cooperative Station Network." Bulletin of the American Meteorological Society 72 (11): 1718–23.

Raff, David, Levi Brekke, Kevin Werner, Andy Wood, and Kathleen White. 2013. "Short-Term Water Management Decisions: User Needs for Improved Climate, Weather, and Hydrologic Information." Technical report CWTS 2013-1. U.S. Army Corps of Engineers. https://www.usbr.gov/research/st/roadmaps/WaterSupply.pdf.

Rajagopalan, Balaji, Kenneth Nowak, James Prairie, Martin Hoerling, Benjamin Harding, Joseph Barsugli, Andrea Ray, and Bradley Udall. 2009. "Water Supply Risk on the Colorado River: Can Management Mitigate?" Water Resources Research 45 (8). https://doi.org/10.1029/2008WR007652.

Ralph, F. Martin, Jonathan J. Rutz, Jason M. Cordeira, Michael Dettinger, Michael Anderson, David Reynolds, Lawrence J. Schick, and Chris Smallcomb. 2019. "A Scale to Characterize the Strength and Impacts of Atmospheric Rivers." Bulletin of the American Meteorological Society 100 (2): 269–89. https://doi.org/10.1175/BAMS-D-18-0023.1.

Rangwala, Imtiaz, Tim Bardsley, Marcus Pescinski, and Jim Miller. 2015. "SNOTEL Sensor Upgrade Has Caused Temperature Record Inhomogeneities for the Intermountain West: Implications for Climate Change Impact Assessments." Research Briefing. University of Colorado Boulder: Western Water Assessement.

Rangwala, Imtiaz, and James R. Miller. 2010. "Twentieth Century Temperature Trends in Colorado's San Juan Mountains." Arctic, Antarctic, and Alpine Research 42 (1): 89–97. https://doi.org/10.1657/1938-4246-42.1.89.

Rangwala, Imtiaz, Lesley L. Smith, Gabriel Senay, Joseph J. Barsugli, Stefanie Kagone, and Michael T. Hobbins. 2019. "Landscape Evaporative Response Index (LERI): A High Resolution Monitoring and Assessment of Evapotranspiration across the Contiguous United States." National and Regional Climate Adaptation Science Centers. https://doi.org/10.21429/43r4-3q68.

"Rapid Refresh (RAP)." n.d. Accessed December 11, 2019. https://rapidrefresh.noaa.gov/.

Rasmussen, Roy, Bruce Baker, John Kochendorfer, Tilden Meyers, Scott Landolt, Alexandre P. Fischer, Jenny Black, et al. 2012. "How Well Are We Measuring Snow: The NOAA/FAA/NCAR Winter Precipitation Test Bed." Bulletin of the American Meteorological Society 93 (6): 811–29. https://doi.org/10.1175/BAMS-D-11-00052.1.

Rasmussen, Roy, Kyoko Ikeda, Changhai Liu, David Gochis, Martyn P. Clark, Aiguo Dai, Ethan D. Gutmann, et al. 2014. "Climate Change Impacts on the Water Balance of the Colorado Headwaters: High-Resolution Regional Climate Model Simulations." Journal of Hydrometeorology 15 (3): 1091–1116. https://doi.org/10.1175/JHM-D-13-0118.1.

Rasmussen, Roy, Changhai Liu, Kyoko Ikeda, David Gochis, David Yates, Fei Chen, Mukul Tewari, et al. 2011. "High-Resolution Coupled Climate Runoff Simulations of Seasonal Snowfall over Colorado: A Process Study of Current and Warmer Climate." Journal of Climate 24 (12): 3015–48. https://doi.org/10.1175/2010JCLI3985.1.

Rasmussen, Roy, Sarah Tessendorf, Lulin Xue, Courtney Weeks, Kyoko Ikeda, Scott Landolt, Dan Breed, Terry Deshler, and Barry Lawrence. 2018. "Evaluation of the Wyoming Weather Modification Pilot Project (WWMPP) Using Two Approaches: Traditional Statistics and Ensemble Modeling." Journal of Applied Meteorology and Climatology 57 (11): 2639–60. https://doi.org/10.1175/JAMC-D-17-0335.1.

Rasmusson, Eugene M., and Thomas H. Carpenter. 1982. "Variations in Tropical Sea Surface Temperature and Surface Wind Fields Associated with the Southern Oscillation/El Niño." Monthly Weather Review 110: 354–84. https://doi.org/10.1175/1520-0493(1982)110<0354:VITSST>2.0.CO;2.

Rauber, Robert M., Bart Geerts, Lulin Xue, Jeffrey French, Katja Friedrich, Roy M. Rasmussen, Sarah A. Tessendorf, Derek R. Blestrud, Melvin L. Kunkel, and Shaun Parkinson. 2019. "Wintertime Orographic Cloud Seeding—A Review." Journal of Applied Meteorology and Climatology 58 (10): 2117–40. https://doi.org/10.1175/JAMC-D-18-0341.1.

Ray, Andrea J., Joseph J. Barsugli, K. B. Averyt, Klaus Wolter, Martin P. Hoerling, Nolan J. Doesken, Bradley Udall, and R. S. Webb. 2008. "Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation." https://wwa.colorado.edu/publications/reports/WWA_ClimateChangeColoradoReport_2008.pdf.

Reclamation. 1969. "Report of the Committee on Probabilities and Test Studies to the Task Force on Operating Criteria for the Colorado River." US Bureau of Reclamation. http://www.riversimulator.org/Resources/USBR/ProbabilitiesOnOperatingCriteriaColoradoRiverBoR1969opt.pdf.

———. 1983. "Colorado River Simulation System Hydrology Data Base." US Bureau of Reclamation. https://www.usbr.gov/lc/region/g4000/NaturalFlow/Upper%20Basin_CRSS%20Hydrology%20Data_Base_1983.pdf.

———. 1985. Colorado River Simulation System CRSS System Overview. Denver, Colorado.

———. 1986. "Lake Powell Evaporation." Salt Lake City, UT: Upper Colorado Regional Office.

———. 2007a. "Draft EIS – Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lakes Powell and Mead, Appendix A – CRSS Model Documentation." https://www.usbr.gov/lc/region/programs/strategies/draftEIS/AppA.pdf.

———. 2007b. "Final EIS – Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead, Appendix N – Analysis of Hydrologic Variability Sensitivity." https://www.usbr.gov/lc/region/programs/strategies/FEIS/index.html.

———. 2007c. "Final EIS – Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead, Appendix U – Review of Science and Methods for Incorporating Climate Change Information into Reclamation's Colorado River Basin Planning Studies." https://www.usbr.gov/lc/region/programs/strategies/FEIS/index.html#VolIII.

———. 2007d. "Final EIS, Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lakes Powell and Mead, Appendix C-Upper Basin States Depletion Schedules." US Bureau of Reclamation. https://www.usbr.gov/lc/region/programs/strategies/FEIS/AppC.pdf.

———. 2007e. "Final EIS – Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead, Chapter 1-Purpose and Need." https://www.usbr.gov/lc/region/programs/strategies/FEIS/Chp1.pdf.

———. 2007f. "Final EIS – Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead, Volume 1." https://www.usbr.gov/lc/region/programs/strategies/FEIS/Vol1Front.pdf.

———. 2010. "Colorado River Modeling Work Group Charter." https://www.usbr.gov/lc/region/programs/climateresearch/Charter_ModelingWorkGroup.pdf.

———. 2011. "West-Wide Climate Risk Assessments: Bias-Corrected and Spatially Downscaled Surface Water Projections." Technical Memorandum No. 86-68210-2011-01.

———. 2012a. "Colorado River Basin Water Supply and Demand Study, Appendix C11." https://www.usbr.gov/lc/region/programs/crbstudy/finalreport/Technical%20Report%20C%20-%20Water%20Demand%20Assessment/TR-C_Appendix11_FINAL.pdf.

———. 2012b. "Colorado River Basin Water Supply and Demand Study, Technical Report B-Water Supply Assessment." US Bureau of Reclamation. https://www.usbr.gov/lc/region/programs/crbstudy/finalreport/Technical%20Report%20B%20-%20Water%20Supply%20Assessment/TR-B_Water_Supply_Assessment_FINAL.pdf.

———. 2012c. "Colorado River Basin Water Supply and Demand Study-Appendix B4, Variable Infiltration Capacity (VIC) Hydrologic Modeling Methods and Simulations." US Bureau of Reclamation. https://www.usbr.gov/lc/region/programs/crbstudy/finalreport/Technical%20Report%20B%20-%20Water%20Supply%20Assessment/TR-B_Appendix4_FINAL.pdf.

———. 2012d. "Colorado River Basin Water Supply and Demand Study-Technical Report C." Technical report. US Bureau of Reclamation. https://www.usbr.gov/lc/region/programs/crbstudy/finalreport/Technical%20Report%20C%20-%20Water%20Demand%20Assessment/TR-C-Water_Demand_Assessmemt_FINAL.pdf.

———. 2012e. "Colorado River Basin Water Supply and Demand Study." US Bureau of Reclamation. https://www.usbr.gov/lc/region/programs/crbstudy/finalreport/Study%20Report/CRBS_Study_Report_FINAL.pdf.

———. 2012f. "Colorado River Basin Water Supply and Demand Study-Technical Report G, CRSS Modeling Assumptions." https://www.usbr.gov/lc/region/programs/crbstudy/finalreport/Technical%20Report%20G%20-%20System%20Reliability%20Analysis%20and%20Evaluation%20of%20Options%20and%20Stategies/TR-G_Appendix2_FINAL_Dec2012.pdf.

———. 2014. "Downscaled CMIP3 and CMIP5 Hydrology Projections – Release of Hydrology Projections, Comparison with Preceding Information and Summary of User Needs." Department of Interior, US Bureau of Reclamation.

———. 2015a. "Colorado River Basin Mid-Term Probabilistic Operations Model (MTOM) Overview and Description." US Bureau of Reclamation.

———. 2015b. "Law of the River| Lower Colorado Region | Bureau of Reclamation." USBR.Gov. June 30, 2015. https://www.usbr.gov/lc/region/pao/lawofrvr.html.

———. 2016a. "Downscaled CMIP3 and CMIP5 Climate Projections - Addendum: Release of Downscaled CMIP5 Climate Projections (LOCA) and Comparison with Preceding Information." Reclamation. http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/.

———. 2016b. "SECURE Water Act Section 9503(c)— Reclamation Climate Change and Water 2016." US Bureau of Reclamation.

———. 2016c. "Colorado River Accounting and Water Use Report: Arizona, California, and Nevada Calendar Year 2015." US Bureau of Reclamation. https://www.usbr.gov/lc/region/g4000/4200Rpts/DecreeRpt/2015/2015.pdf.

———. 2018. "Colorado River Basin Ten Tribes Partnership Tribal Water Study." https://www.usbr.gov/lc/region/programs/crbstudy/tws/finalreport.html.

———. 2019a. "AgriMet." Agrimet. 2019. https://www.usbr.gov/pn/agrimet/proginfo.html.

———. 2019b. "Draft -Binational Task 4, Evaluation of Reclamation's 24-Month Study."

———. 2019c. "Colorado River Basin Drought Contingency Plans-Final Documents." November 2019. https://www.usbr.gov/dcp/finaldocs.html.

———. 2019d. "Colorado River Basin Natural Flow and Salt Data." April 1, 2019. https://www.usbr.gov/lc/region/g4000/NaturalFlow/current.html.

———. 2020. "Exploring Climate and Hydrology Projections from the CMIP5 Archive." US Bureau of Reclamation.

Reclamation, and Colorado Basin River Forecast Center. in preparation. "Draft - Forecast and Reservoir Operation Modeling Uncertainty Scoping (FROMUS) Report."

Redmond, Kelly T. 2003. "Climate Variability in the West: Complex Spatial Structure Associated with Topography, and Observational Issues." In Water and Climate in the Western United States, 29–48. University of Colorado Press.

Redmond, Kelly T., and Roy W. Koch. 1991. "Surface Climate and Streamflow Variability in the Western United States and Their Relationship to Large-Scale Circulation Indices." Water Resources Research 27 (9): 2381–99. https://doi.org/10.1029/91WR00690.

Reges, Henry W., Nolan Doesken, Julian Turner, Noah Newman, Antony Bergantino, and Zach Schwalbe. 2016. "CoCoRaHS: The Evolution and Accomplishments of a Volunteer Rain Gauge Network." Bulletin of the American Meteorological Society 97 (10): 1831–46. https://doi.org/10.1175/BAMS-D-14-00213.1.

Reggiani, Paolo, Murugesu Sivapalan, and S. Majid Hassanizadeh. 1998. "A Unifying Framework for Watershed Thermodynamics: Balance Equations for Mass, Momentum, Energy and Entropy, and the Second Law of Thermodynamics." Advances in Water Resources 22 (4): 367–98. https://doi.org/10.1016/S0309-1708(98)00012-8.

Regonda, Satish Kumar, Balaji Rajagopalan, Martyn P. Clark, and John Pitlick. 2005. "Seasonal Cycle Shifts in Hydroclimatology over the Western United States." Journal of Climate 18 (2): 372–84. https://doi.org/10.1175/JCLI-3272.1.

Revelle, R. R., and P. E. Waggoner. 1983. "Effects of a Carbon Dioxide-Induced Climatic Change on Water Supplies in the Western United States." Report of the Carbon Dioxide Assessment Committee. Washington, D.C.: National Academy of Sciences, National Academy Press.

Reynolds, David. 2015. "Literature Review and Scientific Synthesis on the Efficacy of Winter Orographic Cloud Seeding - A Report to the Bureau of Reclamation." CIRES. https://wcr.colorado.edu/sites/default/files/project/files/Literature%20Review%20and%20Scientific%20Synthesis%20on%20the%20Efficacy%20of%20Winter%20Orographic%20Cloud%20Seeding_BOR_June%2010%202015_with%20Exec%20Summary_0.pdf.

Rice, Jennifer L., Connie A. Woodhouse, and Jeffrey J. Lukas. 2009. "Science and Decision Making: Water Management and Tree-Ring Data in the Western United States." JAWRA Journal of the American Water Resources Association 45 (5): 1248–59. https://doi.org/10.1111/j.1752-1688.2009.00358.x.

Ritchie, Justin, and Hadi Dowlatabadi. 2017. "Why Do Climate Change Scenarios Return to Coal?" Energy 140 (December): 1276–91. https://doi.org/10.1016/j.energy.2017.08.083.

Robertson, Andrew W., and Frédéric Vitart. 2019. Sub-Seasonal to Seasonal Prediction. Elsevier.

Robertson, D. E., P. Pokhrel, and Q. J. Wang. 2013. "Improving Statistical Forecasts of Seasonal Streamflows Using Hydrological Model Output." Hydrology and Earth System Sciences 17 (2): 579–93. https://doi.org/10.5194/hess-17-579-2013.

Ropelewski, Chester F., and Michael S. Halpert. 1987. "Global and Regional Scale Precipitation Patterns Associated with the El Niño/Southern Oscillation (ENSO)." Monthly Weather Review 115: 1606–26. https://doi.org/10.1175/1520-0493(1987)115<1606:GARSPP>2.0.CO;2.

———. 1989. "Precipitation Patterns Associated with the High Index Phase of the Southern Oscillation." Journal of Climate 2: 268–84. https://doi.org/10.1175/1520-0442(1989)002<0268:PPAWTH>2.0.CO;2.

Rosenberg, Eric A., E. A. Clark, A. C. Steinemann, and Dennis P. Lettenmaier. 2013. "On the Contribution of Groundwater Storage to Interannual Streamflow Anomalies in the Colorado River Basin." Hydrology and Earth System Sciences 17 (4): 1475–91. https://doi.org/10.5194/hess-17-1475-2013.

Rosenberg, Eric A., Andrew W. Wood, and Anne C. Steinemann. 2011. "Statistical Applications of Physically Based Hydrologic Models to Seasonal Streamflow Forecasts." Water Resources Research 47 (3). https://doi.org/10.1029/2010WR010101.

———. 2013. "Informing Hydrometric Network Design for Statistical Seasonal Streamflow Forecasts." Journal of Hydrometeorology 14 (5): 1587–1604. https://doi.org/10.1175/JHM-D-12-0136.1.

Rumsey, Christine A., Matthew P. Miller, David D. Susong, Fred D. Tillman, and David W. Anning. 2015. "Regional Scale Estimates of Baseflow and Factors Influencing Baseflow in the Upper Colorado River Basin." Journal of Hydrology: Regional Studies 4 (September): 91–107. https://doi.org/10.1016/j.ejrh.2015.04.008.

Running, Steven, and Peter Thornton. 1996. "Generating Daily Surfaces of Temperature and Precipitation over Complex Topography." In GIS and Environmental Modeling: Progress and Research Issues., 93–98. https://scholarworks.umt.edu/ntsg_pubs/60.

Rupp, David E., John T. Abatzoglou, Katherine C. Hegewisch, and Philip W. Mote. 2013. "Evaluation of CMIP5 20th Century Climate Simulations for the Pacific Northwest USA." Journal of Geophysical Research: Atmospheres 118 (19): 10,884-10,906. https://doi.org/10.1002/jgrd.50843.

Rupp, David E., John T. Abatzoglou, and Philip W. Mote. 2017. "Projections of 21st Century Climate of the Columbia River Basin." Climate Dynamics 49 (5–6): 1783–99. https://doi.org/10.1007/s00382-016-3418-7.

Saha, Suranjana, Shrinivas Moorthi, Xingren Wu, Jiande Wang, Sudhir Nadiga, Patrick Tripp, David Behringer, et al. 2014. "The NCEP Climate Forecast System Version 2." Journal of Climate 27 (6): 2185–2208. https://doi.org/10.1175/JCLI-D-12-00823.1.

Salas, Jose D., J. W. Delleur, V. Yevjevich, and W. L. Lane. 1980. Applied Modeling of Hydrologic Time Series. Littleton, Colorado: Water Resources Publications.

Salas, Jose D. 1992. "Analysis and Modeling of Hydrologic Time Series." In Handbook of Hydrology, David R. Maidment, Editor in Chief. McGraw-Hill, Inc.

Salas, Jose D., Donald Frevert, Jeffrey Rieker, David King, Steffen Meyer, William Lane, and Edith Zagona. 2001. "New Developments on the SAMS Stochastic Hydrology Package." In Bridging the Gap, 1–6. The Rosen Plaza Hotel, Orlando, Florida, United States: American Society of Civil Engineers. https://doi.org/10.1061/40569(2001)143.

Samaniego, Luis, Rohini Kumar, and Sabine Attinger. 2010. "Multiscale Parameter Regionalization of a Grid-Based Hydrologic Model at the Mesoscale." Water Resources Research 46 (5). https://doi.org/10.1029/2008WR007327.

Sammis, Theodore W., Junming Wang, and David R. Miller. 2011. "The Transition of the Blaney-Criddle Formula to the Penman-Monteith Equation in the Western United States," 12.

Sanderson, Benjamin M., Michael Wehner, and Reto Knutti. 2017. "Skill and Independence Weighting for Multi-Model Assessments." Geoscientific Model Development 10 (6): 2379–95. https://doi.org/10.5194/gmd-10-2379-2017.

Scanlon, Bridget R., Zizhan Zhang, Robert C. Reedy, Donald R. Pool, Himanshu Save, Di Long, Jianli Chen, David M. Wolock, Brian D. Conway, and Daniel Winester. 2015. "Hydrologic Implications of GRACE Satellite Data in the Colorado River Basin." Water Resources Research 51 (12): 9891–9903. https://doi.org/10.1002/2015WR018090.

Scanlon, Bridget R., Zizhan Zhang, Himanshu Save, Alexander Y. Sun, Hannes Müller Schmied, Ludovicus P. H. van Beek, David N. Wiese, et al. 2018. "Global Models Underestimate Large Decadal Declining and Rising Water Storage Trends Relative to GRACE Satellite Data." Proceedings of the National Academy of Sciences 115 (6): E1080–89. https://doi.org/10.1073/pnas.1704665115.

Schaake, John C., Qingyun Duan, Vazken Andréassian, Stewart Franks, Alan Hall, and George Leavesley. 2006. "The Model Parameter Estimation Experiment (MOPEX)." Journal of Hydrology, The model parameter estimation experiment, 320 (1): 1–2. https://doi.org/10.1016/j.jhydrol.2005.07.054.

Schaake, John C., Qingyun Duan, Victor Koren, Kenneth E. Mitchell, Paul R. Houser, Eric F. Wood, Alan Robock, et al. 2004. "An Intercomparison of Soil Moisture Fields in the North American Land Data Assimilation System (NLDAS)." Journal of Geophysical Research 109 (D1): D01S90. https://doi.org/10.1029/2002JD003309.

Schaefer, Garry L., and Ron F. Paetzold. 2001. "SNOTEL (SNOwpack TELemetry) and SCAN (Soil Climate Analysis Network)." In Proc. Intl. Workshop on Automated Weather Stations for Applications in Agriculture and Water Resources Management:, 7. Lincoln, NE.

Schlesinger, Michael E., and Navin Ramankutty. 1994. "Low-Frequency Oscillation." Nature 372 (6506): 508–9. https://doi.org/10.1038/372508a0.

Schneider, Dominik, and Noah P. Molotch. 2016. "Real-Time Estimation of Snow Water Equivalent in the Upper Colorado River Basin Using MODIS-Based SWE Reconstructions and SNOTEL Data." Water Resources Research 52 (10): 7892–7910. https://doi.org/10.1002/2016WR019067.

Schneider, Stephen H. 2002. "Can We Estimate the Likelihood of Climatic Changes at 2100?" Climatic Change 52 (4): 441–51. https://doi.org/10.1023/A:1014276210717.

Schubert, Siegfried, David Gutzler, Hailan Wang, Aiguo Dai, Tom Delworth, Clara Deser, Kirsten Findell, et al. 2009. "A U.S. CLIVAR Project to Assess and Compare the Responses of Global Climate Models to Drought-Related SST Forcing Patterns: Overview and Results." Journal of Climate 22 (19): 5251–72. https://doi.org/10.1175/2009JCLI3060.1.

Schulman, Edmund. 1945. "Tree-Ring Hydrology of the Colorado Basin." University of Arizona Bulletin 15 (4): 51.

———. 1956. Dendroclimatic Changes in Semiarid America. University of Arizona Press, Tucson.

Scott, David W. 2015. Multivariate Density Estimation: Theory, Practice, and Visualization. Somerset, UNITED STATES: John Wiley & Sons, Incorporated. http://ebookcentral.proquest.com/lib/ucb/detail.action?docID=1895499.

Seager, Richard, Robert Burgman, Yochanan Kushnir, Amy Clement, Ed Cook, Naomi Naik, and Jennifer Miller. 2008. "Tropical Pacific Forcing of North American Medieval Megadroughts: Testing the Concept with an Atmosphere Model Forced by Coral-Reconstructed SSTs." Journal of Climate 21 (23): 6175–90. https://doi.org/10.1175/2008JCLI2170.1.

Seager, Richard, Naomi Naik, and Gabriel A. Vecchi. 2010. "Thermodynamic and Dynamic Mechanisms for Large-Scale Changes in the Hydrological Cycle in Response to Global Warming." Journal of Climate 23 (17): 4651–68. https://doi.org/10.1175/2010JCLI3655.1.

Seager, Richard, M. Ting, I. Held, Y. Kushnir, J. Lu, G. Vecchi, H.-P. Huang, et al. 2007. "Model Projections of an Imminent Transition to a More Arid Climate in Southwestern North America." Science 316 (5828): 1181–84. https://doi.org/10.1126/science.1139601.

Seager, Richard, Mingfang Ting, Cuihua Li, Naomi Naik, Ben Cook, Jennifer Nakamura, and Haibo Liu. 2013. "Projections of Declining Surface-Water Availability for the Southwestern United States." Nature Climate Change 3 (5): 482–86. https://doi.org/10.1038/nclimate1787.

SEI. 2019. "WEAP (Water Evaluation and Planning)." 2019. https://www.weap21.org.

Senay, Gabriel B., Michael Budde, James Verdin, and Assefa Melesse. 2007. "A Coupled Remote Sensing and Simplified Surface Energy Balance Approach to Estimate Actual Evapotranspiration from Irrigated Fields." Sensors 7 (6): 979–1000. https://doi.org/10.3390/s7060979.

Seo, Dong-Jun, Lee Cajina, Robert Corby, and Tracy Howieson. 2009. "Automatic State Updating for Operational Streamflow Forecasting via Variational Data Assimilation." Journal of Hydrology 367 (3–4): 255–75. https://doi.org/10.1016/j.jhydrol.2009.01.019.

Seo, Dong-Jun, Victor Koren, and Neftali Cajina. 2003. "Real-Time Variational Assimilation of Hydrologic and Hydrometeorological Data into Operational Hydrologic Forecasting." Journal of Hydrometeorology 4: 627–41.

Serinaldi, Francesco, and Chris G. Kilsby. 2015. "Stationarity Is Undead: Uncertainty Dominates the Distribution of Extremes." Advances in Water Resources 77 (March): 17–36. https://doi.org/10.1016/j.advwatres.2014.12.013.

Serreze, Mark C., Martyn P. Clark, Richard L. Armstrong, David A. McGinnis, and Roger S. Pulwarty. 1999. "Characteristics of the Western United States Snowpack from Snowpack Telemetry (SNOTEL) Data." Water Resources Research 35 (7): 2145–60. https://doi.org/10.1029/1999WR900090.

Seyfried, M. S., and B. P. Wilcox. 1995. "Scale and the Nature of Spatial Variability: Field Examples Having Implications for Hydrologic Modeling." Water Resources Research 31 (1): 173–84. https://doi.org/10.1029/94WR02025.

Sharifazari, Salman, and Shahab Araghinejad. 2015. "Development of a Nonparametric Model for Multivariate Hydrological Monthly Series Simulation Considering Climate Change Impacts." Water Resources Management 29 (14): 5309–22. https://doi.org/10.1007/s11269-015-1119-3.

Sharma, Ashish, David G. Tarboton, and Upmanu Lall. 1997. "Streamflow Simulation: A Nonparametric Approach." Water Resources Research 33 (2): 291–308. https://doi.org/10.1029/96WR02839.

Shelton, M. L. 2009. Hydroclimatology: Perspectives and Applications. Cambridge University Press. https://books.google.com/books?id=7a2TspPRWmsC.

Shen, Chaopeng. 2018. "A Transdisciplinary Review of Deep Learning Research and Its Relevance for Water Resources Scientists." Water Resources Research 54 (11): 8558–93. https://doi.org/10.1029/2018WR022643.

Shepherd, Theodore G., Emily Boyd, Raphael A. Calel, Sandra C. Chapman, Suraje Dessai, Ioana M. Dima-West, Hayley J. Fowler, et al. 2018. "Storylines: An Alternative Approach to Representing Uncertainty in Physical Aspects of Climate Change." Climatic Change 151 (3–4): 555–71. https://doi.org/10.1007/s10584-018-2317-9.

Sheppard, Paul R., Andrew C. Comrie, Gregory D. Packin, Kurt Angersbach, and Malcolm K. Hughes. 2002. "The Climate of the US Southwest." Climate Research 21: 219–38. https://doi.org/10.3354/cr021219.

Siler, Nicholas, Cristian Proistosescu, and Stephen Po-Chedley. 2019. "Natural Variability Has Slowed the Decline in Western U.S. Snowpack since the 1980s." Geophysical Research Letters 46 (1): 346–55. https://doi.org/10.1029/2018GL081080.

Singh, V. P. 1995. Computer Models of Watershed Hydrology. Highlands Ranch, CO: Water Resources Publications.

Sitterson, Jan, Chris Knightes, Rajbir Parmar, Kurt Wolfe, Muluken Muche, and Brian Avant. 2017. "An Overview of Rainfall-Runoff Model Types." Washington, D.C.: U.S. Environmental Protection Agency. https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=339328&Lab=NERL.

Sivapalan, Murugesu, Günter Blöschl, Lu Zhang, and Rob Vertessy. 2003. "Downward Approach to Hydrological Prediction." Hydrological Processes 17 (11): 2101–11. https://doi.org/10.1002/hyp.1425.

Skamarock, William C., and Joseph B. Klemp. 2008. "A Time-Split Nonhydrostatic Atmospheric Model for Weather Research and Forecasting Applications." Journal of Computational Physics 227 (7): 3465–85. https://doi.org/10.1016/j.jcp.2007.01.037.

Skiles, S. McKenzie, Mark Flanner, Joseph M. Cook, Marie Dumont, and Thomas H. Painter. 2018. "Radiative Forcing by Light-Absorbing Particles in Snow." Nature Climate Change 8 (11): 964–71. https://doi.org/10.1038/s41558-018-0296-5.

Skiles, S. McKenzie, Thomas H. Painter, Jayne Belnap, Lacey Holland, Richard L. Reynolds, Harland L. Goldstein, and John Lin. 2015. "Regional Variability in Dust-on-Snow Processes and Impacts in the Upper Colorado River Basin." Hydrological Processes 29 (26): 5397–5413. https://doi.org/10.1002/hyp.10569.

Skiles, S. McKenzie, Thomas H. Painter, Jeffrey S. Deems, Ann C. Bryant, and Christopher C. Landry. 2012. "Dust Radiative Forcing in Snow of the Upper Colorado River Basin: 2. Interannual Variability in Radiative Forcing and Snowmelt Rates." Water Resources Research 48 (7). https://doi.org/10.1029/2012WR011986.

Slater, Andrew G. 2016. "Surface Solar Radiation in North America: A Comparison of Observations, Reanalyses, Satellite, and Derived Products." Journal of Hydrometeorology 17 (1): 401–20. https://doi.org/10.1175/JHM-D-15-0087.1.

"SMAP/Sentinel-1 L2 Radiometer/Radar 30-Second Scene 3 Km EASE-Grid Soil Moisture, Version 2." 2018. NASA National Snow and Ice Data Center DAAC. https://doi.org/10.5067/ke1csvxmi95y.

Sospedra-Alfonso, Reinel, Joe R. Melton, and William J. Merryfield. 2015. "Effects of Temperature and Precipitation on Snowpack Variability in the Central Rocky Mountains as a Function of Elevation." Geophysical Research Letters 42 (11): 4429–38. https://doi.org/10.1002/2015GL063898.

Srinivas, V. V., and K. Srinivasan. 2005. "Hybrid Moving Block Bootstrap for Stochastic Simulation of Multi-Site Multi-Season Streamflows." Journal of Hydrology 302 (1): 307–30. https://doi.org/10.1016/j.jhydrol.2004.07.011.

Srivastav, Roshan K., and Slobodan P. Simonovic. 2014. "An Analytical Procedure for Multi-Site, Multi-Season Streamflow Generation Using Maximum Entropy Bootstrapping." Environmental Modelling & Software 59 (September): 59–75. https://doi.org/10.1016/j.envsoft.2014.05.005.

Stahle, David W., Edward R. Cook, Malcolm K. Cleaveland, Matthew D. Therrell, David M. Meko, Henri D. Grissino-Mayer, Emma Watson, and Brian H. Luckman. 2000. "Tree-Ring Data Document 16th Century Megadrought over North America." Eos, Transactions American Geophysical Union 81 (12): 121. https://doi.org/10.1029/00EO00076.

Stahle, David W., Falko K. Fye, Edward R. Cook, and R. Daniel Griffin. 2007. "Tree-Ring Reconstructed Megadroughts over North America since a.d. 1300." Climatic Change 83 (1–2): 133–49. https://doi.org/10.1007/s10584-006-9171-x.

Stainforth, David A., Thomas E. Downing, Richard Washington, Ana Lopez, and Mark New. 2007. "Issues in the Interpretation of Climate Model Ensembles to Inform Decisions." Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 365 (1857): 2163–77. https://doi.org/10.1098/rsta.2007.2073.

Stan, Cristiana, David M. Straus, Jorgen S. Frederiksen, Hai Lin, Eric D. Maloney, and Courtney Schumacher. 2017. "Review of Tropical-Extratropical Teleconnections on Intraseasonal Time Scales: The Subseasonal to Seasonal (S2S) Teleconnection Sub-Project." Reviews of Geophysics 55 (4): 902–37. https://doi.org/10.1002/2016RG000538.

Staschus, Konstantin, and Jerson Kelman. 1988. "Probabilistic Dependable Hydro Capacity: The Benefits of Synthetic Hydrology." In Computerized Decision Support Systems for Water Managers. New York, NY: American Society of Civil Engineers. http://www.kelman.com.br/pdf/probabilistic_dependable/probabilistic%20dependable%20hydro.pdf.

Steinschneider, Scott, Rachel McCrary, Linda O. Mearns, and Casey Brown. 2015. "The Effects of Climate Model Similarity on Probabilistic Climate Projections and the Implications for Local, Risk-Based Adaptation Planning: INTERMODEL CORRELATION AND RISK." Geophysical Research Letters 42 (12): 5014–44. https://doi.org/10.1002/2015GL064529.

Stewart, Iris T., Daniel R. Cayan, and Michael D. Dettinger. 2005. "Changes toward Earlier Streamflow Timing across Western North America." Journal of Climate 18 (8): 1136–55. https://doi.org/10.1175/JCLI3321.1.

Stockton, Charles W. 1975. "Long Term Streamflow Records Reconstructed from Tree-Rings." University of Arizona Press, Tucson.

Stockton, Charles W., and W. R. Boggess. 1979. "Geohydrological Implications of Climate Change on Water Resource Development." Fort Belvoir, VA: U.S. Army Coastal Engineering Research Center.

Stockton, Charles W., and G. C. Jacoby. 1976. "Long-Term Surface-Water Supply and Streamflow Trends in the Upper Colorado River Basin. Lake Powell Research Project Bulletin No. 18, Institute of Geophysics and Planetary Physics." University of California at Los Angeles.

Strachan, Scotty. 2016. "Observing Semi-Arid Ecoclimates across Mountain Gradients in the Great Basin, USA." Dissertation, University of Nevada, Reno.

Strachan, Scotty, and Christopher Daly. 2017. "Testing the Daily PRISM Air Temperature Model on Semiarid Mountain Slopes: Testing PRISM Temperature in Mountains." Journal of Geophysical Research: Atmospheres 122 (11): 5697–5715. https://doi.org/10.1002/2016JD025920.

Stratus Consulting. 2005. "Compendium on Methods and Tools to Evaluate Impacts of, and Vulnerability and Adaptation to, Climate Change-Final Draft Report." UNFCCC Secretariat. https://unfccc.int/files/adaptation/methodologies_for/vulnerability_and_adaptation/application/pdf/consolidated_version_updated_021204.pdf.

Sveinsson, O. G. B., Jose D. Salas, W. L. Lane, and D. K. Frevert. 2007. "Stochastic Analysis, Modeling, and Simulation (SAMS) Version 2007." Manual.

Switanek, Matthew B., and Peter A. Troch. 2011. "Decadal Prediction of Colorado River Streamflow Anomalies Using Ocean-Atmosphere Teleconnections." Geophysical Research Letters 38 (23): n/a-n/a. https://doi.org/10.1029/2011GL049644.

Tapley, Byron D., Bettadpur Srinivas, John C. Ries, Paul F. Thompson, and Michael M. Watkins. 2004. "GRACE Measurements of Mass Variability in the Earth System." Science 305 (5683): 503–5. https://doi.org/10.1126/science.1099192.

Tarboton, David G. 1994. "The Source Hydrology of Severe Sustained Drought in the Southwestern United States." Journal of Hydrology 161 (1–4): 31–69. https://doi.org/10.1016/0022-1694(94)90120-1.

———. 1995. "Hydrologic Scenarios for Severe Sustained Drought in the Southwestern United States." Water Resources Bulletin 35 (5).

Tarboton, David G., Ashish Sharma, and Upmanu Lall. 1998. "Disaggregation Procedures for Stochastic Hydrology Based on Nonparametric Density Estimation." Water Resources Research 34 (1): 107–19. https://doi.org/10.1029/97WR02429.

Tebaldi, Claudia, and Reto Knutti. 2007. "The Use of the Multi-Model Ensemble in Probabilistic Climate Projections." Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 365 (1857): 2053–75. https://doi.org/10.1098/rsta.2007.2076.

Technical Committee on Standardization of Reference Evapotranspiration. 2005. The ASCE Standardized Reference Evapotranspiration Equation. Edited by Richard G. Allen, Ivan A. Walter, Ronald L. Elliott, Terry A. Howell, Daniel Itenfisu, Marvin E. Jensen, and Richard L. Snyder. Reston, VA: American Society of Civil Engineers. https://doi.org/10.1061/9780784408056.

Tessendorf, Sarah A., Jeffrey R. French, Katja Friedrich, Bart Geerts, Robert M. Rauber, Roy M. Rasmussen, Lulin Xue, et al. 2019. "A Transformational Approach to Winter Orographic Weather Modification Research: The SNOWIE Project." Bulletin of the American Meteorological Society 100 (1): 71–92. https://doi.org/10.1175/BAMS-D-17-0152.1.

Texas A&M University. 2019a. "Hydrologic Modeling Inventory Website." TAMU Hydrologic Modeling Inventory. 2019. https://hydrologicmodels.tamu.edu/.

———. 2019b. "Water Rights Analysis Package." 2019. https://ceprofs.civil.tamu.edu/rwurbs/wrap.htm.

Thirel, Guillaume, E. Martin, J.-F. Mahfouf, S. Massart, S. Ricci, and F. Habets. 2010. "A Past Discharges Assimilation System for Ensemble Streamflow Forecasts over France – Part 1: Description and Validation of the Assimilation System." Hydrology and Earth System Sciences 14 (8): 1623–37. https://doi.org/10.5194/hess-14-1623-2010.

Thirel, Guillaume, E. Martin, J.-F. Mahfouf, S. Massart, S. Ricci, F. Regimbeau, and F. Habets. 2010. "A Past Discharge Assimilation System for Ensemble Streamflow Forecasts over France – Part 2: Impact on the Ensemble Streamflow Forecasts." Hydrology and Earth System Sciences 14 (8): 1639–53. https://doi.org/10.5194/hess-14-1639-2010.

Thober, Stephan, Rohini Kumar, Justin Sheffield, Juliane Mai, David Schäfer, and Luis Samaniego. 2015. "Seasonal Soil Moisture Drought Prediction over Europe Using the North American Multi-Model Ensemble (NMME)." Journal of Hydrometeorology 16 (6): 2329–44. https://doi.org/10.1175/JHM-D-15-0053.1.

Thornton, Peter E., Hubert Hasenauer, and Michael A. White. 2000. "Simultaneous Estimation of Daily Solar Radiation and Humidity from Observed Temperature and Precipitation: An Application over Complex Terrain in Austria." Agricultural and Forest Meteorology 104 (4): 255–71. https://doi.org/10.1016/S0168-1923(00)00170-2.

Thornton, Peter E., and Steven W. Running. 1999. "An Improved Algorithm for Estimating Incident Daily Solar Radiation from Measurements of Temperature, Humidity, and Precipitation." Agricultural and Forest Meteorology 93 (4): 211–28. https://doi.org/10.1016/S0168-1923(98)00126-9.

Thornton, Peter E., Steven W. Running, and Michael A. White. 1997. "Generating Surfaces of Daily Meteorological Variables over Large Regions of Complex Terrain." Journal of Hydrology 190 (3–4): 214–51. https://doi.org/10.1016/S0022-1694(96)03128-9.

Thornton, Peter E., M. M. Thornton, B. W. Mayer, Y. Wei, R. Devarakonda, Russell S. Vose, and R. B. Cook. 2016. "Daymet: Daily Surface Weather Data on a 1-Km Grid for North America, Version 3." ORNL DAAC Distributed Active Archive Center for Biogeochemical Dynamics. 2016.

Thrasher, Bridget, Jun Xiong, Weile Wang, Forrest Melton, Andrew Michaelis, and Ramakrishna Nemani. 2013. "Downscaled Climate Projections Suitable for Resource Management." Eos, Transactions American Geophysical Union 94 (37): 321–23. https://doi.org/10.1002/2013EO370002.

Tighi, Shana Goffman. 2006. "Uncertainty Analysis: Mid-Term Operational Model for the Lower Colorado River." Master's, University of Nevada, Las Vegas.

Timm, Oliver Elison, Thomas W. Giambelluca, and Henry F. Diaz. 2015. "Statistical Downscaling of Rainfall Changes in Hawai'i Based on the CMIP5 Global Model Projections: Downscaled Rainfall Changes in Hawai'i." Journal of Geophysical Research: Atmospheres 120 (1): 92–112. https://doi.org/10.1002/2014JD022059.

Tippett, Michael K., Meghana Ranganathan, Michelle L'Heureux, Anthony G. Barnston, and Timothy DelSole. 2017. "Assessing Probabilistic Predictions of ENSO Phase and Intensity from the North American Multimodel Ensemble." Climate Dynamics, May. https://doi.org/10.1007/s00382-017-3721-y.

Tipton, Royce, and Olin Kalmbach. 1965. "Water Supplies of the Colorado River--Available for Use by the States of the Upper Division and for Use from the Main Stem by the States of Arizona, California and Nevada in the Lower Basin." Engineering. Denver, Colorado: Upper Colorado River Commission. https://wwa.colorado.edu/resources/colorado-river/docs/management/Tipton1965.pdf.

Tokarska, Katarzyna B., Martin B. Stolpe, Sebastian Sippel, Erich M. Fischer, Christopher J. Smith, Flavio Lehner, and Reto Knutti. 2020. "Past Warming Trend Constrains Future Warming in CMIP6 Models." Science Advances 6 (12). https://doi.org/10.1126/sciadv.aaz9549.

Tolson, B. A., and C. A. Shoemaker. 2006. "The Dynamically Dimensioned Search (DDS) Algorithm as a Robust Optimization Tool in Hydrologic Modeling." In AGU Fall Meeting Abstracts, 41:H41I-07. http://adsabs.harvard.edu/abs/2006AGUFM.H41I..07T.

Tootle, Glenn A., Singh Ashok K., Thomas C. Piechota, and Farnham Irene. 2007. "Long Lead-Time Forecasting of U.S. Streamflow Using Partial Least Squares Regression." Journal of Hydrologic Engineering 12 (5): 442–51. https://doi.org/10.1061/(ASCE)1084-0699(2007)12:5(442).

Topping, David J., John C. Schmidt, and L.E. Vierra Jr. 2003. "Computation and Analysis of the Instantaneous-Discharge Record for the Colorado River at Lees Ferry, Arizona : May 8, 1921, through September 30, 2000." USGS Numbered Series 1677. Professional Paper. Reston, VA: U.S. Geological Survey. http://pubs.er.usgs.gov/publication/pp1677.

Tourre, Yves M., Balaji Rajagopalan, Yochanan Kushnir, Mathew Barlow, and Warren B. White. 2001. "Patterns of Coherent Decadal and Interdecadal Climate Signals in the Pacific Basin during the 20th Century." Geophysical Research Letters 28 (10): 2069–72. https://doi.org/10.1029/2000GL012780.

Towler, Erin, Debasish PaiMazumder, and James Done. 2018. "Toward the Application of Decadal Climate Predictions." Journal of Applied Meteorology and Climatology 57 (3): 555–68. https://doi.org/10.1175/JAMC-D-17-0113.1.

Udall, Bradley, and Jonathan Overpeck. 2017. "The Twenty-First Century Colorado River Hot Drought and Implications for the Future." Water Resources Research 53 (3): 2404–18. https://doi.org/10.1002/2016WR019638.

URS. 2013. "Assessing Agricultural Consumptive Use in the Upper Colorado River Basin - Phase I." http://www.ucrcommission.com/RepDoc/Studies/Assessing%20_Ag_CU_PhaseI.pdf.

———. 2016. "Assessing Agricultural Consumptive Use in the Upper Colorado River Basin - Phase II." http://www.ucrcommission.com/RepDoc/Studies/Assessing%20_Ag_CU_PhaseII.pdf.

US Army Corps of Engineers. 1971. "HEC-4 Monthly Streamflow Simulation User's Manual." United States Army Corps of Engineers, Department of Hydrologic Engineering Center. https://www.hec.usace.army.mil/publications/ComputerProgramDocumentation/HEC-4_UsersManual_(CPD-4).pdf.

———. 2012. "HEC-ResPRM." 2012. https://www.hec.usace.army.mil/software/hec-resprm/.

US Geological Survey. 1977. "Water Resources Data for Colorado, Water Year 1975. Volume 2, Colorado River Basin." U.S. GEOLOGICAL SURVEY WATER-DATA REPORT CO-75-2. U.S. Geological Survey.

———. 2018a. "Federal Priorities Streamgages (FPS) Mapper." 2018. https://water.usgs.gov/networks/fps/.

———. 2018b. "USGS Water-Year Summary for Site 09315000." 2018. https://waterdata.usgs.gov/nwis/wys_rpt/?site_no=09315000.

———. 2018c. "USGS Water-Year Summary for Site 09380000." 2018. https://waterdata.usgs.gov/nwis/wys_rpt/?site_no=09380000&agency_cd=USGS.

———. n.d. "Water Resources of the United States—Annual Water Data Report—Documentation." Annual Water Data Report. Accessed March 21, 2019. https://wdr.water.usgs.gov/current/documentation.html.

U.S. Secretary of the Interior. 2007. "Record of Decision Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operations for Lake Powell and Lake Mead." U.S. Department of the Interior. https://www.usbr.gov/lc/region/programs/strategies/RecordofDecision.pdf.

USGCRP. 2017. "Climate Science Special Report: Fourth National Climate Assessment, Volume I." Washington, D.C.: U.S Global Change Research Program. doi: 10.7930/J0J964J6.

Van den Dool, Huug M. 1994. "Searching for Analogues, How Long Must We Wait?" Tellus A 46 (3): 314–24. https://doi.org/10.1034/j.1600-0870.1994.t01-2-00006.x.

———. 2003. "Performance and Analysis of the Constructed Analogue Method Applied to U.S. Soil Moisture over 1981–2001." Journal of Geophysical Research 108 (D16): 8617. https://doi.org/10.1029/2002JD003114.

———. 2007. Empirical Methods in Short-Term Climate Prediction. Oxford ; New York: Oxford University Press.

Vano, Julie A., Jeffrey R. Arnold, Bart Nijssen, Martyn P. Clark, Andrew W. Wood, Ethan D. Gutmann, Nans Addor, Joseph Hamman, and Flavio Lehner. 2018. "DOs and DON'Ts for Using Climate Change Information for Water Resource Planning and Management: Guidelines for Study Design." Climate Services 12 (December): 1–13. https://doi.org/10.1016/j.cliser.2018.07.002.

Vano, Julie A., Tapash Das, and Dennis P. Lettenmaier. 2012. "Hydrologic Sensitivities of Colorado River Runoff to Changes in Precipitation and Temperature*." Journal of Hydrometeorology 13 (3): 932–49. https://doi.org/10.1175/JHM-D-11-069.1.

Vano, Julie A., and Dennis P. Lettenmaier. 2014. "A Sensitivity-Based Approach to Evaluating Future Changes in Colorado River Discharge." Climatic Change 122 (4): 621–34. https://doi.org/10.1007/s10584-013-1023-x.

Vano, Julie A., Bradley Udall, Daniel R. Cayan, Jonathan T. Overpeck, Levi D. Brekke, Tapash Das, Holly C. Hartmann, et al. 2014. "Understanding Uncertainties in Future Colorado River Streamflow." Bulletin of the American Meteorological Society 95 (1): 59–78. https://doi.org/10.1175/BAMS-D-12-00228.1.

Verdin, Andrew, Balaji Rajagopalan, William Kleiber, Guillermo Podestá, and Federico Bert. 2018. "A Conditional Stochastic Weather Generator for Seasonal to Multi-Decadal Simulations." Journal of Hydrology 556 (January): 835–46. https://doi.org/10.1016/j.jhydrol.2015.12.036.

Vigaud, N., Andrew W. Robertson, and M. K. Tippett. 2017. "Multimodel Ensembling of Subseasonal Precipitation Forecasts over North America." Monthly Weather Review 145 (10): 3913–28. https://doi.org/10.1175/MWR-D-17-0092.1.

Vliet, Michelle T. H. van, David Wiberg, Sylvain Leduc, and Keywan Riahi. 2016. "Power-Generation System Vulnerability and Adaptation to Changes in Climate and Water Resources." Nature Climate Change 6 (4): 375–80. https://doi.org/10.1038/nclimate2903.

Vogel, Jason M. 2015. "Actionable Science in Practice: Co-Producing Climate Change Information for Water Utility Vulnerability Assessments." Water Utility Climate Alliance.

Vogel, Richard M. 2017. "Stochastic Watershed Models for Hydrologic Risk Management." Water Security 1 (July): 28–35. https://doi.org/10.1016/j.wasec.2017.06.001.

Vose, Russell S., Scott Applequist, Mike Squires, Imke Durre, Matthew J. Menne, Claude N. Williams, Chris Fenimore, Karin Gleason, and Derek Arndt. 2014. "Improved Historical Temperature and Precipitation Time Series for U.S. Climate Divisions." Journal of Applied Meteorology and Climatology 53 (5): 1232–51. https://doi.org/10.1175/JAMC-D-13-0248.1.

Vuuren, Detlef P. van, Jae Edmonds, Mikiko Kainuma, Keywan Riahi, Allison Thomson, Kathy Hibbard, George C. Hurtt, et al. 2011. "The Representative Concentration Pathways: An Overview." Climatic Change 109 (1–2): 5–31. https://doi.org/10.1007/s10584-011-0148-z.

Walton, Daniel, and Alex Hall. 2018. "An Assessment of High-Resolution Gridded Temperature Datasets over California." Journal of Climate 31 (10): 3789–3810. https://doi.org/10.1175/JCLI-D-17-0410.1.

Wang, Q. J., D. E. Robertson, and F. H. S. Chiew. 2009. "A Bayesian Joint Probability Modeling Approach for Seasonal Forecasting of Streamflows at Multiple Sites." Water Resources Research 45 (5). https://doi.org/10.1029/2008WR007355.

Wang, Shih-Yu, Robert R. Gillies, Oi-Yu Chung, and Chaopeng Shen. 2018. "Cross-Basin Decadal Climate Regime Connecting the Colorado River with the Great Salt Lake." Journal of Hydrometeorology 19 (4): 659–65. https://doi.org/10.1175/JHM-D-17-0081.1.

Wang, Shih-Yu, Robert R. Gillies, Lawrence E. Hipps, and Jiming Jin. 2011. "A Transition-Phase Teleconnection of the Pacific Quasi-Decadal Oscillation." Climate Dynamics 36 (3–4): 681–93. https://doi.org/10.1007/s00382-009-0722-5.

Waring, R. H., N. C. Coops, W. Fan, and J. M. Nightingale. 2006. "MODIS Enhanced Vegetation Index Predicts Tree Species Richness across Forested Ecoregions in the Contiguous U.S.A." Remote Sensing of Environment 103 (2): 218–26. https://doi.org/10.1016/j.rse.2006.05.007.

Water Resources and Climate Change Workgroup. 2016. "Looking Forward: Priorities for Managing Freshwater Resources in a Changing Climate." Interagency Climate Change Adaptation Task Force.

Waugh, Darryn W., Adam H. Sobel, and Lorenzo M. Polvani. 2017. "What Is the Polar Vortex and How Does It Influence Weather?" Bulletin of the American Meteorological Society 98 (1): 37–44. https://doi.org/10.1175/BAMS-D-15-00212.1.

Weerts, Albrecht H., Ghada Y. El Serafy, Stef Hummel, Juzer Dhondia, and Herman Gerritsen. 2010. "Application of Generic Data Assimilation Tools (DATools) for Flood Forecasting Purposes." Computers & Geosciences 36 (4): 453–63. https://doi.org/10.1016/j.cageo.2009.07.009.

Weisbecker, Leo. 1974. Snowpack, Cloud-Seeding, and the Colorado River: A Technology Assessment of Weather Modification. University of Oklahoma Press.

Weisheimer, A., and T. N. Palmer. 2014. "On the Reliability of Seasonal Climate Forecasts." Journal of The Royal Society Interface 11 (96): 20131162. https://doi.org/10.1098/rsif.2013.1162.

Welles, Edwin, and Soroosh Sorooshian. 2009. "Scientific Verification of Deterministic River Stage Forecasts." Journal of Hydrometeorology 10 (2): 507–20. https://doi.org/10.1175/2008JHM1022.1.

Welles, Edwin, Soroosh Sorooshian, Gary Carter, and Billy Olsen. 2007. "Hydrologic Verification: A Call for Action and Collaboration." Bulletin of the American Meteorological Society 88 (4): 503–12. https://doi.org/10.1175/BAMS-88-4-503.

Werner, Kevin, David Brandon, Martyn P. Clark, and Subhrendu Gangopadhyay. 2004. "Climate Index Weighting Schemes for NWS ESP-Based Seasonal Volume Forecasts." Journal of Hydrometeorology 5 (6): 1076–90. https://doi.org/10.1175/JHM-381.1.

———. 2005. "Incorporating Medium-Range Numerical Weather Model Output into the Ensemble Streamflow Prediction System of the National Weather Service." Journal of Hydrometeorology 6 (2): 101–14. https://doi.org/10.1175/JHM411.1.

Western Regional Climate Center. n.d. "RAWS USA Climate Archive." RAWS USA Climate Archive.

Westrick, Kenneth J., Pascal Storck, and Clifford F. Mass. 2002. "Description and Evaluation of a Hydrometeorological Forecast System for Mountainous Watersheds." Weather and Forecasting 17 (2): 250–62. https://doi.org/10.1175/1520-0434(2002)017<0250:DAEOAH>2.0.CO;2.

Wetterhall, F., and F. Di Giuseppe. 2018. "The Benefit of Seamless Forecasts for Hydrological Predictions over Europe." Hydrol. Earth Syst. Sci. 22 (6): 3409–20. https://doi.org/10.5194/hess-22-3409-2018.

Wheeler, Kevin G., David E. Rosenberg, and John C. Schmidt. 2019. "Water Resource Modeling of the Colorado River: Present and Future Strategies," 47.

Wilby, Robert L., C. W. Dawson, and E. M. Barrow. 2002. "SDSM — a Decision Support Tool for the Assessment of Regional Climate Change Impacts." Environmental Modelling & Software 17 (2): 145–57. https://doi.org/10.1016/S1364-8152(01)00060-3.

Wilby, Robert L., and T. M. L. Wigley. 1997. "Downscaling General Circulation Model Output: A Review of Methods and Limitations." Progress in Physical Geography: Earth and Environment 21 (4): 530–48. https://doi.org/10.1177/030913339702100403.

Wilby, Robert L., Hany Hassan, and Keisuke Hanaki. 1998. "Statistical Downscaling of Hydrometeorological Variables Using General Circulation Model Output." Journal of Hydrology 205 (1–2): 1–19. https://doi.org/10.1016/S0022-1694(97)00130-3.

Williams, Mark W., Eran Hood, Noah P. Molotch, Nel Caine, Rory Cowie, and Fengjing Liu. 2015. "The 'Teflon Basin' Myth: Hydrology and Hydrochemistry of a Seasonally Snow-Covered Catchment." Plant Ecology & Diversity 8 (5–6): 639–61. https://doi.org/10.1080/17550874.2015.1123318.

Wilson, Rob, Edward Cook, Rosanne D'Arrigo, Nadja Riedwyl, Michael N. Evans, Alexander Tudhope, and Rob Allan. 2010. "Reconstructing ENSO: The Influence of Method, Proxy Data, Climate Forcing and Teleconnections." Journal of Quaternary Science 25 (1): 62–78. https://doi.org/10.1002/jqs.1297.

Wise, Erika K. 2010. "Spatiotemporal Variability of the Precipitation Dipole Transition Zone in the Western United States." Geophysical Research Letters 37 (7): n/a-n/a. https://doi.org/10.1029/2009GL042193.

———. 2015. "Tropical Pacific and Northern Hemisphere Influences on the Coherence of Pacific Decadal Oscillation Reconstructions." International Journal of Climatology 35 (1): 154–60. https://doi.org/10.1002/joc.3966.

Wisser, Dominik, Steve Frolking, Ellen M. Douglas, Balazs M. Fekete, Charles J. Vörösmarty, and Andreas H. Schumann. 2008. "Global Irrigation Water Demand: Variability and Uncertainties Arising from Agricultural and Climate Data Sets." Geophysical Research Letters 35 (24). https://doi.org/10.1029/2008GL035296.

Wolter, Klaus. 2002. "Climate Projections: Assessing Water Year (WY) 2002 Forecasts and Developing WY 2003 Forecasts." CWRRI Information Series Report. Fort Collins, Colorado: Colorado Water Resources Research Institute.

Wolter, Klaus, Randall Dole, and Catherine A. Smith. 1999. "Short-Term Climate Extremes over the Continental U.S. and ENSO. Part I: Seasonal Temperatures." Journal of Climate 12: 3255–72. https://doi.org/10.1175/1520-0442(1999)012<3255:STCEOT>2.0.CO;2.

Wolter, Klaus, and Michael S. Timlin. 2011. "El Niño/Southern Oscillation Behaviour since 1871 as Diagnosed in an Extended Multivariate ENSO Index (MEI.Ext)." International Journal of Climatology 31 (7): 1074–87. https://doi.org/10.1002/joc.2336.

Wood, Andrew W., L. Ruby Leung, V. Sridhar, and Dennis P. Lettenmaier. 2004. "Hydrologic Implications of Dynamical and Statistical Approaches to Downscaling Climate Model Outputs." Climatic Change 62 (1–3): 189–216. https://doi.org/10.1023/B:CLIM.0000013685.99609.9e.

Wood, Andrew W. 2008. "The University of Washington Surface Water Monitor: An Experimental Platform for National Hydrologic Assessment and Prediction." Proceedings of the AMS 22nd Conference on Hydrology, New Orleans. http://www.hydro.washington.edu/forecast/monitor/info/Wood_SWMonitor_AMS08.pdf.

Wood, Andrew W., S. Arumugam, and Pablo A. Mendoza. 2018. "The Post-Processing of Seasonal Streamflow Forecasts, Chapter 7.3 in the Handbook of Hydrometeorological Ensemble Forecasting." In Handbook of Hydrometeorological Ensemble Forecasting. Springer-Verlag GmbH, Berlin Heidelberg. https://link.springer.com/referenceworkentry/10.1007/978-3-642-40457-3_37-2.

Wood, Andrew W., Arun Kumar, and Dennis P. Lettenmaier. 2005. "A Retrospective Assessment of National Centers for Environmental Prediction Climate Model–Based Ensemble Hydrologic Forecasting in the Western United States." Journal of Geophysical Research: Atmospheres 110 (D4). https://doi.org/10.1029/2004JD004508.

Wood, Andrew W., and Dennis P. Lettenmaier. 2006. "A Test Bed for New Seasonal Hydrologic Forecasting Approaches in the Western United States." Bulletin of the American Meteorological Society 87 (12): 1699–1712. https://doi.org/10.1175/BAMS-87-12-1699.

Wood, Andrew W., Edwin P. Maurer, Arun Kumar, and Dennis P. Lettenmaier. 2002. "Long-Range Experimental Hydrologic Forecasting for the Eastern United States." Journal of Geophysical Research: Atmospheres 107 (D20): ACL 6-1-ACL 6-15. https://doi.org/10.1029/2001JD000659.

Wood, Andrew W., Thomas C. Pagano, Maury Roos, and Michael Anderson. 2016. "Tracing the Origins of ESP: HEPEX Historical Hydrology Series, Edition 1." HEPEX (blog). April 26, 2016. https://hepex.irstea.fr/tracing-the-origins-of-esp/.

Wood, Andrew W., and John C. Schaake. 2008. "Correcting Errors in Streamflow Forecast Ensemble Mean and Spread." Journal of Hydrometeorology 9 (1): 132–48. https://doi.org/10.1175/2007JHM862.1.

Wood, Eric F., Joshua K. Roundy, Tara J. Troy, Rens van Beek, Marc Bierkens, Eleanor Blyth, Ad de Roo, et al. 2012. "Reply to Comment by Keith J. Beven and Hannah L. Cloke on 'Hyperresolution Global Land Surface Modeling: Meeting a Grand Challenge for Monitoring Earth's Terrestrial Water.'" Water Resources Research 48 (1). https://doi.org/10.1029/2011WR011202.

Woodbury, M., M. Baldo, D. Yates, and L. Kaatz. 2012. "Joint Front Range Climate Change Vulnerability Study." Denver: Water Research Foundation.

Woodhouse, Connie A. 2003. "A 431-Yr Reconstruction of Western Colorado Snowpack from Tree Rings." Journal of Climate 16: 11.

———. 2012. "A Catalogue of 20th and 21st Century Droughts for the Upper Colorado River Basin." Bureau of Reclamation, Lower Colorado Region. https://cwoodhouse.faculty.arizona.edu/content/catalogue-20th-and-21st-century-droughts-upper-colorado-river-basin.

Woodhouse, Connie A., Stephen T. Gray, and David M. Meko. 2006. "Updated Streamflow Reconstructions for the Upper Colorado River Basin." Water Resources Research 42 (5). https://doi.org/10.1029/2005WR004455.

Woodhouse, Connie A., Kenneth E. Kunkel, David R. Easterling, and Edward R. Cook. 2005. "The Twentieth-Century Pluvial in the Western United States." Geophysical Research Letters 32 (7): n/a-n/a. https://doi.org/10.1029/2005GL022413.

Woodhouse, Connie A., and Jeffrey J. Lukas. 2006. "Drought, Tree Rings and Water Resource Management in Colorado." Canadian Water Resources Journal 31 (4): 297–310. https://doi.org/10.4296/cwrj3104297.

Woodhouse, Connie A., Jeffrey J. Lukas, Kiyomi Morino, David M. Meko, and Katherine K. Hirschboeck. 2016. "Using the Past to Plan for the Future— the Value of Paleoclimate Reconstructions for Water Resource Planning." In Water Policy and Planning in a Variable and Changing Climate. Drought and Water Crises. CRC Press. https://doi.org/10.1201/b19534.

Woodhouse, Connie A., David M. Meko, Glen M. MacDonald, Dave W. Stahle, and Edward R. Cook. 2010. "A 1,200-Year Perspective of 21st Century Drought in Southwestern North America." Proceedings of the National Academy of Sciences 107 (50): 21283–88. https://doi.org/10.1073/pnas.0911197107.

Woodhouse, Connie A., and Jonathan T. Overpeck. 1998. "2000 Years of Drought Variability in the Central United States." Bulletin of the American Meteorological Society 79 (12): 2693–2714. https://doi.org/10.1175/1520-0477(1998)079<2693:YODVIT>2.0.CO;2.

Woodhouse, Connie A., and Gregory T. Pederson. 2018. "Investigating Runoff Efficiency in Upper Colorado River Streamflow over Past Centuries." Water Resources Research 54 (1): 286–300. https://doi.org/10.1002/2017WR021663.

Woodhouse, Connie A., Gregory T. Pederson, Kiyomi Morino, Stephanie A. McAfee, and Gregory J. McCabe. 2016. "Increasing Influence of Air Temperature on Upper Colorado River Streamflow." Geophysical Research Letters 43 (5): 2174–81. https://doi.org/10.1002/2015GL067613.

World Meteorological Organization. 2008. Guide to Meteorological Instruments and Methods of Observation. Geneva, Switzerland: World Meteorological Organization.

———. 2013. "Sub-Seasonal to Seasonal Prediction Research Implementation Plan." Geneva. http://s2sprediction.net/static/documents.

———. 2017. "Coupled Data Assimilation for Integrated Earth System Analysis and Prediction: Goals, Challengesand Recommendations." WWRP 2017-3. https://www.wmo.int/pages/prog/arep/wwrp/new/documents/Final_WWRP_2017_3_27_July.pdf.

Wu, Limin, Dong-Jun Seo, Julie Demargne, James D. Brown, Shuzheng Cong, and John C. Schaake. 2011. "Generation of Ensemble Precipitation Forecast from Single-Valued Quantitative Precipitation Forecast for Hydrologic Ensemble Prediction." Journal of Hydrology 399 (3–4): 281–98. https://doi.org/10.1016/j.jhydrol.2011.01.013.

Wurbs, Ralph. 1994. "Computer Models for Water Resources Planning and Management." IWR Report 94-NDS-7. Institute for Water Resources, US Army Corps of Engineers. https://apps.dtic.mil/dtic/tr/fulltext/u2/a295807.pdf.

———. 2012. "Reservoir/River System Management Models." Texas Water Journal 3 (1): 16.

Xia, Youlong, Kenneth Mitchell, Michael Ek, Justin Sheffield, Brian Cosgrove, Eric Wood, Lifeng Luo, et al. 2012. "Continental-Scale Water and Energy Flux Analysis and Validation for the North American Land Data Assimilation System Project Phase 2 (NLDAS-2): 1. Intercomparison and Application of Model Products." Journal of Geophysical Research: Atmospheres 117 (D3): n/a-n/a. https://doi.org/10.1029/2011JD016048.

Xiao, Mu, Bradley Udall, and Dennis P. Lettenmaier. 2018. "On the Causes of Declining Colorado River Streamflows." Water Resources Research 54 (9): 6739–56. https://doi.org/10.1029/2018WR023153.

Yang, Daqing, Barry E. Goodison, Shig Ishida, and Carl S. Benson. 1998. "Adjustment of Daily Precipitation Data at 10 Climate Stations in Alaska: Application of World Meteorological Organization Intercomparison Results." Water Resources Research 34 (2): 241–56. https://doi.org/10.1029/97WR02681.

Yapo, Patrice Ogou, Hoshin Vijai Gupta, and Soroosh Sorooshian. 1998. "Multi-Objective Global Optimization for Hydrologic Models." Journal of Hydrology 204 (1): 83–97. https://doi.org/10.1016/S0022-1694(97)00107-8.

Yaseen, Zaher Mundher, Ahmed El-shafie, Othman Jaafar, Haitham Abdulmohsin Afan, and Khamis Naba Sayl. 2015. "Artificial Intelligence Based Models for Stream-Flow Forecasting: 2000–2015." Journal of Hydrology 530 (November): 829–44. https://doi.org/10.1016/j.jhydrol.2015.10.038.

Yeager, Stephen G., G. Danabasoglu, N. A. Rosenbloom, W. Strand, S. C. Bates, G. A. Meehl, A. R. Karspeck, et al. 2018. "Predicting Near-Term Changes in the Earth System: A Large Ensemble of Initialized Decadal Prediction Simulations Using the Community Earth System Model." Bulletin of the American Meteorological Society 99 (9): 1867–86. https://doi.org/10.1175/BAMS-D-17-0098.1.

Yu, Jin-Yi, and Yuhao Zou. 2013. "The Enhanced Drying Effect of Central-Pacific El Niño on US Winter." Environmental Research Letters 8 (1): 014019. https://doi.org/10.1088/1748-9326/8/1/014019.

Yuan, Xing, Eric F. Wood, Joshua K. Roundy, and Ming Pan. 2013. "CFSv2-Based Seasonal Hydroclimatic Forecasts over the Conterminous United States." Journal of Climate 26 (13): 4828–47. https://doi.org/10.1175/JCLI-D-12-00683.1.

Zachariassen, John, Karl F. Zeller, Ned Nikolov, and Tom McClelland. 2003. "A Review of the Forest Service Remote Automated Weather Station (RAWS) Network." RMRS-GTR-119. Ft. Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. https://doi.org/10.2737/RMRS-GTR-119.

Zagona, Edith, Terrance J. Fulp, Richard Shane, Timothy Magee, and H. Morgan Goranflo. 2001. "Riverware: A Generalized Tool for Complex Reservoir System Modeling." JAWRA Journal of the American Water Resources Association 37 (4): 913–29. https://doi.org/10.1111/j.1752-1688.2001.tb05522.x.

Zagona, Edith. 2010. "Riverware's Integrated Modeling and Analysis Tools for Long-Term Planning under Uncertainty," 12.

Zeng, Xubin, Patrick Broxton, and Nicholas Dawson. 2018. "Snowpack Change from 1982 to 2016 over Conterminous United States." Geophysical Research Letters, December. https://doi.org/10.1029/2018GL079621.

Zhang, Chidong. 2013. "Madden–Julian Oscillation: Bridging Weather and Climate." Bulletin of the American Meteorological Society 94 (12): 1849–70. https://doi.org/10.1175/BAMS-D-12-00026.1.

Zhang, Lanhui, Chansheng He, Mingmin Zhang, and Yi Zhu. 2019. "Evaluation of the SMOS and SMAP Soil Moisture Products under Different Vegetation Types against Two Sparse in Situ Networks over Arid Mountainous Watersheds, Northwest China." Science China Earth Sciences 62 (4): 703–18. https://doi.org/10.1007/s11430-018-9308-9.

Zhao, R. J., Y. L. Zhang, L. R. Fang, X. R. Liu, and Q. S. Zhang. 1980. "The Xinanjiang Model." In Hydrological Forecasting Proceedings Oxford Symposium, 129:351–56.

Zhou, Shuntai, Michelle L'Heureux, Scott Weaver, and Arun Kumar. 2012. "A Composite Study of the MJO Influence on the Surface Air Temperature and Precipitation over the Continental United States." Climate Dynamics 38 (7–8): 1459–71. https://doi.org/10.1007/s00382-011-1001-9.

Glossary

ablation
The loss of snow from the snowpack due to melting, evaporation, or wind.

absolute error
The difference between the measured and actual values of *x*.

albedo
The percentage of incoming light that is reflected off of a surface.

aleatory uncertainty
Uncertainty due to randomness in the behavior of a system (i.e., natural variability)

anomaly
A deviation from the expected or normal value.

atmospheric river (AR)
A long and concentrated plume of low-level (<5,000') moisture originating in the tropical Pacific.

autocorrelation
Correlation between consecutive values of the same time series, typically due to time-dependencies in the dataset.

bank storage
Water that seeps into and out of the bed and banks of a stream, lake, or reservoir depending on relative water levels.

bias correction
Adjustments to raw model output (e.g., from a climate model, or streamflow forecast model) using observations in a reference period.

boundary conditions
Conditions that govern the evolution of climate for a given area (e.g., ocean heat flux, soil moisture, sea-ice and snowpack conditions) and can help forecast the future climate state when included in a model.

calibration
The process of comparing a model with the real system, followed by multiple revisions and comparisons so that the model outputs more closely resemble outcomes in the real system.

climate forcing
A factor causing a difference between the incoming and outgoing energy of the Earth's climate system, e.g., increases in greenhouse-gas concentrations.

climatology
In forecasting and modeling, refers to the historical average climate used as a baseline (e.g., "compared to climatology"). Synonymous with climate normal.

coefficient of variation (CV)
A common measure of variability in a dataset; the standard deviation divided by the mean.

consumptive use
The amount of diverted water that is lost during usage via evapotranspiration, evaporation, or seepage and is thus unavailable for subsequent use.

convection
The vertical transport of heat and moisture in the atmosphere, typically due to an air parcel rising if it is warmer than the surrounding atmosphere.

covariate
A variable (e.g., temperature) whose value changes when the variable under study changes (e.g., precipitation).

cross-correlation
A method for estimating to what degree two variables or datasets are correlated.

cumulative distribution function (CDF)
A function describing the probability that a random variable, such as streamflow, is less than or equal to a specified value. CDF-based probabilities are often expressed in terms of percent exceedance or non-exceedance.

Darcy's Law
The mathematical expression that describes fluid flow through a porous medium (e.g., soil).

datum
The base, or 0.0-foot gage-height (stage), for a stream gage.

dead pool
The point at which the water level of a lake or reservoir is so low, water can no longer be discharged or released downstream.

deterministic
Referring to a system or model in which a given input always produces the same output; the input strictly determines the output.

dewpoint
The local temperature that the air would need to be cooled to (assuming atmospheric pressure and moisture content are constant) in order to achieve a relative humidity (RH) of 100%.

dipole
A pair of two equal and opposing centers of action, usually separated by a distance.

discharge
Volume of water flowing past a given point in the stream in a given period of time; synonymous with streamflow.

distributed
In hydrologic modeling, a distributed model explicitly accounts for spatial variability by dividing basins into grid cells. Contrast with **lumped** model.

downscaling
Method to take data at coarse scales, e.g., from a GCM, and translate those data to more local scales.

dynamical
In modeling, refers to the use of a physical model, i.e., basic physical equations represent some or most of the relevant processes.

environmental flow
Water that is left in or released into a river to manage the quantity, quality, and timing of flow in order to sustain the river's ecosystem.

epistemic uncertainty
Uncertainty due to incomplete knowledge of the behavior of a system.

evapotranspiration
A combination of evaporation from the land surface and water bodies, and transpiration of water from plant surfaces to the atmosphere. Generally includes sublimation from the snow surface as well.

fixed lapse rate
A constant rate of change of an atmospheric variable, usually temperature, with elevation.

flow routing
The process of determining the flow hydrograph at sequential points along a stream based on a known hydrograph upstream.

forcing - see **climate forcing or weather forcing**

forecast
A prediction of future hydrologic or climate conditions based on the initial (current) conditions and factors known to influence the evolution of the physical system.

Gaussian filter
A mathematical filter used to remove noise and emphasize a specific frequency of a signal; uses a bell-shaped statistical distribution.

gridded data
Data that is represented in a two-dimensional gridded matrix of graphical contours, interpolated or otherwise derived from a set of point observations.

heat flux
The rate of heat energy transfer from one surface or layer of the atmosphere to the next.

hindcast
A forecast run for a past date or period, using the same model version as for real-time forecasts; used for model calibration and to "spin up" forecast models. Same as **reforecast**.

hydraulic conductivity
A measure of the ease with which water flows through a medium, such as soil or sediment.

hydroclimate
The aggregate of climatic and hydrologic processes and characteristics, and linkages between them, for a watershed or region.

hydrograph
A graph of the volume of water flowing past a location per unit time.

hydrometeorology
A branch of meteorology and hydrology that studies the transfer of water and energy between the land surface and the lower atmosphere.

imaging spectrometer
An instrument used for measuring wavelengths of light spectra in order to create a spectrally-resolved image of an object or area.

in situ
Referring to a ground-based measurement site that is fixed in place.

inhomogeneity
A change in the mean or variance of a time-series of data (such as weather observations) that is caused by changes in the observing station or network, not in the climate itself.

Interim Guidelines
The Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead, signed by the Secretary of the Interior in December 2007. The guidelines expire in 2026. https://www.usbr.gov/lc/region/programs/strategies.html

internal variability
Variability in climate that comes from chaotic and unpredictable fluctuations of the Earth's oceans and atmosphere.

interpolation
The process of calculating the value of a function or set of data between two known values.

isothermal
A dynamic in which temperature remains constant while other aspects of the system change.

jet stream
A narrow band of very strong winds in the upper atmosphere that follows the boundary between warmer and colder air masses.

kriging
A smoothing technique that calculates minimum error-variance estimates for unsampled values.

kurtosis
A measure of the sharpness of the peak of a probability distribution.

lag-1 autocorrelation
Serial correlation between data values at adjacent time steps.

lapse rate
The rate of change of an atmospheric variable, such as temperature, with elevation. A lapse rate is adiabatic when no heat exchange occurs between the given air parcel and its surroundings.

latency
The lag, relative to real-time, for producing and releasing a dataset that represents real-time conditions.

latent heat flux
The flow of heat from the Earth's surface to the atmosphere that involves evaporation and condensation of water; the energy absorbed/released during a phase change of a substance.

Law of the River
A collection of compacts, federal laws, court decisions and decrees, contracts, and regulatory guidelines that apportions the water and regulates the use and management of the Colorado River among the seven basin states and Mexico.

LiDAR (or lidar)
Light detection and ranging; a remote sensing method which uses pulsed lasers of light to measure the variable distances from the sensor to the land surface.

longwave radiation
Infrared energy emitted by the Earth and its atmosphere at wavelengths between about 5 and 25 micrometers.

Lower Basin
The portions of the Colorado River Basin in Arizona, California, Nevada, New Mexico and Utah that are downstream of the Colorado River Compact point at Lee Ferry, Arizona.

lumped model
In hydrologic modeling, a lumped model represents individual sub-basins or elevation zones as a single unit, averaging spatial characteristics across that unit. Contrast with **distributed** model.

Markov chain
A mathematical system in which transitions from one state to another are dependent on the current state and time elapsed.

megadrought
A sustained and widespread drought that lasts at least 10-15 years, though definitions in the literature have varied.

metadata
Data that gives information about other data or describes its own dataset.

mid-latitude cyclone

A large (~500-2000 km) storm system that has a low-pressure center, cyclonic (counter-clockwise) flow, and a cold front. Over the western U.S., **mid-latitude cyclones** almost always move from west to east and are effective at producing precipitation over broad areas.

Minute 319

The binding agreement signed in 2012 by the International Boundary and Water Commission, United States and Mexico, to advance the 1944 Water Treaty between both countries and establish better basin operations and water allocation, and humanitarian measures.

Modoki

An El Niño event that has its warmest SST anomalies located in the central equatorial Pacific; same as "CP" El Niño.

multicollinearity

A condition in which multiple explanatory variables that predict variation in a response variable are themselves correlated with each other.

multiple linear regression

A form of regression in which a model is created by fitting a linear equation over the observed data, typically for two or more explanatory (independent) variables and a response (dependent) variable.

multivariate

Referring to statistical methods in which there are multiple response (dependent) variables being examined.

natural flow

Gaged flow that has been adjusted to remove the effects of upstream human activity such as storage or diversion. Equivalent to **naturalized flow, virgin flow**, and **undepleted flow**.

naturalized flow – see *natural flow*

nearest neighbor method

A nonparametric method that examines the distances between a data point (e.g., a sampled value) and the closest data points to it in *x-y* space ("nearest neighbors," e.g., historical values) and thereby obtains either a classification for the data point (such as wet, dry, or normal) or a set of nearest neighbors (i.e., K-NN).

nonparametric

A statistical method that assumes no underlying mathematical function for a sample of observations.

orographic lift

A process in which air is forced to rise and subsequently cool due to physical barriers such as hills or mountains. This mechanism leads to increased condensation and precipitation over higher terrain.

p

A statistical hypothesis test; the probability of obtaining a particular result purely by chance; a test of statistical significance.

paleohydrology
The study of hydrologic events and processes prior to the instrumental (gaged) record, typically using environmental proxies such as tree rings.

parameterized
Referring to a key variable or factor that is represented in a model by an estimated value (**parameter**) based on observations, rather than being explicitly modeled through physical equations.

parametric
A statistical method that assumes an underlying mathematical function, specified by a set of characteristics, or parameters (e.g., mean and standard deviation) for a sample of observations.

persistence
In hydrology, the tendency of high flows to follow high flows, and low flows to follow low flows. Hydrologic time series with persistence are **autocorrelated**.

phreatophytes
Plants with deep root systems that are dependent on water from the water table or adjacent soil moisture reserves.

pluvial
An extended period, typically 5 years or longer, of abnormally wet conditions; the opposite of drought.

principal components regression (PCR)
A statistical technique for analyzing and developing multiple regressions from data with multiple potential explanatory variables.

prior appropriation
"First in time, first in right." The prevailing doctrine of water rights for the western United States; a legal system that determines water rights by the earliest date of diversion or storage for beneficial use.

probability density function (PDF)
A function, or curve, that defines the shape of a probability distribution for a continuous random variable.

projection
A long-term (typically 10-100 years) forecast of future hydroclimatic conditions that is contingent on specified other conditions occurring during the forecast period, typically a particular scenario of greenhouse gas emissions.

quantiles
Divisions of the range of observations of a variable into equal-sized groups.

r
Correlation coefficient. The strength and direction of a linear relationship between two variables.

R²

Coefficient of determination. The proportion of variance in a dependent variable that's explained by the independent variables in a regression model.

radiometer

An instrument used to detect and measure the intensity of radiant energy, i.e., shortwave energy emitted from the sun and reflected by clouds, and longwave energy emitted from the earth's surface.

raster

A digital image or computer mapping format consisting of rows of colored pixels.

reanalysis

An analysis of historical climate or hydrologic conditions that assimilates observed data into a modeling environment to produce consistent fields of variables over the entire period of analysis.

reference evapotranspiration

An estimate of the upper bound of evapotranspiration losses from irrigated croplands, and thereby the water need for irrigation.

regression

A statistical technique used for modeling the linear relationship between two or more variables, e.g., snowpack and seasonal streamflow.

relative humidity (RH)

The amount of moisture in the atmosphere relative to the amount that would be present if the air were saturated. RH is expressed in percent, and is a function of both moisture content and air temperature.

remote sensing

The science and techniques for obtaining information from sensors placed on satellites, aircraft, or other platforms distant from the object(s) being sensed.

residual

The difference between the observed value and the estimated value of the quantity of interest.

resolution

The level of detail in model output; the ability to distinguish two points in space (or time) as separate.

> *spatial resolution* - Resolution across space, i.e., the ability to separate small details in a spatial representation such as in an image or model.
> *temporal resolution* - Resolution in time, i.e., hourly, daily, monthly, or annual. Equivalent to time step.

return flow

The water diverted from a river or stream that returns to a water source and is available for consumptive use by others downstream.

runoff
Precipitation that flows toward streams on the surface of the ground or within the ground. Runoff as it is routed and measured within channels is *streamflow*.

runoff efficiency
The fraction of annual precipitation in a basin or other area that becomes runoff, i.e., not lost through evapotranspiration.

sensible heat flux
The flow of heat from the Earth's surface to the atmosphere without phase changes in the water, or the energy directly absorbed/released by an object without a phase change occurring.

shortwave radiation
Incoming solar radiation consisting of visible, near-ultraviolet, and near-infrared spectra. The wavelength spectrum is between 0.2 and 3.0 micrometers.

skew
The degree of asymmetry in a given probability distribution from a Gaussian or normal (i.e., bell-shaped) distribution.

skill
The accuracy of the forecast relative to a baseline "naïve" forecast, such as the climatological average for that day. A forecast that performs better than the baseline forecast is said to have positive skill.

smoothing filter
A mathematical filter designed to enhance the signal-to-noise ratio in a dataset over certain frequencies. Common signal smoothing techniques include moving average and Gaussian algorithms.

snow water equivalent (SWE)
The depth, often expressed in inches, of liquid water contained within the snowpack that would theoretically result if you melted the snowpack instantaneously.

snow course
A linear site used from which manual measurements are taken periodically, to represent snowpack conditions for larger area. Courses are typically about 1,000' long and are situated in areas protected from wind in order to get the most accurate snowpack measurements.

snow pillow
A device (e.g., at SNOTEL sites) that provides a value of the average water equivalent of snow that has accumulated on it; typically the pillow contains antifreeze and has a pressure sensor that measures the weight pressing down on the pillow.

stationarity
The condition in which the statistical properties of the sample data, including their probability distribution and related parameters, are stable over time.

statistically significant
Unlikely to occur by chance alone, as indicated by one of several statistical tests.

stepwise regression
The process of building a regression model from a set of values by entering and removing predictor variables in a step-by-step manner.

stochastic method
A statistical method in which randomness is considered and included in the model used to generate output; the same input may produce different outputs in successive model runs.

stratosphere
The region of the upper atmosphere extending from the top of the troposphere to the base of the mesosphere; it begins about 11–15 km above the surface in the mid-latitudes.

streamflow
Water flow within a river channel, typically expressed in cubic feet per second for flow rate, or in acre-feet for flow volume. Synonymous with **discharge**.

sublimation
When water (i.e., snow and ice) or another substance transitions from the solid phase to the vapor phase without going through the intermediate liquid phase; a major source of snowpack loss over the course of the season.

surface energy balance
The net balance of the exchange of energy between the Earth's surface and the atmosphere.

teleconnection
A physical linkage between a change in atmospheric/oceanic circulation in one region (e.g., ENSO; the tropical Pacific) and a shift in weather or climate in a distant region (e.g., the Colorado River Basin).

temperature inversion
When temperature increases with height in a layer of the atmosphere, as opposed to the typical gradient of temperature decreasing with height.

tercile
Any of the two points that divide an ordered distribution into three parts, each containing a third of the population.

tilt
A shift in probabilities toward a certain outcome.

transpiration
Water discharged into the atmosphere from plant surfaces.

troposphere
The layer of the atmosphere from the Earth's surface up to the tropopause (~11–15 km) below the stratosphere; characterized by decreasing temperature with height, vertical wind motion, water vapor content, and sensible weather (clouds, rain, etc.).

undercatch

When less precipitation is captured by a precipitation gage than actually falls; more likely to occur with snow, especially under windy conditions.

unregulated flow

Observed streamflow adjusted for some, but not all upstream activities, depending on the location and application.

Upper Basin

The parts of the Colorado River Basin in Colorado, Utah, Wyoming, Arizona, and New Mexico that are upstream of the Colorado River Compact point at Lee Ferry, Arizona.

validation

The process of comparing a model and its behavior and outputs to the real system, after calibration.

variance

An instance of difference in the data set. In regard to statistics, variance is the square of the standard deviation of a variable from its mean in the data set.

wavelet analysis

A method for determining the dominant frequencies constituting the overall time-varying signal in a dataset.

Acronyms & Abbreviations

24MS
24-Month Study Model

AET
actual evapotranspiration

AgriMET
Cooperative Agricultural Weather Network

AgWxNet
Agricultural Weather Network

AHPS
Advanced Hydrologic Prediction Service

ALEXI
Atmosphere-Land Exchange Inversion

AMJ
April-May-June

AMO
Atlantic Multidecadal Oscillation

ANN
artificial neural network

AOP
Annual Operating Plan

AR
atmospheric river

AR-1
first-order autoregression

ARkStorm
Atmospheric River 1,000-year Storm

ASCE
American Society of Civil Engineers

ASO
Airborne Snow Observatory

ASOS
Automated Surface Observing System

AVHRR
Advanced Very High-Resolution Radiometer

AWOS
Automated Weather Observing System

BCCA
Bias-Corrected Constructed Analog

BCSD
Bias-Corrected Spatial Disaggregation (downscaling method)

BCSD5
BCSD applied to CMIP5

BOR
United States Bureau of Reclamation

BREB
Bowen Ratio Energy Balance method

C3S
Copernicus Climate Change Service

CA
Constructed Analogues

CADSWES
Center for Advanced Decision Support for Water and Environmental Systems

CADWR
California Department of Water Resources

CanCM4i
Canadian Coupled Model, 4th generation (global climate model)

CBRFC
Colorado Basin River Forecast Center

CCA
Canonical Correlation Analysis

CCSM4
Community Climate System Model, version 4 (global climate model)

CDEC
California Data Exchange Center

CDF
cumulative distribution function

CESM
Community Earth System Model (global climate model)

CFS
Climate/Coupled Forecast System

CFSv2
Coupled Forecast System version 2 (NOAA climate forecast model)

CHPS
Community Hydrologic Prediction System

CIMIS
California Irrigation Management Information System

CIR
crop irrigation requirement

CIRES
Cooperative Institute for Research in Environmental Sciences

CLIMAS
Climate Assessment for the Southwest

CLM
Community Land Model

CM2.1
Coupled Physical Model, version 2.1 (global climate model)

CMIP
Coupled Model Intercomparison Project (coordinated archive of global climate model output)

CNRFC
California-Nevada River Forecast Center

CoAgMET
Colorado Agricultural Meteorological Network

CoCoRaHS
Community Collaborative Rain, Hail and Snow Network

CODOS
Colorado Dust-on-Snow

CONUS
contiguous United States (the lower 48 states)

COOP
Cooperative Observer Program

CP
Central Pacific

CPC
Climate Prediction Center

CRB
Colorado River Basin

CRBPP
Colorado River Basin Pilot Project

CRPSS
Continuous Ranked Probability Skill Score

CRSM
Colorado River Simulation Model

CRSP
Colorado River Storage Project

CRSS
Colorado River Simulation System

CRWAS
Colorado River Water Availability Study
CSAS

CRWAS
Center for Snow and Avalanche Studies

CTSM
Community Terrestrial Systems Model

CU
consumptive use

CUL
consumptive uses and losses

CV
coefficient of variation

CVP/SWP
Central Valley Project/State Water Project

CWCB
Colorado Water Conservation Board

CWEST
Center for Water, Earth Science and
Technology

DA
data assimilation

Daymet v.3
daily gridded surface meteorological data

DCP
Drought Contingency Plan

DEM
digital elevation model

DEOS
Delaware Environmental Observing System

DHSVM
Distributed Hydrology Soil Vegetation
Model

DJF
December-January-February

DMDU
Decision Making Under Deep Uncertainty

DMI
Data Management Interface

DOD
Department of Defense

DOE
Department of Energy

DOW
Doppler [radar] on Wheels

DRI
Desert Research Institute

DTR
diurnal temperature range

EC
eddy-covariance method

EC
Environment Canada

ECCA
ensemble canonical correlation analysis

ECMWF
European Centre for Medium-Range
Weather Forecasts

EDDI
Evaporative Demand Drought Index

EFAS
European Flood Awareness System

EIS
Environmental Impact Statement

En-GARD
Ensemble Generalized Analog Regression Downscaling

ENSO
El Niño-Southern Oscillation

EOF
empirical orthogonal function

EP
Eastern Pacific

ERC
energy release component

ESI
Evaporative Stress Index

ESM
coupled Earth system model

ESP
ensemble streamflow prediction

ESRL
Earth System Research Laboratory

ET
evapotranspiration

ET$_0$
Reference (crop) evapotranspiration

EVI
Enhanced Vegetation Index

FAA
Federal Aviation Administration

FAWN
Florida Automated Weather Network

FEWS
Famine Early Warning System

FEWS
Flood Early Warning System

FIRO
forecast-informed reservoir operations

FLOR
Forecast-oriented Low Ocean Resolution (global climate model)

FORTRAN
Formula Translation programming language

FPS
Federal Priority Streamgages

FROMUS
Forecast and Reservoir Operation Modeling Uncertainty Scoping

fSCA
fractional snow covered area

FWS
U.S. Fish and Wildlife Service

GCM
global climate model, or general circulation model

GEFS
Global Ensemble Forecast System

GEM
Global Environmental Multiscale model

GEOS
Goddard Earth Observing System (global climate model)

GeoTiff
Georeferenced Tagged Image File Format

GFDL
Geophysical Fluid Dynamics Laboratory

GFS
Global Forecast System model

GHCN
Global Historical Climatology Network

GHCN-D
Global Historical Climate Network-Daily

GHG
greenhouse gas

GIS
geographic information system

GLOFAS
Global Flood Awareness System

GLOFFIS
Global Flood Forecast Information System

GOES
Geostationary Operational Environmental Satellite

GRACE
Gravity Recovery and Climate Experiment

GRIB
gridded binary or general regularly-distributed information in binary form

gridMET
Gridded Surface Meteorological dataset

GSSHA
Gridded Surface/Subsurface Hydrologic Analysis

GW
groundwater

HCCD
Historical Canadian Climate Data

HCN
Historical Climatology Network

HDA
hydrologic data assimilation

HDSC
Hydrometeorological Design Studies Center

HEFS
Hydrologic Ensemble Forecast Service

HESP
Hierarchical Ensemble Streamflow Prediction

HL-RDHM
Hydrologic Laboratory-Research Distributed Hydrologic Model

HMT
Hydromet Testbed

HP
hydrological processor

HRRR
High Resolution Rapid Refresh (weather model)

HSS
Heidke Skill Score

HTESSEL
Land-surface Hydrology Tiled ECMWF Scheme for Surface Exchanges over Land

HUC
Hydrologic Unit Code

HUC4
A 4-digit Hydrologic Unit Code, referring to large sub-basins (e.g., Gunnison River)

HUC12
A 12-digit Hydrologic Unit Code, referring to small watersheds

ICAR
Intermediate Complexity Atmospheric Research model

ICS
intentionally created surplus

IDW
inverse distance weighting

IFS
integrated forecast system

IHC
initial hydrologic conditions

INSTAAR
Institute of Arctic and Alpine Research

IPCC
Intergovernmental Panel on Climate Change

IPO
Interdecadal Pacific Oscillation

IRI
International Research Institute

iRON
Interactive Roaring Fork Observing Network

ISM
Index Sequential Method

JFM
January-February-March

JJA
June-July-August

K-NN
K-Nearest Neighbor

Landsat
Land Remote-Sensing Satellite (System)

LAST
Lane's Applied Stochastic Techniques

LERI
Landscape Evaporative Response Index

lidar
light detection and ranging

LOCA
Localized Constructed Analog

LSM
land surface model

M&I
municipal and industrial (water use category)

MACA
Multivariate Adaptive Constructed Analog

maf
million acre-feet

MAM
March-April-May

MEFP
Meteorological Ensemble Forecast Processor

METRIC
Mapping Evapotranspiration at high Resolution with Internalized Calibration

MJO
Madden-Julian Oscillation

MMEFS
Met-Model Ensemble Forecast System

MOCOM
Multi-Objective Complex evolution

MODDRFS
MODIS Dust Radiative Forcing in Snow

MODIS
Moderate Resolution Imaging Spectroradiometer

MODIS LST (MYD11A2)
Moderate Resolution Imaging Spectroradiometer Land Surface Temperature (MYD11A2)

MODSCAG
MODIS Snow Covered Area and Grain-size

MPR
Multiscale Parameter Regionalization

MRM
Multiple Run Management

MT-CLIM (or MTCLIM)
Mountain Climate simulator

MTOM
Mid-Term Probabilistic Operations Model

NA-CORDEX
North American Coordinated Regional Downscaling Experiment

NAM
North American Monsoon

NAO
North Atlantic Oscillation

NARCCAP
North American Regional Climate Change Assessment Program

NARR
North American Regional Reanalysis

NASA
National Aeronautics and Space Administration

NASA JPL
NASA Jet Propulsion Laboratory

NCAR
National Center for Atmospheric Research

NCCASC
North Central Climate Adaptation Science Center

NCECONET
North Carolina Environment and Climate Observing Network

NCEI
National Centers for Environmental Information

NCEP
National Centers for Environmental Prediction

nClimDiv
new Climate Divisional (NOAA climate dataset)

NDBC
National Data Buoy Center

NDVI
Normalized Difference Vegetation Index

NDWI
Normalized Difference Water Index

NEMO
Nucleus for European Modelling of the Ocean (global ocean model)

NevCan
Nevada Climate-ecohydrological Assessment Network

NGWOS
Next-Generation Water Observing System

NHMM
Bayesian Nonhomogenous Hidden Markov Model

NICENET
Nevada Integrated Climate and Evapotranspiration Network

NIDIS
National Integrated Drought Information System

NLDAS
North American Land Data Assimilation System

NMME
North American Multi-Model Ensemble

NN R1
NCEP/NCAR Reanalysis

NOAA
National Oceanic and Atmospheric Administration

NOAH
Neural Optimization Applied Hydrology

Noah-MP
Noah-Multi-parameterization Model

NOHRSC
National Operational Hydrologic Remote Sensing Center

NPP
Nonparametric paleohydrologic method

NRCS
Natural Resource Conservation Service

NSF
National Science Foundation

NSIDC
National Snow and Ice Data Center

NSMN
National Soil Moisture Network

NVDWR
Nevada Department of Water Resources

NWCC
National Water and Climate Center

NWIS
National Water Information System

NWM
National Water Model

NWP
numerical weather prediction

NWS
National Weather Service

NWSRFS
National Weather Service River Forecast System

NZI
New Zealand Index

OCN
Optimal Climate Normals

OHD
Office of Hydrologic Development

OK Mesonet
Oklahoma Mesoscale Network

ONI
Oceanic Niño Index

OWAQ
Office of Weather and Air Quality

OWP
Office of Water Prediction

PC
principal components

PCA
principal components analysis

PCR
principal components regression

PDO
Pacific Decadal Oscillation

PDSI
Palmer Drought Severity Index

PET
potential evapotranspiration

PGW
pseudo-global warming

PRISM
Parameter-elevation Relationships on Independent Slopes Model

PSD
Physical Sciences Division

QBO
Quasi-Biennial Oscillation

QDO
Quasi-Decadal Oscillation

QM
quantile mapping

QPE
Quantitative Precipitation Estimate

QPF
Quantitative Precipitation Forecast

QTE
Quantitative Temperature Estimate

QTF
Quantitative Temperature Forecast

radar
radio detection and ranging

RAP
Rapid Refresh (weather model)

RAWS
Remote Automated Weather Station Network

RCM
Regional Climate Model

RCP
Representative Concentration Pathway

RE
reduction-of-error

RFC
River Forecast Center

RFS
River Forecasting System

RH
relative humidity

RiverSMART
RiverWare Study Manager and Research Tool

RMSE
root mean squared error

S/I
seasonal to interannual

S2S
subseasonal to seasonal

Sac-SMA
Sacramento Soil Moisture Accounting Model

SAMS
Stochastic Analysis Modeling and Simulation

SCA
snow-covered area

SCAN
Soil Climate Analysis Network

SCE
Shuffled Complex Evolution

SCF
seasonal climate forecast

SE
standard error

SECURE
Science and Engineering to
Comprehensively Understand and
Responsibly Enhance Water

SFWMD
South Florida Water Management District

SM
soil moisture

SMA
Soil Moisture Accounting

SMAP
Soil Moisture Active Passive

SMHI
Swedish Meteorological and Hydrological
Institute

SMLR
Screening Multiple Linear Regression

SMOS
Soil Moisture and Ocean Salinity

SNODAS
Snow Data Assimilation System

SNOTEL
Snow Telemetry

SOI
Southern Oscillation Index

SON
September-October-November

SPoRT
Short-term Prediction Research Transition

SRES
Special Report on Emissions Scenarios

SRP
Salt River Project

SSEBOP
Simplified Surface Energy Balance

SSEBOP ET
Simplified Surface Energy Balance
Evapotranspiration

SSP
Societally Significant Pathway

SST
sea surface temperatures

SSW
stratospheric sudden warming

SubX
Subseasonal Experiment

SUMMA
Structure for Unifying Multiple Modeling
Alternatives

SVD
singular value decomposition

SW
surface water

SWANN
Snow-Water Artificial Neural Network
Modeling System

SWcasts
Southwest Forecasts

SWE
snow water equivalent

SWOT
Surface Water and Ocean Topography

SWS
Statistical Water Supply

Tair
air temperature

Tdew
dew point temperature

TopoWx
Topography Weather (climate dataset)

TVA
Tennessee Valley Authority

UC
Upper Colorado Region (Reclamation)

UCAR
University Corporation for Atmospheric Research

UCBOR
Upper Colorado Bureau of Reclamation

UCRB
Upper Colorado River Basin

UCRC
Upper Colorado River Commission

UCRSFIG
Upper Colorado Region State-Federal Interagency Group

USACE
U.S. Army Corps of Engineers

USBR
U.S. Bureau of Reclamation

USCRN
U.S. Climate Reference Network

USDA
U.S. Department of Agriculture

USGCRP
U.S. Global Change Research Program

USGS
U.S. Geological Survey

USHCN
United States Historical Climatology Network

VIC
Variable Infiltration Capacity (model)

VIIRS
Visible Infrared Imaging Radiometer Suite

VPD
vapor pressure deficit

WBAN
Weather Bureau Army Navy

WCRP
World Climate Research Program

WFO
Weather Forecast Office

WPC
Weather Prediction Center

WRCC
Western Regional Climate Center

WRF
Weather Research and Forecasting

WRF-Hydro
WRF coupled with additional models to represent hydrologic processes

WSF
water supply forecast

WSWC
Western States Water Council

WUCA
Water Utility Climate Alliance

WWA
Western Water Assessment

WWCRA
West-Wide Climate Risk Assessments

WWMPP
Wyoming Weather Modification Pilot
Project