Colorado River Basin Climate and Hydrology

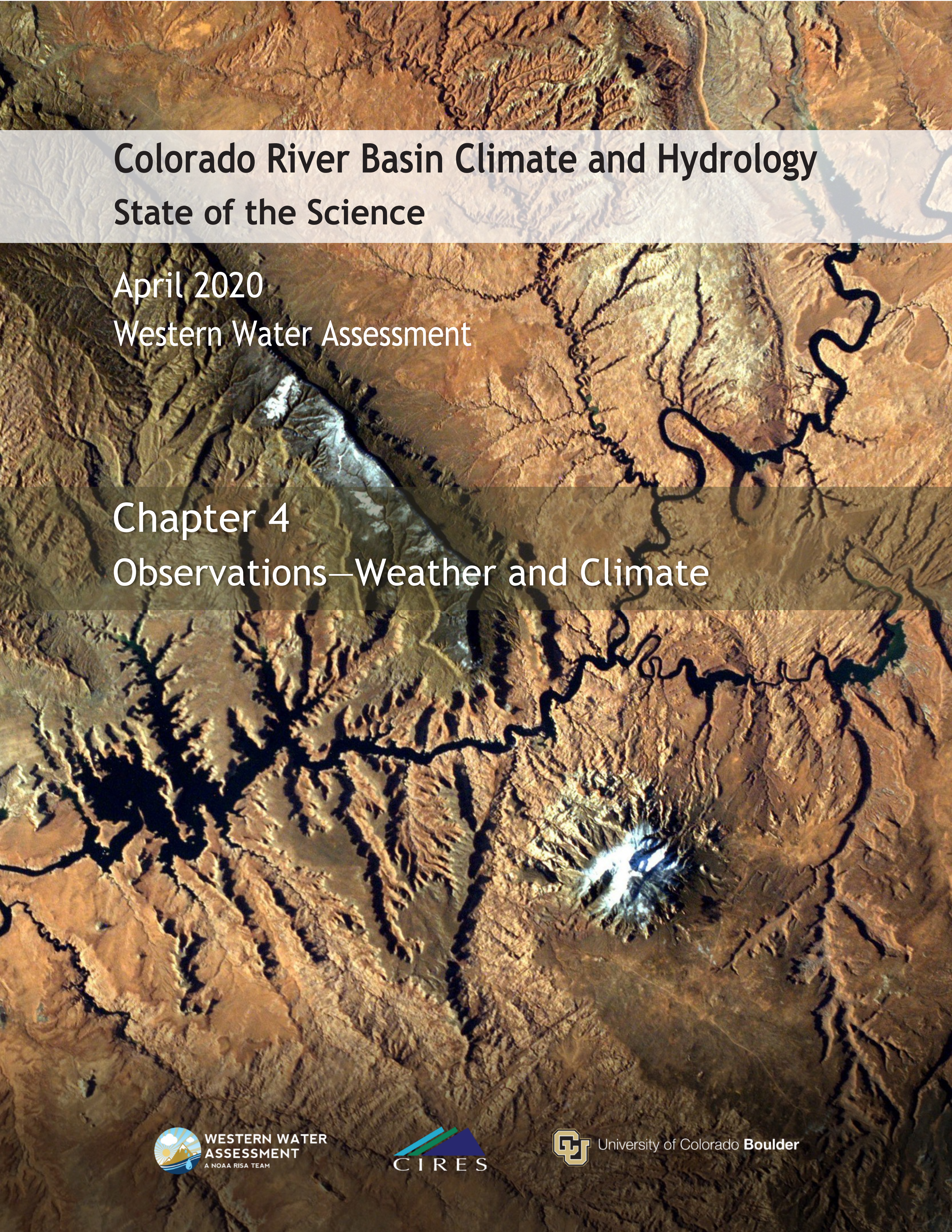
State of the Science

April 2020

Western Water Assessment

Chapter 4

Observations—Weather and Climate



WESTERN WATER ASSESSMENT
A NOAA RISA TEAM

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University of Colorado **Boulder**

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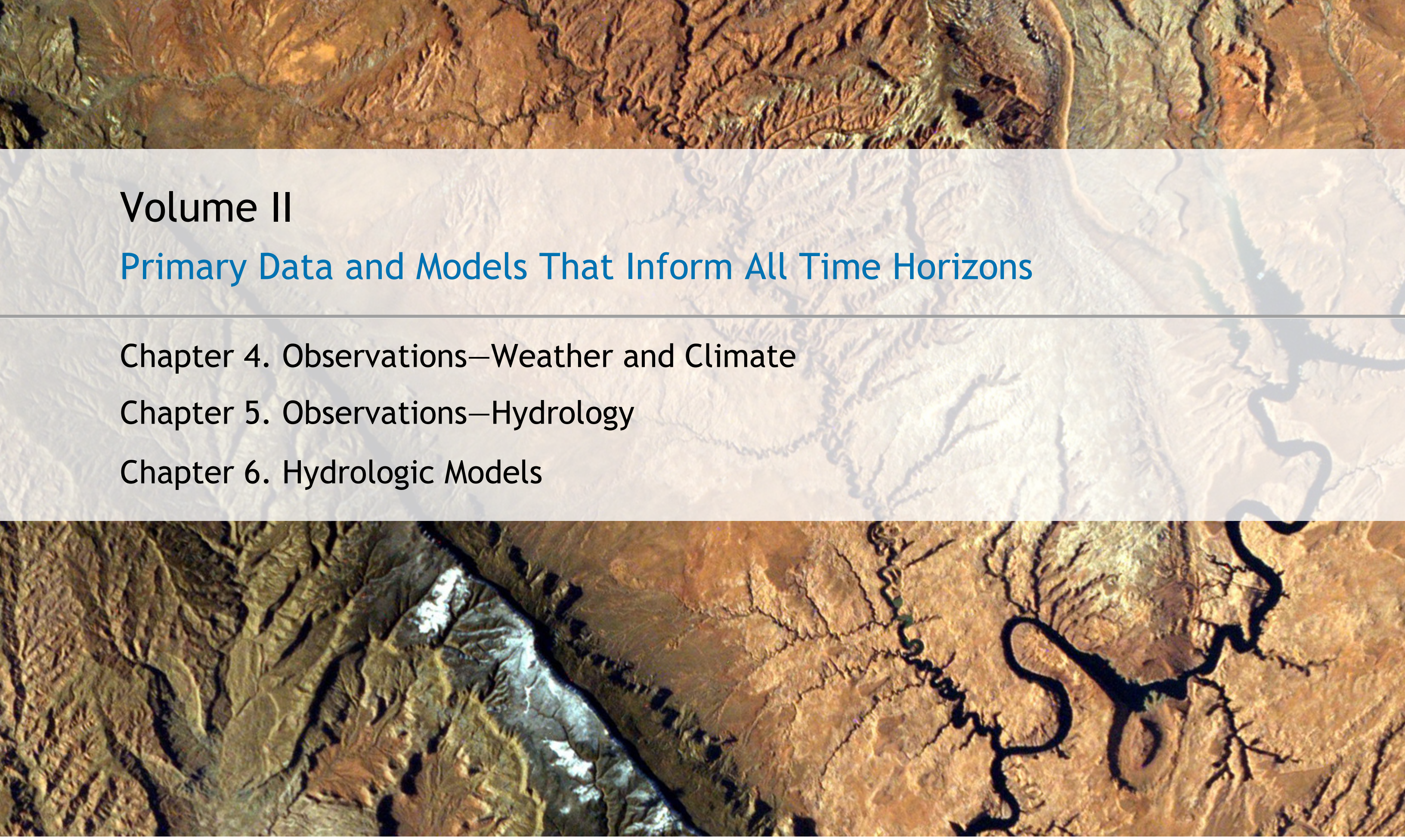

Volume II

Primary Data and Models That Inform All Time Horizons

Chapter 4. Observations—Weather and Climate

Chapter 5. Observations—Hydrology

Chapter 6. Hydrologic Models

Volume II of the Colorado River Basin State of the Science report focuses on primary data and models that are relevant across all time scales. While Volumes III and IV concentrate on short- to mid-term forecasting and long-term outcomes, respectively, the data and models addressed in this volume can be applied to Colorado River Basin studies performed at all of those time scales. The chapters in this volume describe how primary weather, climate, and hydrology data are collected and how datasets of other variables are built from primary data. A simple regurgitation of the vast literature about the primary data would not serve the goals of this report. The focus, instead, is on compiling, summarizing, and offering objective assessment of the data and the work that has been done to make it available. The objective of this volume is to be a uniquely useful reference for readers.

Chapter 4 is a reference for weather and climate data. It begins with a description of the methods and equipment that have been used to collect weather data, from the installation of the first weather stations in the basin in the late 1800s, to the emergence of remotely-sensed distributed data. It explains how point data become gridded datasets, how missing data are treated, how large scale data are disaggregated, which datasets have common source data, and how quantitative biases can be introduced. Knowledge about the methods behind, and idiosyncrasies of, the datasets, along with their strengths and weaknesses is presented to help readers determine which data sources are better fits for their applications. The chapter provides a detailed comparison of 11 gridded datasets. It explains things to consider when comparing values and trends from these datasets, and practical and scientific considerations when selecting a gridded dataset.

Chapter 5 is a reference to hydrology data—snowpack, streamflow, soil moisture, evaporation, and evapotranspiration—that are key inputs to streamflow forecasting and system modeling. Snowpack, soil moisture, and evaporation/evapotranspiration data are all gathered using three methods—in situ measurements, modeled estimates, and remote sensing. Chapter 5 provides a comprehensive description of the multiple data sets developed by each method, and an explanation of the advantages and limitations of each. Streamflow, on the other hand, has been measured in essentially the same way across the basin since measurements commenced at the end of the 19th century: stream gages that measure stream stage, which is subsequently translated to flow by a rating curve that is essentially an empirical hydraulic model of the gage site. This chapter explains the uncertainties in the gage record, which arise from measurement error but to a larger degree from errors in the rating curves. Measured streamflows are naturalized or deregulated for use in models. This process introduces more uncertainty, and the sources and implications of this uncertainty are thoroughly described in this chapter. The chapter closes with a summary of challenges and opportunities regarding hydrology data.

Chapter 6 is devoted to describing the evolution, application, and trade-offs of a number of runoff and land surface models that are the foundation of applications at the smallest time scale, streamflow forecasting, to the largest time scale, climate change projections. This chapter is complemented by Chapters 8 and 11, which place hydrology models in the context of forecasting and projection applications, and by Chapters 4 and 5, which describe the provenance and qualities of the data used to force and validate hydrology models. The advantages and disadvantages of the hydrology models are summarized and their usefulness for either forecasting or simulating climate sensitivity or both is assessed. Not surprisingly, the evolution of hydrologic models follows a path of increasing complexity, from empirical conceptual runoff models, to simple water balance models, which led to distributed land surface models and fine-scale physically explicit models and finally to coupled land-atmosphere models. Models of all of these types continue to be applied in the basin, and Chapter 6 describes the models currently in use in the basin and explores emerging models and approaches that could improve forecasting and projection. The chapter closes with an examination of knowledge gaps, challenges and opportunities for improvement.

Chapter 4

Observations—Weather and Climate

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Key points

- Weather and climate data are collected and interpolated for specific reasons, so not all data and datasets are suitable for all uses. Users should be cautious about "off-label" use of climate data and should thoroughly investigate the suitability of data before it is applied outside of its planned uses.
- Users of weather and climate datasets should be aware that the data reflect average or summary conditions over their spatial and temporal resolution and should not expect a gridded product to accurately reflect conditions at any particular point on the landscape at any given point in time. This is particularly true for high-relief landscapes like the Colorado River Basin.
- Most of the existing high-resolution gridded datasets share some base information or use similar processing, or both, so they are not strictly independent.
- There is not now, and likely never will be, perfect weather and climate data. Producers of climate information need to communicate, and users should be cognizant of, the strengths and weaknesses of the data they choose and how climate data choices influence their conclusions.
- In the Colorado River Basin, the highest elevations have the lowest weather station densities and likely the least precise and accurate weather information. This is especially problematic for water resource questions, because such a large fraction of the runoff is generated at high elevations.

4.1 Introduction

Weather and climate are important drivers of many hydrologic processes and thus have a profound influence on water availability in the Colorado River Basin (Nash and Gleick 1991; Christensen et al. 2004; Barnett and Pierce 2009; Rasmussen et al. 2011; Vano, Das, and Lettenmaier 2012). There is increasing awareness of the fact that weather and climate also influence water demand for agricultural (Wisser et al. 2008), municipal (Kenney et al. 2008), and industrial (van Vliet et al. 2016) uses. Accordingly, any assessment of hydrologic variability in the Colorado River Basin must consider the underlying weather and climate variability in spatially and temporally explicit ways, which makes climate data and datasets (gridded interpolations of station observations and potentially other information) particularly critical.

Most climate data were initially collected in the context of weather observation in particular locations and largely for specific reasons, such as assessing irrigation demand, evaluating water supply, or ensuring aviation safety (Tables 4.1 and 4.2). These primarily purpose-driven measurements, however, are now used in much broader ways. As part of spatially extensive networks, long-term records are used to understand spatio-temporal variability in climate and in the hydrologic processes it influences.

Table 4.1

Planned uses and operating agencies for station networks commonly used in hydrologic research within the Colorado River Basin.

Network/Operating Agency	Planned Uses	Citations and Information
Cooperative Observer Program (COOP)	Routine weather and climate monitoring to track changes, improve forecasts, and assist with public safety	National Oceanic and Atmospheric Administration (NOAA) 2019; National Weather Service (NWS), n.d.; Iowa State University, n.d.
NWS via volunteers		
Automated Surface Observing System/Automated Weather Observing System (ASOS/AWOS)	Aviation, weather monitoring	National Weather Service (NWS), n.d.; Iowa State University, n.d.; National Oceanic and Atmospheric Administration (NOAA), n.d.; Federal Aviation Administration (FAA) 2019; National Oceanic and Atmospheric Administration (NOAA), n.d.; Iowa State University, n.d.
NWS/FAA		
Snow Telemetry Network (SNOTEL)	Monitoring snow for water resources	Schaefer and Paetzold 2001; Natural Resource Conservation Service (NRCS), n.d.
NRCS		
Remote Automated Weather Station Network (RAWS)	Fire weather (primarily)	Zachariassen et al. 2003; Western Regional Climate Center (WRCC), n.d.; National Interagency Fire Center (NIFC), n.d
USFS, BLM, NPS, BIA, FEMA, FWS, state		
Cooperative Agricultural Weather Network (AgriMET)	Agriculture; ET calculation	Reclamation 2019a
Reclamation		
Colorado Mesonet (CoAgMET)	Agriculture; ET calculation	Colorado State University (CSU) 2019
Colorado Climate Center at CSU		
Soil Climate Analysis Network (SCAN)	Agriculture; ET calculation	Schaefer and Paetzold 2001; Natural Resource Conservation Service (NRCS), n.d.; Iowa State University, n.d.
NRCS		

Network/Operating Agency	Planned Uses	Citations and Information
Community Collaborative Rain, Hail and Snow Network (CoCoRaHS)	Precipitation measurement	Doesken and Reges 2010; Reges et al. 2016; "CoCoRaHS: Community Collaborative Rain, Hail & Snow Network" n.d.
Colorado Climate Center at Colorado State University via volunteers		
US Climate Reference Network (USCRN)	Long-term climate monitoring	NOAA National Centers for Environmental Information n.d.; NOAA National Environmental, Satellite, Data, and Information Service 2007; Diamond et al. 2013
NOAA		

For many purposes, however, weather station data are not sufficient. Individual station records can contain gaps when measurements were not made. Moreover, there is incomplete spatial coverage. To resolve these problems, point weather data have been used to develop gridded data products. In the development of gridded datasets, the landscape is overlain with a grid, and station observations are interpolated or aggregated to estimate a value for each grid cell. This process is carried out at regular time steps (most frequently daily or monthly) for some number of years (e.g., 1950–2010). Because multiple stations—and potentially other types of data—are used in the development of the gridded data, the resulting products are spatially and temporally complete, i.e., there are values for every grid cell and the time series contain no gaps.

Within the Colorado River Basin, weather and climate data are used for a number of purposes. First, weather and climate data are used to calibrate hydrologic and streamflow forecast models used in scientific studies and for water resource management decisions. Once these models have been calibrated, weather and climate data are used as inputs to drive them. Climate data, particularly gridded datasets, have also been used extensively to downscale and bias-correct climate model projections that are then used as inputs to hydrologic models. The output from these future simulations is then used in a variety of ways to assess the reliability of water supplies in the Colorado River Basin under a range of future climate conditions (Vano, Das, and Lettenmaier 2012; Vano and Lettenmaier 2014; Ayers et al. 2016). In addition to their use as model inputs, compiled weather data have been used to analyze climate patterns and trends across the basin (Hidalgo and Dracup 2003; Mo, Schemm, and Yoo 2009; Nowak et al. 2012) and to better understand historical patterns of hydrologic variability (McCabe and Wolock 2007; Woodhouse et al. 2016; McCabe et al. 2017). Climate data have also been used in the analysis and calibration of paleoclimate proxies, primarily tree rings, that then provide long-term histories of streamflow, temperature, precipitation, and snow in the basin (Meko et al. 2007; Woodhouse and Pederson 2018).

Table 4.2

General information about station networks commonly used in hydrologic research within the Colorado River Basin. Network start year indicates the earliest available data collected, but not all stations in the network have coverage back to the start of the network. The "Available Variables" column describes the most common variables available from the network, although there can be data gaps, and some stations may provide additional variables.

Network	Available Variables	Minimum Temporal Resolution	Network Start Year
Cooperative Observer Program (COOP)	Maximum temperature, minimum temperature, snowfall, precipitation	Daily	1890
Automated Surface Observing System/Automated Weather Observing System (ASOS/AWOS)	Temperature, pressure, wind, dewpoint, precipitation (type, amount, intensity), visibility, ceiling height, other comments	Hourly or sub-hourly; some stations collect 1- and 5-minute observations	ASOS: late 1980s/1990s, AWOS implemented earlier
Snow Telemetry Network (SNOTEL)	Temperature, precipitation, snow water equivalent. Usually also solar radiation, snow depth, wind, humidity; subset of stations: soil moisture and temperature	Sub-daily; some stations are hourly	1979
Remote Automated Weather Station Network (RAWS)	Precipitation, wind, air temperature, humidity, fuel temperature, fuel moisture, solar radiation	10-minute	Late 1970s, early 1980s
Cooperative Agricultural Weather Network (AgriMET)	Temperature, precipitation, humidity, soil temperature and moisture, wind, radiation	Some variables at 15 minutes	Early 1980s
Colorado Mesonet (CoAgMET)	Temperature, humidity, wind, radiation, precipitation, soil temperature	5-minute	Early 1990s
Soil Climate Analysis Network (SCAN)	Soil temperature and moisture, humidity, wind, radiation, precipitation, temperature	Hourly	Early 1990s
Community Collaborative Rain, Hail and Snow Network (CoCoRaHS)	Precipitation, snowfall, hail, and flood reports; some evapotranspiration	Daily	1998
US Climate Reference Network (USCRN)	Temperature, precipitation, wind speed, humidity, radiation, soil temperature and moisture	Hourly	2003

Numerous approaches have been taken to provide these data in ways that meet diverse user needs. Most data products fall into one of four main categories: 1) in situ point data collected at weather stations, 2) statistically interpolated data, 3) physically interpolated data (i.e., reanalyses), and 4) spatially continuous data derived from a remotely sensed product. This chapter focuses on in situ data and statistically interpolated data, as these are the kinds of data that have been used most frequently to understand the hydrology of the basin. However, one product discussed here, the North American Land Data Assimilation Scheme (NLDAS-2) is derived from reanalysis (Xia et al. 2012).

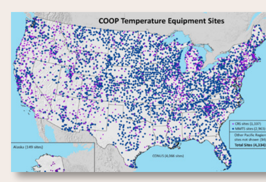
4.2 In situ observations

In situ weather station data are simply records of weather variables (e.g., temperature and precipitation) at specific locations. These stations are the underlying source of all weather and climate information from the late 1800s, when the first weather stations were installed in the Colorado River Basin, until the late 20th century, when remotely sensed climate monitoring from satellites first became widely available (Davis 2007). Although the first weather stations in the basin were put into place in the late 1800s, there were relatively few stations, and their spatial coverage was quite limited (Figure 4.1). As the number of stations has increased over time, their spatial distribution has increased, as has the diversity of environments that they sample in the basin (McAfee et al. 2019). That said, weather station coverage is still more complete in river valleys where towns and cities are located, and few high-quality stations were installed at high elevations prior to the late 1970s or early 1980s (McAfee et al. 2019).

Weather recording technology has also changed over time. Figure 4.2a shows a COOP station in Granger, Utah from around 1930. Temperature is measured inside a Cotton Region Shelter with a liquid thermometer. While some COOP stations still use these sensors, others use an electronic thermometer referred to as Maximum Minimum Temperature System or MMTS inside a shield composed of white plates. Both can be seen in Figure 4.2b, the COOP station in Logan at Utah State University. Automated Weather Observing System, or ASOS, stations (Figure 4.2c) also use electronic temperature sensors.

Almost all weather stations record daily minimum and maximum temperature and daily precipitation (the total liquid content of all rain, snow, and other precipitation that accumulates in a rain gage). The intended or primary use of the station dictates where it is located, what other variables it measures, and the temporal resolution of those data.

NWS Cooperative Observer Program



Link: https://www.weather.gov/coop/

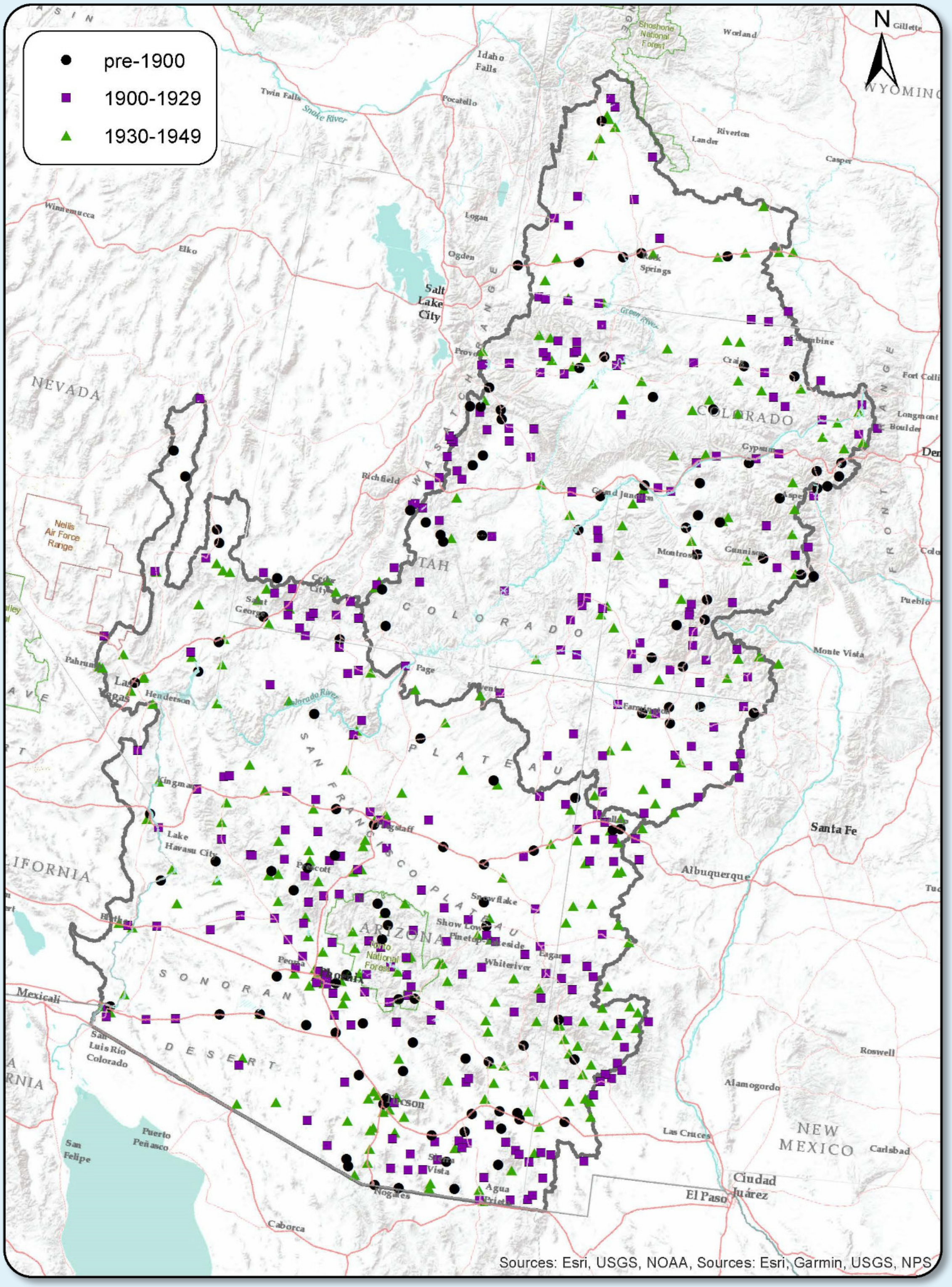


Figure 4.1

Map showing stations from the Global Historical Climatology Network located in or near the Colorado River Basin that have first record dates prior to 1950.

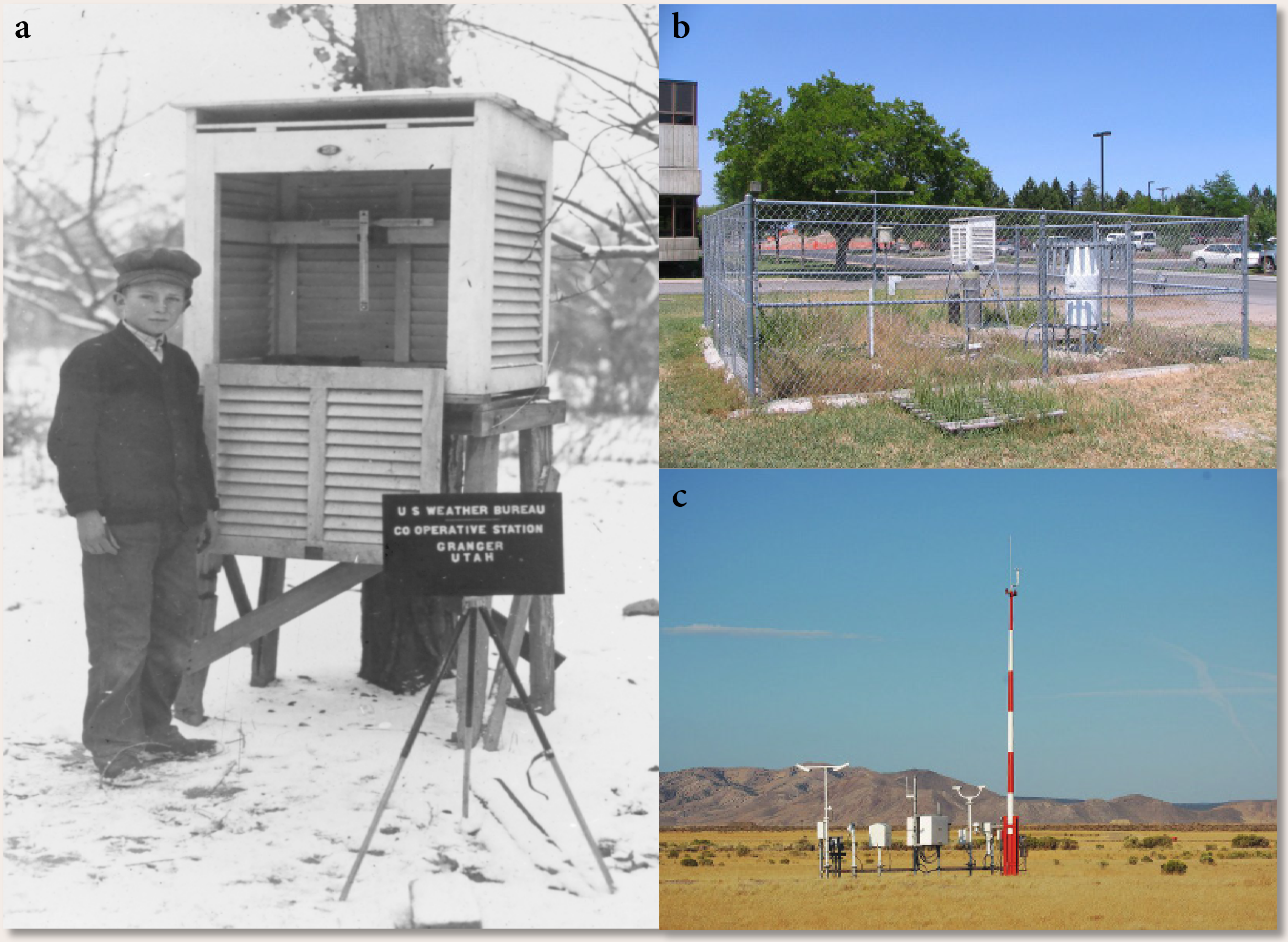


Figure 4.2

Photos of (a) a COOP station in Granger, UT, taken around 1930, (b) the COOP station at Utah State University which measures temperatures using both a Cotton Region Shelter and the Minimum Maximum Temperature System. (c) the ASOS station at Milford, UT. Panel a is from the NOAA Photo Library. Panels b and c are from the Western Regional Climate Center Station Pictures resource.

The need to monitor for specific reasons has led to the development of specific weather station networks—collections of stations using very similar instrumentation designed to measure weather for an explicit purpose. For example, the SNOTEL network was developed primarily to assess water resource availability in the western United States (Schaefer and Paetzold 2001). (It is possible for a station to belong to multiple networks. For example, the weather station at Grand Junction Walker Field is an ASOS station that also belongs to the COOP network.)

Because much of the western U.S. relies on water delivered as winter precipitation and stored in mountain snowpacks (e.g., Christensen et al.

2004), stations in the SNOTEL network are typically located in small valleys in the mountains, where snow collects (Schaefer and Paetzold 2001). Stations are instrumented to provide multiple measurements of the snowpack such as snowfall, snow depth, and snow water equivalent (SWE) that are not routinely measured at other networks. They are also often designed to function in areas with deep snow by, for example, measuring precipitation at heights well above 6 feet, although the World Meteorological Organization notes that most gages are placed about 3 feet above the surface (World Meteorological Organization 2008). Normally, the use of tall rain gages would enhance undercatch, because wind speeds increase with height; however, this may not influence the degree of undercatch at SNOTEL stations because many SNOTEL sites are forested (Serreze et al. 1999). Figure 4.3 shows the Arapaho Ridge SNOTEL station in Colorado. The view of the rain gage relative to the surrounding vegetation suggests that the gage is taller than three feet. The SNOTEL station also includes a snow-depth sensor and a snow pillow, equipment that is relatively standard for SNOTEL stations but not common in other weather station networks.

Figure 4.3
Photo of the Arapaho Ridge SNOTEL site northwest of Longs Peak in Colorado. (Source: Brian Domonkos, Natural Resources Conservation Service)

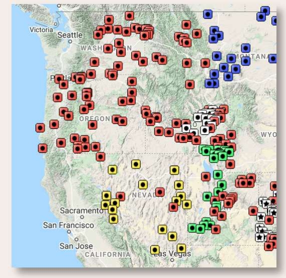
Tables 4.1 and 4.2 describe the characteristics of seven station networks that are common across the western U.S. and that are frequently used to understand hydrology and consumer demand in the Colorado River Basin. These tables are not comprehensive; there are smaller and more localized networks that may also be used in hydrologic analyses. In some cases, data from smaller networks are provided via similar, more comprehensive networks. For example, the AgriMet webpage provides access to data from NICENet, AgWxNet, and some state-run stations that provide similar kinds of measurements (Reclamation 2019a).

Figure 4.4 shows stations in or within 6.2 miles (10 km) of the basin in the Soil Climate Analysis Network (SCAN), and the AgriMET, CoAgMet, SNOTEL, RAWS, and COOP networks. Only stations that reported in the 21st century (i.e., stations that have an end date later than 2000) are shown. RAWS and COOP station locations were identified from the Global Historical Climatology Network (GHCN) database on the basis of their identification codes. The GHCN is an extensive collection of global weather station data that meet minimum criteria for record length and metadata (Menne et al. 2012). Station records included within the GHCN are subjected to automated quality control and assurance checks (Peterson, Vose, et al. 1998; Durre et al. 2010).

Although different station networks were developed for different purposes, all station data are prone to a common set of errors. Missing data is a common problem that occurs at both manual and automated stations because of equipment malfunction and reporting failures. Station records are also prone to inhomogeneities—non-climatic changes in the mean or variance of the data—caused by changes in instrumentation, time of observation, local surroundings, and even observers, as well as by relocation of the entire station (Karl et al. 1986; Karl, Diaz, and Kukla 1988; Quayle et al. 1991; Peterson, Easterling, et al. 1998; Menne and Williams 2009; Menne, Williams, and Vose 2009). Some of these inhomogeneities are correctable, and some are not. One notable recent example of this is the inhomogeneity in minimum temperature at SNOTEL sites caused by a network-wide changeover to new thermometers beginning in the mid-1990s and extending through the early 2000s (Oyler, Dobrowski, et al. 2015).

In Colorado, the change in instrumentation occurred primarily in 2004–2006 (Rangwala et al. 2015). The change in instrumentation led to the appearance of rapidly warming minimum but not maximum temperatures and a correspondingly sharp reduction in the daily temperature range (Rangwala et al. 2015). This particular inhomogeneity appears to be correctable, either through comparison with near-by stations as in Oyler, Dobrowski, et al. (2015), or through corrections developed by the Natural Resources Conservation Service (Ma 2017). In general, there are any number of mechanisms for correcting inhomogeneities (Menne and Williams 2009; Peterson, Easterling, et al. 1998; Hamlet and Lettenmaier 2005), most of which rely on the presence of a nearby station with a homogenous record. Inhomogeneities may be more difficult to correct in areas where, or during times when, there are few weather stations to compare the suspect station against.

USBR Agrimet Network Map



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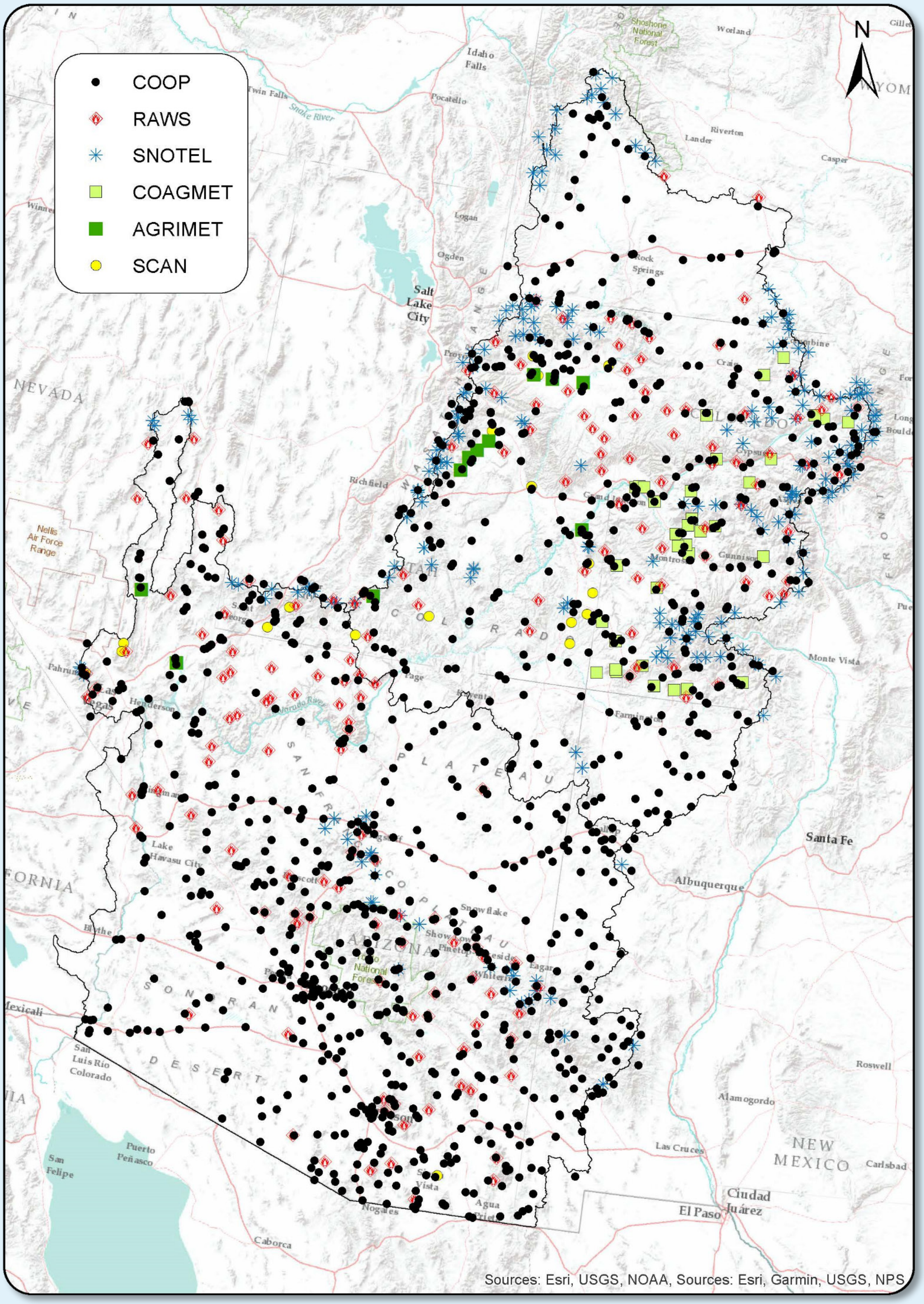


Figure 4.4

Locations of presumably active weather stations in or near the Colorado River Basin. COOP and RAWS locations were derived from the GHCN, so COOP and RAWS stations not included in the GHCN are not shown on the map. Likewise, stations in the COOP network but that are also ASOS or AWOS stations may not be represented on this map depending on their coding the in the GHCN.

Inhomogeneities that develop due to gradual changes in the surrounding environment can be more challenging to adjust for (Menne, Williams, and Vose 2009). The presence of multiple kinds of inhomogeneities in a record, for example, at a station that is moved from one location to another while also being impacted by urbanization, may further complicate correcting the record.

Precipitation measurements are also affected by undercatch, where less precipitation is captured by the gage than actually falls. Undercatch occurs because of 1) evaporation from the gage; 2) wetting error (i.e., water that adheres to the sides of the gage and may not be fully measured); 3) turbulence, wherein turbulent air flow over the mouth of the gage pushes rain drops and snowflakes away from the gage opening; and 4) for snow, bridging across the top of the gage, which makes it more likely that precipitation will be lost before measurement. The last can also shift the apparent timing and intensity of precipitation if snow accumulates over the mouth of the gage only to fall in, all at once, at a later time. The degree of undercatch varies with the type of gage used, the use and kind of shielding, wind speed, precipitation phase, and precipitation intensity (Adam and Lettenmaier 2003; Goodison, Louie, and Yang 1998). Numerous studies have evaluated catch efficiency for a range of gage and shield combinations. A clear finding is that unshielded gages measure less rain and snow than shielded gages (Hanson, Johnson, and Rango 1999; Rasmussen et al. 2012). This may be of concern because some networks, like CoCoRaHS (Reges et al. 2016) and RAWS (National Wildfire Coordinating Group 2014) use unshielded gages. Owing to the high variability in undercatch due to equipment combined with environmental conditions, making accurate correction is difficult, although some attempts have been made (e.g., Yang et al. 1998).

Although rain and snow are particularly difficult to quantify, any meteorological measurement can contain error. Stations that are not regularly maintained and calibrated can collect inaccurate or imprecise data, even in the absence of damage (Leeper, Rennie, and Palecki 2015). As with precipitation, different models of temperature sensors and logging equipment may measure slightly different values (Lin and Hubbard 2004), and different types of shielding on temperature sensors can also modify the temperature observed because they differ in the degree of shading and airflow past the temperature sensor they provide (Hubbard, Lin, and Walter-Shea 2001). Liquid thermometers can also be subject to parallax error (Linacre 1992), for example, when a thermometer at a fixed height is read by observers of different heights. Measurement error associated with other variables is also expected (Linacre 1992). Recording errors of all kinds can also be a problem, particularly for manual stations (Leeper, Rennie, and Palecki 2015; Menne et al. 2012; Linacre 1992).

Consequently, another consideration in the use of station data is whether and in what way the data have been quality controlled (QC) prior to release. Not all networks conduct extensive QC, those that do may use different procedures, and QC protocols may evolve over time. The AgriMet network regularly maintains and calibrates equipment, applies automated checks to sub-daily data collected at its stations, flags potentially erroneous values in near real-time and then uses manual checks daily (Hamel, n.d.). The SNOTEL network also relies on a combination of equipment maintenance, flagging, and eyes-on evaluations of data (Kuiper et al. 2014). Other networks, such as RAWS, may have less standardized quality control (Zachariassen et al. 2003; Brown et al. 2011). Integrative networks typically apply their own checks. The Global Historical Climatology Networks investigate data records independently and in relationship to nearby stations, typically flagging suspect data (e.g., Global Historical Climatology Network; Durre et al. 2010; Menne et al. 2012).

In general, in situ weather station data are most appropriate for characterizing the climate variables they were designed to measure in their immediate surroundings, assuming that they are routinely and appropriately maintained. However, many stations have proven to be useful outside of their intended purpose, especially when analyzed in innovative ways. For example, SNOTEL stations are designed primarily to describe the depth and water content of the snowpack, understand how it developed over the course of the season, and track year-to-year variability in the snowpack at that location. Although SNOTEL stations were not necessarily designed for long-term climate monitoring, they are generally well maintained stations that, barring the instrumentation-related inhomogeneity, would be effective in tracking temperature trends in higher elevations. RAWS stations have been used for a much larger array of applications than originally intended (Brown et al. 2011). AgriMet stations are not designed to track snowpack, most notably because they are not usually instrumented with a snow pillow and snow-depth sensor. They are, however, equipped with both tipping bucket and weighing precipitation gages. When both types of precipitation measurements are available, they can be leveraged to effectively distinguish rain and snow (Strachan 2016). In other cases, beneficial uses have been identified for what would otherwise be errors or weaknesses. For example, the placement of COOP stations in populated areas has diminished their ability to track regional climate variability (without correction), but it has allowed the detection and quantification of urban heat islands.

Agrimet Weather Station Equipment and Sensors

AgriMet
Cooperative Agricultural Weather Network

Link: https://www.usbr.gov/pn/agrimet/aginfo/sensors.html

4.3 Statistically interpolated gridded data

Statistically interpolated data fill spatial gaps between existing point measurements using a variety of techniques. Most statistically interpolated data are aggregated to represent grids or rasters of varying spatial resolution; however, there are some climate data provided not for regular grids, but for irregular areas like climate divisions, counties, or basins. Some of these irregular area products are themselves developed from gridded products. For example, the latest (2019) version of the climate division data are derived from a roughly 3.1-mi (5-km) resolution gridded product called nClimGrid (Vose et al. 2014).

The interpolation used to make gridded data may be based solely on observations, with the value at a given point based on some, usually distance weighted, function of values at nearby stations. This is more common for coarser resolution (> 0.5°) products. Most higher-resolution (< 10-mile) products, however, also incorporate some physiographic information to more accurately reflect the strong influence of terrain on spatial variability in climate. For example, all of the products described in this chapter incorporate an adjustment for the lapse rate or expected decrease in temperature with elevation. Different statistical methods for interpolation are used in different products. Although they are not discussed here, Daly (2006) provides an overview of commonly used interpolation methods.

Gridded data products

For most hydrologic modeling applications, relatively high-resolution gridded data are preferable, so the focus here is on selected, commonly used products listed in Table 4.3 and described in Table 4.4.

Table 4.3

General information about gridded data products commonly used in hydrologic research within the Colorado River Basin. Definitions are provided in the glossary.

Product Name	Variables	Spatial Resolution	Spatial Coverage	Temporal Resolution	Temporal Coverage
PRISM AN81d	Tmax, Tmin, Tmean, Tdew, VPDmax, VPDmin, Prcp	30 sec (~0.5 mi) & 2.5 min (~2.5 mi)	CONUS	Daily	1981–near present
PRISM AN81m	Tmax, Tmin, Tmean, Tdew, VPDmax, VPDmin, Prcp	30 sec (~0.5 mi) & 2.5 min (~2.5 mi)	CONUS	Monthly	1895–near present
PRISM LT81m	Tmax, Tmin, Tmean, Tdew, VPDmax, VPDmin, Prcp, VPR	30 sec (~0.5 mi)	CONUS	Monthly	1895–near present
TopoWx	Tmax, Tmin	30 sec (~0.5 mi)	CONUS	Daily, monthly	1948–2016

Product Name	Variables	Spatial Resolution	Spatial Coverage	Temporal Resolution	Temporal Coverage
Livneh 2013/ Maurer 2002	Tmax, Tmin, Prcp, Wind, SolRad & VIC-simulated baseflow, canopy water, ground heat flux, sensible heat flux, latent heat flux, net radiation, SWE, soil moisture, surface runoff, total ET	L: 1/16° (~3.8 mi) M: 1/8° (~7.5 mi)	CONUS & Columbia River Basin	Sub-daily, Daily, monthly	L: 1915–2011 M: 1950–2000
Livneh 2015	Tmax, Tmin, Prcp, Wind, SolRad & VIC-simulated baseflow, canopy water, ground heat flux, sensible heat flux, latent heat flux, net radiation, SWE, soil moisture, surface runoff, total ET	1/16° (~3.8 mi)	N. America south of 53°N through Mexico	Daily, monthly	1950–2013
gridMET	Tmax, Tmin, Prcp, RHmin, RHmax, SpecHum, Wind, SolRad & derived burning index, fuel moisture, ERC, PDSI, rET-alfalfa, rET-grass, VPD	2.5 min (~2.5 mi)	CONUS	Daily	1979–very near present
Hamlet 2005	Tmax, Tmin, Prcp, Wind	1/8° (~7.5 mi)	CONUS plus Columbia River Basin	Daily	1915–2003
Hamlet 2010	Tmax, Tmin, Prcp, Wind	1/16° (~3.8 mi)	CONUS plus Columbia River Basin	Daily	1915–2006
Daymet v. 3	Tmax, Tmin, Prcp, SolRad, DayLength, VPR, SWE	1 km (~0.6 mi)	N. America, north of 14°N	Daily	1980–end of last full year
Newman gridded ensembles	Prcp, Tave, DTR	1/8° (~7.5 mi)	CONUS & portions of Mexico and Canada	Daily	1980–2016
nClimGrid	Tmax, Tmin, Prcp	5 km (~3.1 mi)	CONUS	Monthly	1895–present
NLDAS-2	Tave, SpecHum, Prcp, Wind, Pres, SolRad, DLWR, & numerous land-surface model outputs derived from the forcing variables	1/8° (~7.5 mi)	CONUS, parts of Canada and Mexico, (125° to 67°W, 25° to 53°N)	Hourly	1979–near present

PRISM (Parameter-elevation Relationships on Independent Slopes Model) was one of the first higher-resolution (< 10-mile) gridded climate products (Daly et al. 1994, 1997, 2002, 2008), and it is one of the few to extend back to the late 19th century. Because of its long history and good temporal coverage, PRISM has long been considered a solid climate data choice. It also incorporates one of the most diverse networks of stations (Table 4.4), particularly for precipitation. Many new, higher-resolution gridded products have been developed over the last 10–20 years. Development decisions regarding the spatial and temporal (daily versus monthly) resolution, the time span of the product, and which variables to supply—although most supply only temperature or precipitation, or both—are made to match the product to its intended use and the developers' assessment of what the underlying data can reasonably support.

PRISM

Link:
http://www.prism.oregonstate.edu/

Table 4.4

Input data and development methodologies used in the production of commonly used gridded climate datasets.

Product Name Documentation	Input Data	Key methodologies	Notes & Access
PRISM AN81d / PRISM AN81m Daly, Neilson, and Phillips (1994); Daly, Taylor, and Gibson (1997); Daly et al. (2002; 2008); Daly, Smith, and Olson (2015; PRISM 2016)	All networks listed in Table 4.2, plus Canadian and Mexican federal networks, numerous smaller networks, RADAR data, and information from the NCEP/NCAR Reanalysis	Normals are developed using the PRISM methodology, wherein the regression accounts for distance to the coast, elevation, cold-air pooling, and boundary layer thickness. Climatologically aided interpretation is then used to develop the temporally varying datasets. Some radar data also used to inform precipitation.	PRISM aims to make a "best estimate" given available information. Additional details about adjustments between daily and monthly data for different versions of each are provided in PRISM (2016) Table 5. Access: http://www.prism.oregonstate.edu/ (2.5 min, free) prism_orders@nacse.org (30 sec, $)
PRISM LT81m Daly, Neilson, and Phillips (1994); Daly, Taylor, and Gibson (1997); Daly et al. (2002; 2008); PRISM (2016); Daly, Smith, and Olson (2015)	AGRIMET, ASOS, AWOS & WBAN, COOP, RAWS, SNOTEL, Canadian and Mexican federal networks, and stations run by the H.J. Andrews Experimental Forest, the Western Regional Climate Center, the Minnesota Climatology Working Group, and the North Dakota State Water Commission	Normals are developed using the PRISM methodology, wherein the regression accounts for distance to the coast, elevation, cold-air pooling, and boundary layer thickness. Climatologically aided interpretation is then used to develop the temporally varying datasets. Some information from RADAR is also used to inform precipitation.	The LT81m version aims for "temporal consistency" and so uses only networks with 20+ year records. Access: prism_orders@nacse.org ($)

Product Name / Documentation	Input Data	Key methodologies	Notes & Access
TopoWx Oyler, Dobrowski, et al. (2015); Oyler, Ballantyne, et al. (2015); Oyler et al. (2016); Oyler, n.d.	GHCN-D (incl. COOP, ASOS, WBAN, RAWS, SNOTEL), SNOTEL, RAWS that might not be in GHCN-D. Requires 5+ years data, MODIS LST (MYD11A2)	Station records are homogenized and gap-filled prior to interpolation. A terrain index based on the PRISM DEM is used to predict cold-air pooling. Grids of monthly averages are derived using kriging; geographically weighted regression is used to interpolate daily anomalies, which are added to the monthly averages to get daily values.	Annual updates will incorporate both new observations and model enhancements, resulting in improved datasets, but versions will be incompatible. Access: http://www.scrimhub.org/resources/topowx/ (free)
Livneh 2013/ Maurer 2002 Maurer et al. (2002); Livneh et al. (2013); NOAA ESRL, n.d.; Livneh, n.d.	COOP temperature and precipitation from stations with 20+ years of data. Environment Canada stations in Canada and Mexican Meteorological Service Stations in Mexico, with gap-filling as needed from NCEP/NCAR Reanalysis and GPCP precipitation. Wind from NCEP/NCAR R1. Wind values before 1948 are the average of available years.	Temperatures were adjusted to the elevation of the grid cell before interpolation assuming a constant lapse rate of -6.5°C/km (-3.6°F/1000 ft). Precipitation amounts were adjusted to be consistent with patterns in the 1961-90 PRISM climatology. VIC uses MTCLIM to estimate humidity and radiation variables from temperature and precipitation.	Access: https://www.esrl.noaa.gov/psd/data/gridded/data.livneh.html (free) or http://ciresgroups.colorado.edu/livneh/data/daily-obserational-hydrometeorology-data-set-conus-extent-canadian-extent-columbia-river-basin (Livneh, free) http://www.engr.scu.edu/~emaurer/gridded_obs/index_gridded_obs.html (Maurer updated, free)
Livneh 2015 Maurer et al. (2002); Livneh et al. (2013, 2015); Livneh, n.d.	As in Livneh et al. (2013): COOP stations in the U.S. with 20+ years of data, Environment Canada (EC) stations in Canada, Mexican Meteorological Service stations in Mexico	Methods are similar to L13/M02. Precipitation was adjusted to the 1981-2020 PRISM climatology in CONUS and the Vose et al. (2014) climatology in Mexico and Canada.	One of the goals was to reduce spatial inhomo-geneities associated with differing national precipitation measurement standards for better hydrologic simulation in transboundary basins. Access: https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.nodc:0129374;view=html (free) or ftp://192.12.137.7/pub/dcp/archive/OBS/livneh2014.1_16deg/ (free)

Product Name Documentation	Input Data	Key methodologies	Notes & Access
gridMET Abatzoglou (2013; 2019)	NLDAS-2, PRISM, Climate Forecast System Reanalysis for the previous few days to week	Daily NLDAS-2 output is interpolated to the PRISM grid and then temperature, precipitation, and humidity are adjusted to display spatial variability as in PRISM. No higher resolution information is incorporated for any other variable.	Access: http://www.climatologylab.org/gridmet.html (free)
Hamlet 2005 Maurer et al. (2002); Hamlet and Lettenmaier (2005)	Stations with at least one complete year (365 consecutive days) and at least five total years of data from COOP, EC, monthly U.S. Historical Climatology Network (USHCN), Historical Canadian Climate Data (HCCD); Wind from Maurer et al. (2002) where wind values before 1949 are the average of available years.	Smoothed COOP and EC data are adjusted against smoothed homogenized data (USHCN and HCCD) at monthly time scales to account for major inhomogeneities. Elevation adjustment and interpolation as per Maurer et al. (2002) except that the lapse rate was -6.1°C/km (-3.3°F/1000 ft). Precipitation is adjusted to the PRISM climatology.	The goal in Hamlet and Lettenmaier (2005) was to develop a more temporally homogenous dataset otherwise similar to Maurer et al. (2002).
Hamlet 2010 Maurer et al. (2002); Hamlet and Lettenmaier (2005); Deems and Hamlet (2010)	COOP, EC, monthly USHCN, HCCD; Wind from Maurer et al. (2002)	Hamlet 2010 is constructed similarly to Hamlet 2005, but temperature is also adjusted to match the PRISM climatology.	Additional details about the Hamlet 2010 data product were found in Henn et al. 2018 and Lundquist et al. 2015
Daymet v.3 Thornton, Running, and White (1997); Thornton and Running (1999); Thornton, Hasenauer, and White (2000); Thornton et al. (2016)	GHCN	Locally derived elevation relationships and distance weighted regressions are used to estimate Tmax, Tmin, and precipitation. All other variables are estimated as a function of one or more of Tmax, Tmin, and precipitation using MTCLIM algorithms.	Access: https://daymet.ornl.gov/ (free)

Product Name Documentation	Input Data	Key methodologies	Notes & Access
Newman gridded ensembles Clark and Slater (2006); Newman et al. (2015; 2019)	GHCN and SNOTEL stations not included in GCHN	This is developed using the probabilistic interpolation method of Clark and Slater (2006). For each grid point, T, DTR, and P are calculated as a function of distance-weighted station values, latitude, longitude, slope, aspect, and elevation. Uncertainty is gaged from the regression residuals, and then ensemble members are developed by combining the outcome of the regression with a random value generated from the uncertainty and a field of spatially and temporally correlated random numbers.	The goal was to estimate potential uncertainty associated with preparing gridded climate data. Access: https://www.earthsystemgrid.org/dataset/gridded_precip_and_temp.html or https://doi.org/10.5065/D6TH8JR2 (free)
nClimGrid Vose et al. (2014); NOAA, n.d.	GHCN stations in the COOP, ASOS, RAWS, SNOTEL, EC, and Mexican Meteorological Service networks, but only temperature is used from RAWS. Only stations with 10+ years of data since 1950 are included.	Station values are adjusted for known biases, homogenized, and then interpolated in a way that accounts for latitude, longitude, elevation, distance to coast, cold-air pooling, slope, and aspect effects.	This is the gridded data underlying the climate division data nClimDiv. Access: https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C00332 (free)
NLDAS-2 Cosgrove 2003; Mitchell 2004; Xia et al. 2012	NARR for most variables, CPC and radar for precipitation over U.S. (NARR over Canada and Mexico), satellite data for shortwave radiation augments NARR	Coarse output is interpolated from ~20 mi to ~7.5 mi resolution and temporally interpolated to hours. Temperatures are adjusted assuming a static -6.5°C/km (-3.6°F/1000 ft) lapse rate. Spatial patterns in precipitation are matched to those in PRISM.	Access: https://ldas.gsfc.nasa.gov/nldas/nldas-2-forcing-data and https://disc.gsfc.nasa.gov/datasets?keywords=NLDAS (free)

All of the higher resolution products explicitly account for changes in temperature with elevation, although they do so in different ways (Table 4.4, Figure 4.5). Most products include a mechanism to adjust for changes in precipitation with elevation, as well. Interestingly, many use the elevational change in precipitation estimated by PRISM (Figure 4.6). Other decisions made in the construction of a dataset are typically made to avoid specific problems that arise from changes in the number, type, and location of stations and the common measurement errors described above.

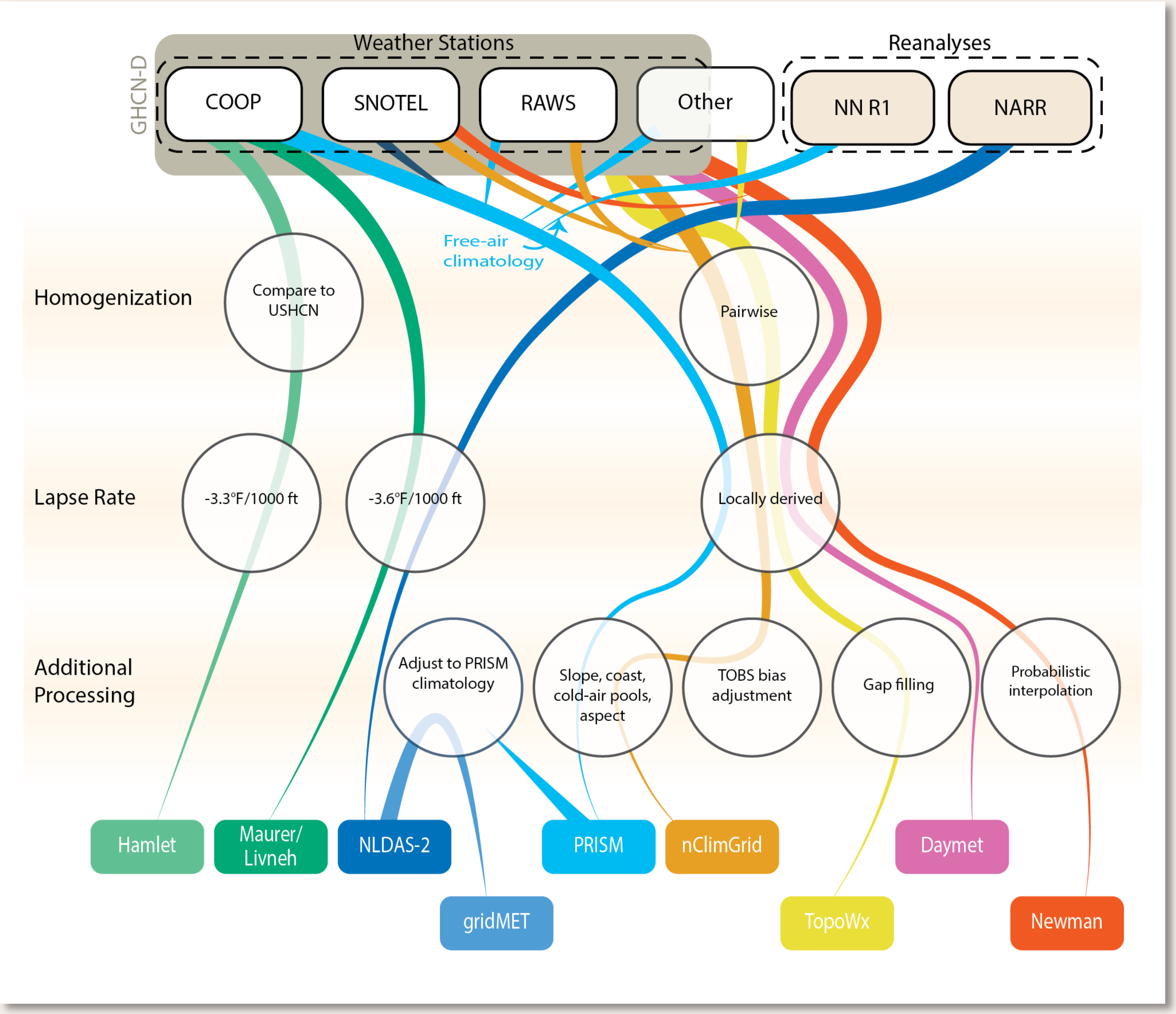


Figure 4.5
Flow diagram of the data sources and processes used to produce the high-resolution gridded temperature products featured in this chapter. Note that the diagram does not accurately indicate the order of processing. For example, gap-filling in TopoWx occurs prior to adjustment for cold-air pooling. In addition to differences in choice of network, products may select different stations from the same network.

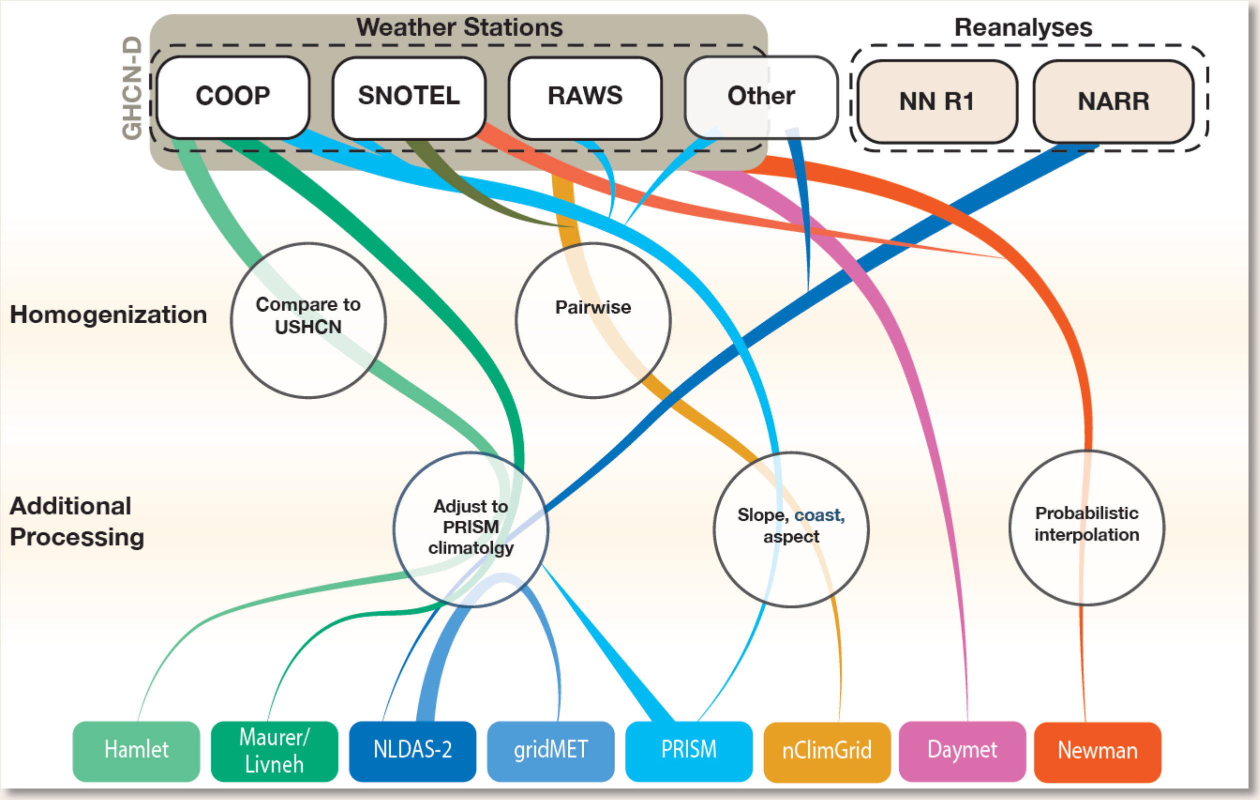


Figure 4.6
Flow diagram of the data sources and processes used to produce the high-resolution gridded precipitation products featured in this chapter. In addition to differences in choice of network, products may select different stations from the same network.

Common choices that must be made in developing a gridded data product include 1) which station network or networks to use, 2) which stations to use from those networks, 3) whether additional data from satellites, radar, or reanalysis is included, 4) what statistical method to use for interpolation, 5) how to account for changes in temperature and precipitation related to elevation, aspect, slope, or other aspects of the terrain, and 6) whether to apply any additional corrections, such as filling gaps in the data, accounting for undercatch, or homogenizing—correcting shifts in the measured climate that are due to changes in the station or the area around the station rather than to actual changes in regional climate.

These choices introduce some disagreement between different products, although there are clear similarities, as well. Figure 4.7 shows time series of average water year minimum and maximum temperature and total water-year precipitation averaged over the Upper Colorado Basin for several of the products listed in Tables 4.3 and 4.4.

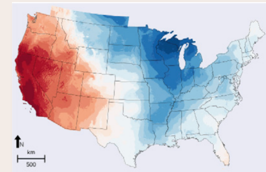
There are clearly strong correlations between the products. All of the datasets that provide precipitation data estimate that basin-wide average water-year precipitation is between 15.5” and 16” (1981–2010 average). They all show that water year 1997 was quite wet—estimates range between 21.0” and 22.1"—and that 2002 was dry—between 9.7” and 10.2”. Earlier in the record, however, there are much larger differences between precipitation estimates. For example, in 1927, the Livneh et al. (2013) data estimate 3.2” more precipitation over the Upper Colorado Basin than PRISM does. Likewise, all of the datasets indicate increasing temperatures since the 1970s. All indicate that 1934 and 2000 were particularly warm years and that the mid-1970s had relatively low minimum temperatures.

These plots also clearly demonstrate that both Livneh datasets estimate substantially cooler minimum temperatures than the other datasets, even though their estimates for maximum temperature are similar to the other data products. Early in the 20th century, the PRISM and nClimGrid data sets provide similar estimates of minimum temperature, but nClimGrid estimates cooler maximum temperatures.

Newman et al. (2019) outline a few common sources of differences between gridded datasets. Numerous other dataset comparison papers such as Behnke et al. (2016), Henn et al. (2018) Lundquist et al. (2015), and Walton and Hall (2018) also discuss the source of discrepancies between data products. One of these is the choice of which weather stations to use. Products that use more weather stations or a more spatially diverse set of weather stations are more likely to capture detailed spatial patterns in temperature and precipitation. Almost all of the products rely directly or indirectly on data from the COOP network, although they may not sample the same stations owing to differences in selection criteria. Exactly which stations are chosen in any area by any product may not be clear without in-depth inspection of the documentation or correspondence with the data developers. For more discussion on this, see Guentchev, Barsugli, and Eischeid (2010) and Newman et al. (2019).

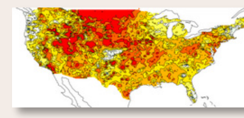
Other choices made in developing gridded datasets also clearly influence the outcome. Gridded datasets, like the Livneh data, that use a fixed lapse rate of -3.6°F/1000 feet (-6.5°C/km) tend to estimate colder temperatures, especially colder minimum temperatures and particularly during the winter when cold air pooling is common, than other products (Newman et al. 2015), as can be seen in Figure 4.7. Other choices probably also cause differences between different datasets, but it is not always possible to draw clear lines between those choices (e.g., statistical interpolation method) and the results (Newman et al. 2019). Products like that described in Newman et al. (2015) use “probabilistic interpolation” to account for uncertainty by producing multiple reasonable spatial patterns of temperature and precipitation for each time step.

TopoWx



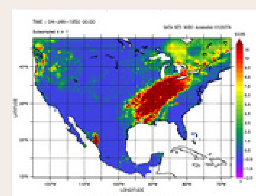
Link: http://www.scrimhub.org/resources/topowx/

Livneh 2013/Maurer 2002



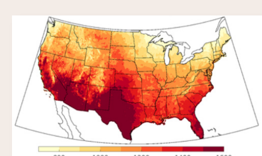
Link: https://www.esrl.noaa.gov/psd/data/gridded/data.livneh.html

Livneh 2015



Link: https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.nodc:0129374;view=html

gridMET



Link: http://www.climatologylab.org/gridmet.html

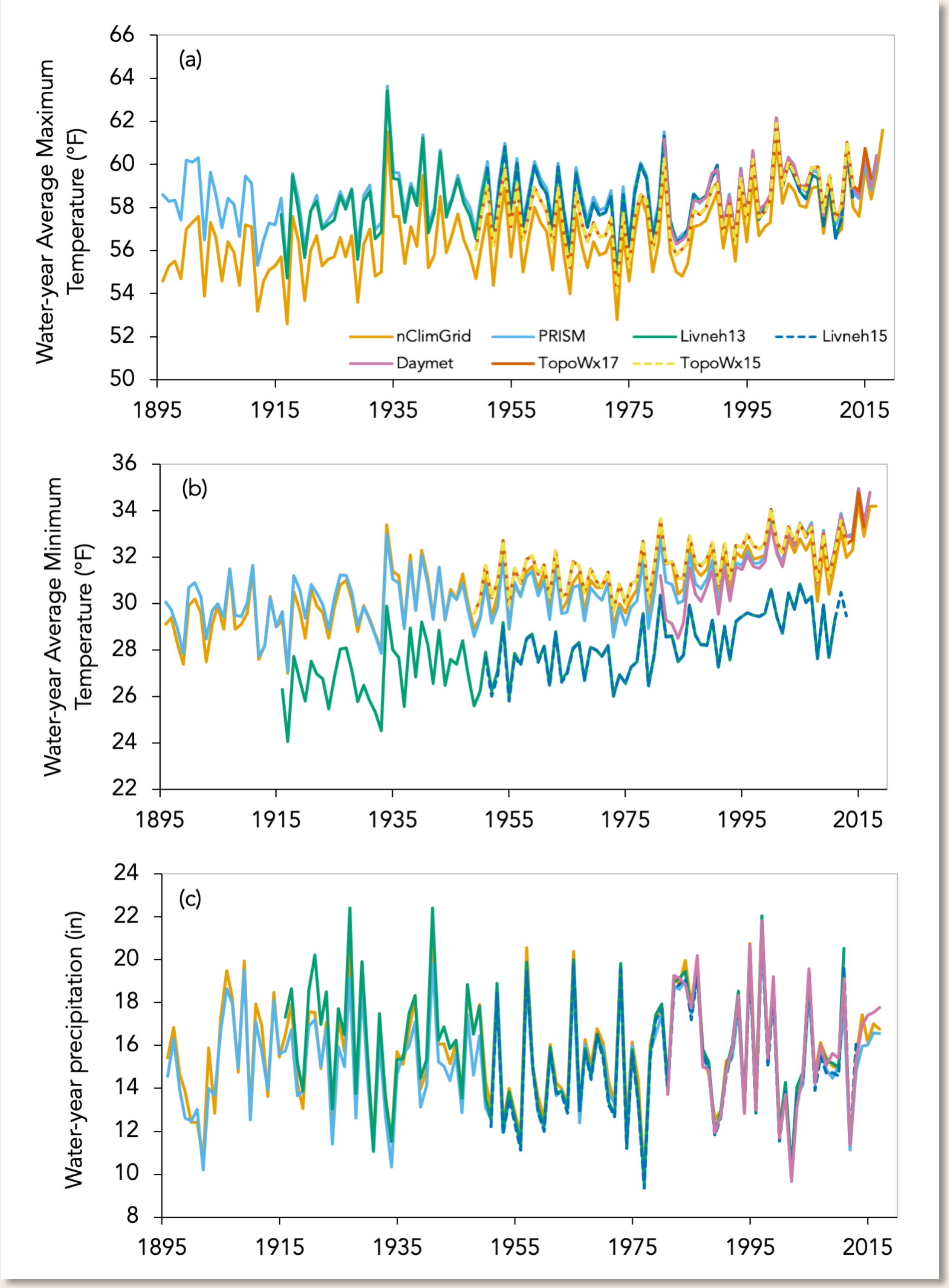


Figure 4.7
Time series of average water-year maximum (a) and minimum (b) temperature and water-year total precipitation (c) averaged over the Upper Colorado Basin. Note that Livneh15 provides monthly precipitation data as the average of the daily precipitation rate. Monthly totals were calculated by multiplying the daily rate by the number of the days in each month, ignoring February 29 in leap years.

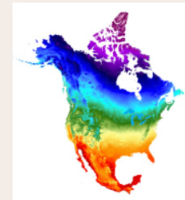
Tables 4.3 and 4.4 describe the characteristics of 11 statistically interpolated gridded products that are commonly used for hydrologic applications in the western U.S. Despite disagreeing in some ways, these gridded products are also not entirely independent. Because the number of weather stations is limited, particularly at higher elevations, most products share at least some base information. There can also be closer interrelationships between products. For example, the Livneh et al. (2013) product uses the Maurer et al. (2002) methodology and is, in fact, billed as an "update and extension" of the earlier effort.

Livneh et al. (2015) uses those same methods for temperature, with additional data from Mexico and southern Canada to produce a gridded product with coverage for all of North America south of 53°N. As a result, their estimates of water-year average temperature over the Upper Basin are nearly identical—the largest difference between the two is 0.24°F in minimum temperature, while differences in maximum temperature are even smaller. GridMET is made by taking the 1/8° (7.5-mi, 12-km) resolution North American Land Data Assimilation System (NLDAS-2) reanalysis and downscaling it to 2.5mi (4 km), using PRISM to guide the interpolation (Abatzoglou 2013). Thus, temporal variability in gridMET will track that in NLDAS-2, while its spatial patterns should be very similar, if not identical, to those in PRISM.

As noted above and shown in Figure 4.6, many products account for fine-scale spatial patterns in precipitation by adjusting their precipitation patterns to match those in PRISM. Among the eight products mapped in Figure 4.6, only Daymet and Newman do not use PRISM to adjust precipitation for elevation (TopoWx does not produce precipitation estimates). Henn et al. (2018) note that PRISM is used to adjust the spatial variability of precipitation in data produced by Livneh et al. (2013, 2015), Maurer et al. (2002), Hamlet and Lettenmaier (2005), Deems and Hamlet (2010), NLDAS-2 (Cosgrove 2003; Mitchell 2004; Xia et al. 2012), and the Climate Prediction Center (CPC) unified gage-based analysis of daily precipitation (Higgins et al. 2000). Interestingly, NLDAS-2 incorporates CPC precipitation early in product development (Cosgrove 2003; Mitchell 2004; Xia et al. 2012), so NLDAS-2 uses PRISM precipitation once indirectly and once directly. GridMET, which further downscales NLDAS-2 to PRISM, essentially uses PRISM to adjust precipitation three times (Abatzoglou 2013).

Fewer gridded products provide information on climate variables such as wind, humidity, and radiation. Wind is an essential variable in hydrology. It is critical for assessing snow redistribution (Liston and Elder 2006). It is also required to accurately estimate evapotranspiration. Hobbins et al. (2012) noted that winds are particularly important in driving evapotranspiration over parts of the Colorado River Basin during the spring

Daymet



Link:
https://daymet.ornl.gov

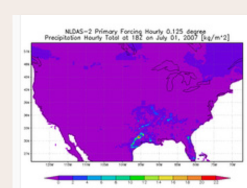
Newman

Link:
https://www.earthsystemgrid.org/dataset/gridded_precip_and_temp.html

NClimGrid

Link:
https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C00332

NLDAS-2



Link:
https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.nodc:0129374;view=html

and summer. Yet gridded wind variables are among the least certain and robust of all climate variables. Figure 4.8 shows the development pathways for wind in the datasets evaluated here. Essentially all wind variables in high-resolution data products are derived from the NCEP/NCAR Reanalysis (Kalnay et al. 1996; Maurer et al. 2002; Hamlet and Lettenmaier 2005; Deems and Hamlet 2010; Livneh et al. 2013; 2015) or from the North American Regional Reanalysis (Mesinger et al. 2006; Cosgrove 2003; Mitchell 2004; Xia et al. 2012; Abatzoglou 2013). Because there are few, if any, higher resolution wind products to correct against, most high-resolution wind estimates do not actually contain any high-resolution patterns in wind. They simply reproduce the coarse winds in smaller grid boxes.

Dataset developers encounter similar problems in constructing high-resolution fields of radiation and humidity (Figure 4.9). The gridMET dataset interpolates NLDAS-2 humidity and radiation outputs without any additional adjustment (Abatzoglou 2013). The Daymet, Maurer, and Livneh datasets all use some formulation of the MTCLIM algorithm (Thornton, Running, and White 1997; Thornton and Running 1999; Thornton, Hasenauer, and White 2000) to estimate humidity and radiation from temperature. PRISM provides humidity estimates (dewpoint temperature and vapor pressure deficit), but not radiation, calculated from station-measured relative humidity and air temperature (Daly, Smith, and Olson 2015).

CBRFC use of weather observations and gridded data

As described in Chapters 5, 6 and 8, the Colorado Basin River Forecast Center (CBRFC) forecast model system requires values for temperature and precipitation that are area-averaged for each forecast zone (an elevation band within a catchment) represented in the model. The CBRFC generates these mean areal temperature (MAT) and precipitation (MAP) values for each forecast zone in real-time to drive the daily production of seasonal water supply forecasts and the daily (sometimes sub-daily) production of short-range (1-10 days) streamflow forecasts. The CBRFC has also generated them retrospectively, to create a historical dataset (1981-2015) that is used for forecast model calibration and verification. In both cases, the precipitation values are much more important to the forecast outcomes than the temperature values, and thus greater attention is given to the precipitation input data. The approach used to generate the MAT and MAP values has some commonalities with the gridded products described above, although the final real-time inputs (meteorological forcings) used to drive the CBRFC forecast models are spatially "lumped" and not on a uniform grid like the gridded products described above. The CBRFC endeavors to make the real-time data and the historical calibration data as similar as possible, so that the forecast model is trained on data that is comparable to, if not identical to, what it sees in real-time.

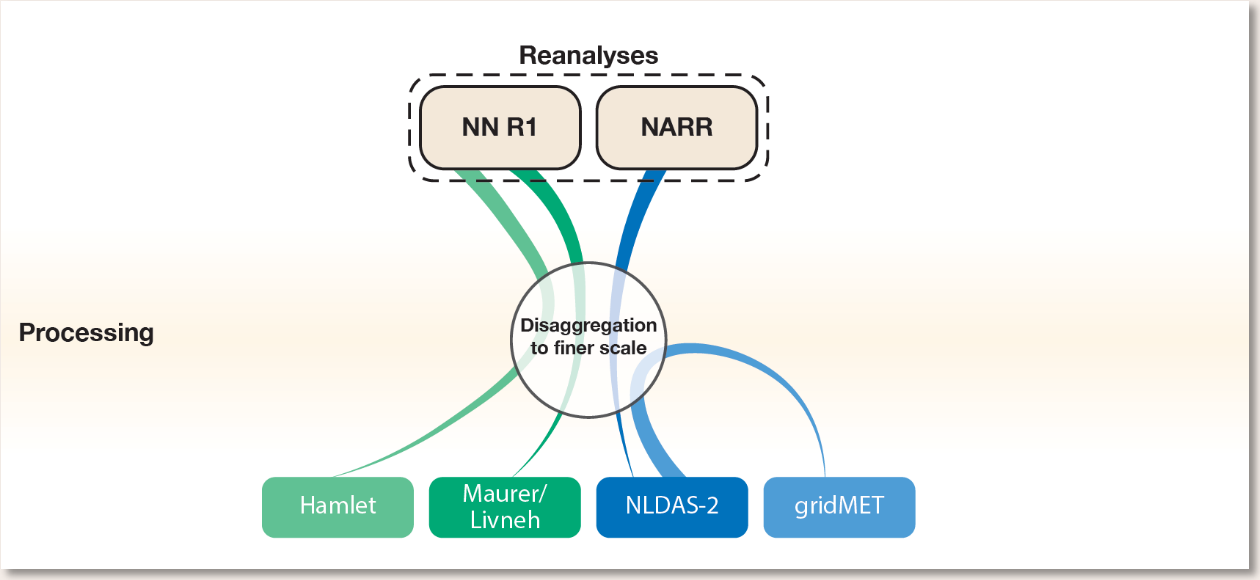


Figure 4.8
Flow diagram of the data sources and processes used to produce the high-resolution gridded wind products featured here.

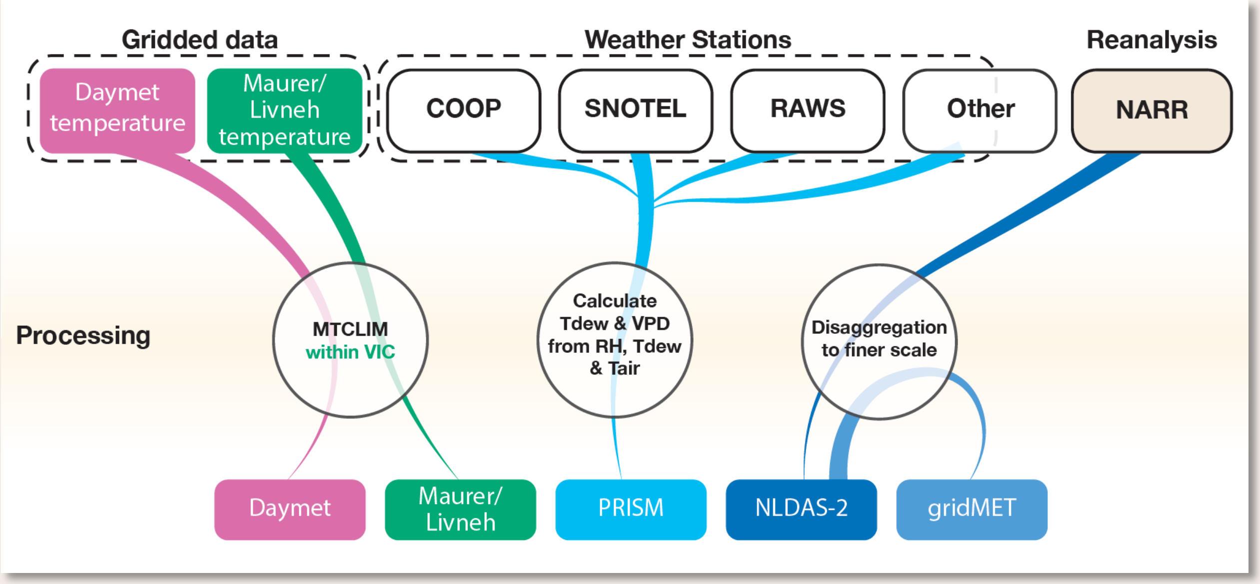


Figure 4.9
Flow diagram of the data sources and processes used to produce the high-resolution gridded humidity products featured here.

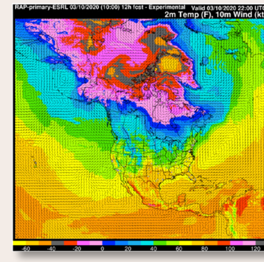
For the Upper Basin watersheds, which are generally snowmelt-dominated, real-time temperature and precipitation observations—the vast majority from SNOTEL stations—are used to directly produce the areal averages for forecast zones using station weightings determined through model calibration. The stations that are used have been pre-screened and vetted during the calibration process. Automated procedures identify potentially erroneous station values, which can be then manually corrected by forecasters. Freezing-level data from Rapid Refresh, NOAA's hourly operational weather reanalysis, is used to run the SNOW-17 model which types the precipitation as rain or snow. The data used for real-time operations and for calibration are very similar, with the calibration data having undergone additional quality control procedures.

For the Lower Basin watersheds, which are generally rainfall-dominated and respond more quickly to precipitation events, a denser station coverage is employed, with temperature and precipitation observations from multiple station networks, and then augmented by radar-based precipitation estimates to generate the real-time data. The radar data is most useful during the warm season when there is a larger radius of accurate information from the radar, due to reflection differences between rain and snow. The observations from all available stations are used, with no prior screening of stations, to create the highest possible station density. But the station temperature and precipitation values themselves are quality-controlled as in the Upper Basin. As in the Upper Basin, freezing-level data and SNOW-17 are used to type the precipitation into rain and snow. The real-time precipitation observations and radar precipitation estimates are transferred to a 4-km grid using an interpolation algorithm in the Multi-sensor Precipitation Estimate (MPE) software, the temperature observations are likewise transferred to a 4-km grid, and the grid cells within each forecast zone are then averaged to create the MAT and MAP data.

The historical calibration data for the Lower Basin are generated in a similar manner as the real-time data, except only the station precipitation data are used—not radar-based estimates—and a different algorithm and a finer grid (800-m) are used for the intermediate gridding step. The CBRFC has also generated a matching 800-m gridded historical dataset for the Upper Basin, but it is not used for operations or calibration at this time. Both of these intermediate 800-m gridded datasets can be made available to researchers.

In some respects, the real-time and historical meteorological forcings for the Colorado River Basin used by CBRFC can be considered to be of higher quality for hydrological modeling than many of the gridded datasets described earlier, since they are produced at higher resolution (at least during intermediate steps), use a greater number of stations, and use more rigorous quality control.

Rapid Refresh



Link: https://rapidrefresh.noaa.gov/

The CBRFC recently worked with Utah State University to evaluate a physically based snow model that uses an energy balance to estimate snowpack processes, rather than just temperature and precipitation. Adoption of the potentially more accurate snow model, however, would require additional observational data that better characterized, at a minimum, surface radiation balance (P. Miller, pers. comm.). Due to the increased complexity of the energy balance model, real-time data may not be available for use within an operational framework. Increased model complexity may not necessarily yield more accurate results; for example, while radiation data are collected by a number of weather station networks focused on agricultural and water resource monitoring (Slater 2016), all but one of the gridded meteorological datasets discussed above that provide information on the surface radiation balance provide simulated—not observed—radiation fluxes (NLDAS-2 uses remotely sensed insolation).

4.4 Strengths and weaknesses of gridded data products

All gridded products that incorporate station data are likely to share common strengths and weaknesses related to those data. For example, any product that incorporates gage-measured precipitation—as do all of the datasets evaluated here—will display precipitation amounts that reflect undercatch (see Section 14.2) and therefore underestimate precipitation, particularly precipitation that falls as snow, unless some correction is applied, as in Newman et al. (2015). Because different areas may experience higher winds, receive a greater fraction of precipitation as snow, or use predominantly different styles of precipitation gage, the influence of undercatch may vary spatially.

The sparseness of observational data at high elevations—particularly prior to the late 1970s/early 1980s initiation of the SNOTEL and RAWS networks (Zachariassen et al. 2003; Schaefer and Paetzold 2001)—is another common weakness across all gridded data products. When and where the station network is sparse, there is greater opportunity for gridded datasets to differ as a result of other choices made in their development (e.g., lapse rate adjustment, interpolation method, etc.) (Walton and Hall 2018). Over the upper Colorado River Basin, this tends to lead to greater disagreement among datasets prior to the late 1970s and especially before the 1950s when there were generally fewer stations than in more recent decades (see Figure 4.7). There are also larger disagreements in areas with fewer weather stations, such as at higher elevations. For example, Henn et al. (2018) show greater absolute and relative differences between precipitation datasets at higher elevations in the Rocky Mountains. Figures in McAfee et al. (2019) suggest somewhat greater differences between datasets in temperature trends at higher elevations than trends at lower elevations, although there is some variability by month. However, the same paucity of high-elevation stations, and particularly high-elevation stations with long records, means that there is very limited ability to evaluate gridded products or weather simulations against independent observations. This is especially problematic in the context of water resources, as the alpine regions are critical water supply areas within the Colorado River Basin (see Chapter 2).

As discussed above, choices about dataset construction are typically made so that the resulting data products are most appropriate for their intended purpose. As a result, different gridded data products have distinct characteristics. For example, TopoWx fills gaps and homogenizes data prior to gridding; as a result, temperature trends in TopoWx appear to be less variable in space than temperature trends in other products (see Figure 3 in Oyler et al. 2015). Because of limited station observations, it is difficult to determine whether spatially smooth gradients of trend or more spatially complex distributions of trend reflecting local variability in the sign and magnitude of trend represent actual changes. In the San Juan Mountains, temperature trends between 1990 and 2005 were similar at COOP and SNOTEL stations, despite the fact that the SNOTEL stations were, on average, located about 2580 feet higher in elevation than the COOP stations (Rangwala and Miller 2010), suggesting that trends may be more spatially consistent at least in some parts of the western U.S. While some data characteristics may seem consistent with the choices made in their construction or with known characteristics of the underlying station network or networks used, a new analysis and review by Newman, Clark, Longman, et al. (2019) highlights the fact that not all discrepancies between datasets are predictable based on their compilation. Some strengths and weaknesses of the datasets described in Tables 4.3 and 4.4 are listed in Table 4.5.

Table 4.5

Strengths and weaknesses associated with each of the gridded products described in Tables 4.3 and 4.4

Product Name	Strengths	Weaknesses
PRISM AN81d	Very high resolution (~0.5 mi, 800 m) daily product. Ability to capture cold-air pooling in many environments. Data available to near present (lag typically around 6 months).	Free daily product only available back to 1981.
PRISM AN81m and LT81m	Record extends back to 1895. Ability to capture cold-air pooling in many environments. Responsive to coastal, aspect, slope influence. Long history of use and well-known caveats. Data available to near present (lag typically around 6 months).	Temporally changing station network. There can be slight differences in values and spatial patterns with updates. More temporally stable data (LT81m) are not free.

Product Name	Strengths	Weaknesses
TopoWx	Very high spatial resolution (~0.5 mi, 800 m) daily data back to 1948. Homogenization and gap filling make data product potentially suitable for trend analysis. Incorporation of satellite data provides additional insight to spatial temperature patterns.	Only temperature is available. Homogenization could mask real spatial diversity in trends. There can be slight differences in values and spatial patterns with updates.
Livneh 2013/ Maurer 2002	Daily data available back to 1915 (1950 for Maurer). Internally consistent hydrometeorological variables simulated by VIC are provided.	Lapse rates may be too steep and temporally stable. It is unclear whether cold-air pooling can be evaluated—it may be possible in areas with particularly dense station coverage. There do not appear to be plans to update data past 2011. Precipitation is adjusted to PRISM, so spatial pattern will be similar to PRISM.
Livneh 2015	Daily data with coverage over Mexico and parts of Canada back to 1950. Internally consistent hydrometeorological variables are provided.	Lapse rates may be too steep. It is unclear whether or not cold-air pooling can be evaluated—it may be possible in areas with particularly dense station coverage. There do not appear to be plans to update data past 2013. Precipitation is adjusted to PRISM, so spatial pattern will be similar to PRISM.
gridMET	High-resolution (2.5 mi, 4 km) daily data with multiple variables suitable for ecological and fire weather modeling. Data are available in very near real time, but the last few days to weeks are based on the Climate Forecast System, rather than NLDAS-2.	Data are only available back to 1979. Variables other than temperature and precipitation are interpolated to 2.5mi (4 km), but are not adjusted for physiography at that scale, so variables may not be physically consistent. Precipitation and temperature are adjusted to PRISM, so spatial patterns will be similar to PRISM.
Hamlet 2005	Long-term temperature and precipitation trends are adjusted to match USHCN, so may be suitable for trend analysis. Daily data back to 1915.	Data are only available through 2003 and not specifically updated. Lapse rates may be too steep and static owing to fixed lapse rate. Precipitation is adjusted to PRISM, so spatial pattern will be similar to PRISM.
Hamlet 2010	Long-term temperature and precipitation trends are adjusted to match USHCN, so may be suitable for trend analysis. Daily data back to 1915.	Data are only available through 2010 and do not appear to be updated. Precipitation and temperature are

Product Name	Strengths	Weaknesses
		adjusted to PRISM, so spatial patterns will be similar to PRISM.
Daymet v. 3	Very high (~0.6 mi, 1 km) resolution daily data, with multiple variables suitable for ecological modeling. Data are updated frequently so data are available for very near present. Files of input station data for each grid cell are provided, so users can accurately identify stations used. Coverage for all of N. America	Data are only available back to 1980. Interpolation methods may not be able to capture very fine scale variability in precipitation.
Newman gridded ensembles	These provide multiple estimates of daily temperature and precipitation for each day for uncertainty quantification and can be used to explicitly predict the probability of precipitation occurrence.	The spatial resolution is relatively coarse. Data are only available through 2012 and update potential/schedule are unclear. Intended use requires a large amount of data.
nClimGrid (gridded data underlying the climate division data nClimDiv)	Monthly data are available back to 1895. Data are homogenized so may be suitable for trend analysis. Data are updated frequently. Spatio-temporal summaries, ranking, etc., are readily available through Climate at a Glance.	This is a relatively new product; caveats associated with the data are not yet well defined.
NLDAS-2	Sub-daily records for a full suite of meteorological variables are available. Data are available for close to present.	The spatial resolution is relatively coarse. Data are interpolated reanalysis, which are relatively prone to error. Behnke et al. (2016) note NLDAS-2 has some of the highest errors relative to station observations.

For users with particular needs, there may be relatively little choice in which data product to use. Applications that require spatially continuous hourly data are limited to NLDAS-2 of the datasets evaluated here. In other cases, there may appear to be greater choice, but apparently different products may be very similar. Only the Maurer et al. (2002), Livneh et al. (2013 and 2015), Hamlet and Lettenmaier (2005), and Deems and Hamlet (2010) products provide daily precipitation data that extend back prior to the early 1980s or late 1970s. These five products differ very little from each other in underlying data or construction methodology. All are based exclusively on COOP data in the U.S., although there are some differences in which specific stations were used (Hamlet and Lettenmaier 2005). All except Hamlet 2010 (Deems and Hamlet 2010) use pre-defined temperature lapse rates (-3.6°F/1000 feet [-6.5°C/km] or -3.3°F/1000 feet [-6.1°C/km]) that are, at least for minimum temperature, steeper over the Upper Basin than observed in other data products (McAfee et al. 2019; Newman et al. 2015). Hamlet (2010) scales temperature to the PRISM climatology (Deems and Hamlet 2010). All of the products adjust precipitation patterns to the PRISM climatology, although they use different normal periods. All employ the same SYMAP interpolation. The primary differences between these products are that 1) they are supplied over different time periods and domains at different spatial resolutions, 2) the Hamlet (2005 and 2010) method homogenizes station data prior to interpolation, which the Maurer and Livneh methods do not (Maurer et al. 2002; Livneh et al. 2013; 2015; Hamlet and Lettenmaier 2005; Deems and Hamlet 2010), and 3) they adjust their precipitation to different PRISM precipitation climatologies—1961–1990 for most vs. 1981–2010 for Livneh et al. (2015)—that display slightly different spatial patterns in precipitation.

4.5 Considerations in the analysis of gridded data products

Many of the characteristics of station and gridded data products discussed above imply certain limitations in their analysis. As noted by Newman et al. (2019), choices about which data to include, and particularly the density of input data, can have a significant influence on the effective resolution of the data. For example, a nominally high-resolution product based on a small number of stations may not be able to accurately reflect fine-scale spatial patterns, especially in complex terrain, such as in the Colorado River Basin. Users should also be aware that gridded products do not reflect variability that occurs at finer scales than their nominal resolution. For example, a product with 2.5 x 2.5 mi resolution will reflect the average temperature over 6.25 square miles, but local temperatures may vary substantially within that area. Likewise, a daily precipitation total does not imply information about when during the day precipitation fell or how heavy it was. A final consideration most pertinent to daily data is that different stations may use different start and end times for their day (e.g., 9:00 a.m. vs. local midnight vs. 0:00 UTC), and those may change over time, so a given day may not cover the exact same period of time (see (Menne et al. 2012; Leeper, Rennie, and Palecki 2015).

Intercomparison

The first consideration is related to dataset intercomparison. Because different datasets are developed using different methods, disagreement in poorly observed areas may be expected (Walton and Hall 2018). Shared underlying station data can and should lead to agreement in areas where the station network is densest, so agreement between datasets in those areas or between specific grid cells and stations in those grid cells that contribute to the gridded product may not be effective measures of similarity or quality (Daly 2006). For example, Behnke et al. (2016) find the Livneh et al. (2013) and Maurer et al. (2002) datasets, which use only COOP stations, to have relatively small biases in mean precipitation and maximum temperature, but they compare the gridded dataset to a set of weather stations that is likely dominated by COOP stations because of the chosen time period (1981–2010) and data completeness criteria. Station siting may also influence the representativeness of gridded products. Physiographic features that are not well sampled in the observational network may not be accurately portrayed in even the most complex and highest resolution gridded products. For example, Strachan and Daly (2017) found that systematic undersampling of mid-slope locations in the Great Basin drove biases in the representation of temperature patterns in PRISM, even at very high spatial resolutions. Gutmann et al. (2012) found that leeside precipitation amounts were overestimated in PRISM in parts of southwestern Colorado where there were few weather stations on leeward slopes.

It is also important to be aware of interdependence between datasets beyond shared underlying data, so that agreement between those products is not over-interpreted in terms of confidence. Adjusting precipitation patterns in gridded datasets to match the PRISM climatology is very common, as is application of a pre-determined static lapse rate for both minimum and maximum temperatures (Figure 4.5). Even homogenization practices are very similar. TopoWx (Oyler, Ballantyne, et al. 2015) and nClimGrid (Vose et al. 2014) both use the pairwise comparison method described in Menne and Williams (2009), and Hamlet homogenizes station data to USHCN records, which are homogenized using the Menne and Williams (2009) pairwise method.

Analysis of trends

The second major consideration is related to the analysis of trends. Ideally, trend analysis should only be performed on data that are known to be free from inhomogeneities. As a result, many producers of gridded data caution against the use of their data for trend analysis. Redundancy in the input data might make it less likely that gridded data will display inhomogeneities particular to an individual station—for example, due to a station move (Groisman and Easterling 1994). In areas with few stations, however, inhomogeneities in individual stations, or the loss of an individual station, may be reflected in gridded products (McAfee, Guentchev, and Eischeid 2014). Inhomogeneities that impact an entire station network are often reflected in gridded data (Groisman and Easterling 1994; Oyler, Dobrowski, et al. 2015). Adding data from new station networks preferentially located in different kinds of locations or using different instrumentation than existing stations can also induce inhomogeneities in gridded data (McAfee et al. 2019) even when steps have been taken to mitigate the impact. Known network-wide or common spatially extensive causes of inhomogeneity in the region include changes in the time of observation (Karl et al. 1986) and instrumentation (Quayle et al. 1991) at COOP sites, urbanization (Karl, Diaz, and Kukla 1988; Hausfather et al. 2013), changes in instrumentation at SNOTEL sites (Oyler, Ballantyne, et al. 2015), and introduction of new station networks (McAfee et al. 2019). Even the PRISM LT81m dataset, which includes only longer-duration station networks, is not recommended for trend analysis (PRISM 2016). Of the data products evaluated here, only nClimGrid, TopoWx, and the Hamlet products are homogenized in a way that may make them suitable for trend analysis (Oyler, Ballantyne, et al. 2015; Oyler et al. 2016; Hamlet and Lettenmaier 2005; Deems and Hamlet 2010; Vose et al. 2014; Walton and Hall 2018). Gap-filling and homogenization, however, could mask real spatial variability in trends, so homogenized data may be more appropriate for characterizing regional trends than highly local ones. The effects of homogenization can be seen in the precipitation trend maps shown in Henn et al. (2018) Figure 7. The trend patterns in the homogenized Hamlet et al. 2010 data (Deems and Hamlet 2010) are spatially smoother than in the other products evaluated. The trend maps shown in Henn et al. (2018) also demonstrate that while major features of the 1982-2006 trend patterns are replicated—reductions in precipitation over the Lower Colorado Basin and increasing precipitation over California—there are localized differences in trend patterns and magnitudes over parts of the Upper Colorado Basin.

Because of the complex ways in which choices about data selection, adjustment, and interpolation combine (Newman et al. 2019), it may be impossible to know whether gridded data contain detectable inhomogeneities without thorough statistical investigation. Guentchev, Barsugli, and Eischeid (2010) analyzed precipitation from the Maurer, BL (which is similar in construction to the Maurer data, but uses different stations and is not described Table 4.4), and PRISM datasets over the full Colorado River Basin for the second half of the 20th century. PRISM had the highest percent of grid cells without detectable inhomogeneities (88%), followed by Maurer (83%) and BL (77%). While all of the datasets were generally free of inhomogeneities, the inhomogeneities that exist were in the same places in all datasets. They tended to be clustered in specific, largely high-elevation sub-basins in the Lower Basin: the Little Colorado, the Lower Colorado-Lake Mead, and the Upper Gila. Repeating this type of analysis for the increased selection of temperature and precipitation data that are available now, as well as for specific time periods, would be beneficial and would help researchers in the region identify datasets that might be suitable for climate trend analysis or for use in hydrologic models whose output will be analyzed for long-term variability.

4.6 Considerations in gridded data product selection

The single most important thing to know about selecting a gridded data product is that there is no perfect product—if there were perfect observations for every point, there would still be "errors" in all of the gridded products. For example, Gutmann et al. (2012) note that gridded precipitation from the Weather Research and Forecasting Model (WRF) and the 1971–2000 PRISM climatology predict different amounts of precipitation spillover from the windward to leeward side in parts of the San Juan Mountains. This is an area that did not have good leeside station coverage until recently; data from one station installed in late 2008 suggest that WRF was providing more accurate precipitation totals. Nor is there a best product, although there might be a best choice for certain applications. Data selection is necessarily based on both practical and scientific considerations. Many of the considerations that go into choosing a historical gridded climate data product are similar to those that might be used in climate change evaluation. In-depth discussion of the topic is provided by Vano et al. (2018) and Daly (2006), but some practical and scientific guidance for data selection is briefly outlined here.

Practical considerations

From a practical standpoint, a user might reasonably consider eight criteria about data products in choosing which to use. Many of the practical considerations are easily assessed with basic product metadata.

1. Does the data product supply the weather or climate variables necessary for the application? Some analyses or modeling efforts may require a single variable, while others might require a much more extensive suite of variables. It is often easier to use multiple variables from a single gridded product because they are likely to be provided on the same grid, minimizing geospatial processing.

2. Does the data product provide data with the appropriate temporal coverage? Specific considerations related to temporal coverage include the length of the dataset, how frequently it is updated, and latency—the lag in data availability relative to real-time. There may also be concerns related to how new data are released. Some data products, such as TopoWx, may release updates with new versions of historical data and, thus, may not be directly comparable to previous versions (although the two versions of TopoWx shown here are essentially identical over the Upper Basin). In this case, updating the data product may require downloading an entirely new database for the full period. Others, such as gridMET, simply extend the length of the data product during most updates.

3. Does the data product provide data at the appropriate temporal frequency? Monthly data are somewhat more widely available than daily

data, which are, in turn, much more common than sub-daily data—at least at high spatial resolution.

4. Does the data product cover the necessary spatial domain? For applications entirely within the Colorado River Basin, this is not often of concern. Most products provide reasonable coverage over the contiguous United States. However, applications that include transnational river basins (e.g., Rio Grande, Columbia), may require data to be consistent across national boundaries, and such data products are less common.

5. Is the data product at the appropriate spatial resolution? Questions about spatial resolution may be practical—a model operates at X mi^2 resolution and requires input data at that resolution—or scientific—the process in question occurs at Y mi^2 scale and cannot be detected in coarser data. Conversely, the spatial resolution of a data product will also influence computational time and storage demands, so data that are too finely scaled may be inconvenient.

6. What resources are required to use the data? Although many data products are served free of cost, some data (e.g., PRISM LT81m) are only available for purchase. The decision to use a product that is not free would be contingent on funding and potentially on the user's ability to justify the cost to a funder. Resource issues related to file conversion—for example, from GRIB to GeoTiff for model compatibility—data storage or other processing steps could also influence the choice of dataset.

7. Is it necessary to assess uncertainty, use multiple scenarios, or identify a single type of scenario? Only the Newman et al. 2015 dataset is explicitly designed to provide uncertainty quantification. However, it may be possible to include multiple datasets with input data and development techniques that are as different as possible. Related considerations may include whether specific datasets seem to routinely provide "best case" (e.g., robust average flows, modest flood peaks), middle-of-the-road, or "worst case" (e.g., lower total flow, high flood peaks) outcomes and which of those is most appropriate for the decision at hand.

8. Are there any other practical considerations? There may be questions about whether a model being used has been parameterized with a specific climate dataset and whether there are consistency issues that need to be considered—for example, a desire to compare results from a new study with a previous one that would be simplified by using the same climate data.

Scientific considerations

There are also scientific considerations related to dataset choice. Unlike the practical decisions, however, consideration of the scientific characteristics of data typically require a more in-depth knowledge of the data product. Daly (2006) provides a discussion around dataset choice in relation to physiographic features, along with background information on how common interpolation techniques handle physiography. Scientific considerations may apply particularly in post-hoc analysis of the results, in assessing the confidence and uncertainty around certain statements, as well as in gauging how widely the results could be applied to other regions, systems, or time periods.

1. Is the effective resolution of the grid cell consistent with its nominal or apparent resolution? As computational capacity has improved, it has become possible to interpolate climate data to a very fine apparent resolution, even though little to no new information has been incorporated. For example, gridded data with a nominally high spatial resolution that rely on a low-density station network may have a lower effective than apparent resolution (Newman et al. 2019). The gridMET process adds additional climate-relevant information to NLDAS-2-derived temperature, precipitation, and humidity, but simply interpolates winds and radiation, so the effective resolution of gridMET wind and radiation are the NLDAS-2 resolution, not their nominal ~2.5-mi resolution (Abatzoglou 2013).

2. Do data need to be internally physically consistent? In some cases, detailed process modeling may require suites of variables that are physically consistent. For example, some applications need data that can accurately reflect a drop in temperatures caused by evaporation or melting of precipitation in order to better forecast precipitation amount, intensity, and whether it will fall as rain, snow, or freezing precipitation (e.g., Barros and Lettenmaier 1994; Kain, Goss, and Baldwin 2000). The ARkStorm@Tahoe project—which simulated snowfall and flooding caused by a single significant storm event to evaluate environmental and socio-economic impacts and real-time response mechanisms—required such a complex data set in order to develop realistic and accurate timelines and spatial maps of flooding and related hazards in a topographically complex region (Albano et al. 2016). Producing such data typically requires dynamical generation or downscaling (e.g., Gutmann et al. 2012). Most observationally based gridded data products probably cannot provide this level of internal consistency, but it is also not clear how many applications would require this.

3. How might known data characteristics influence an application? Data intercomparisons, such as (Behnke et al. 2016; Henn et al. 2018; Walton

and Hall 2018) and many others evaluate whether certain datasets are relatively cool or warm, or wet or dry in certain locations, and data documentation often highlights known errors, strengths and weaknesses in data products. However, it can be difficult to determine which data are most correct, either because station data are lacking, and there is no real ground-truth, or because the available station data were used to produce the gridded data and do not provide an independent check (Daly 2006). More detailed studies might be required to understand which datasets are more accurate and why. There is also the question of how much errors or biases impact any given application. For example, Strachan and Daly (2017) found that cool biases in PRISM, related to the siting of available input stations, impacted growing-degree day calculations more than they influenced assessment of the length of the frost-free season or temperature-based estimates of the percent of precipitation falling as snow. In that case, users analyzing growing degree days might be particularly cautious about their subsequent interpretations and conclusions.

4. Is it appropriate to use records with particular types of inhomogeneities? Data containing inhomogeneities that impact only how climate is recorded (e.g., inhomogeneities related to changes in instrumentation) are likely to be problematic in many applications and can lead to misleading conclusions (e.g., Oyler, Dobrowski, et al. 2015). But inhomogeneities related to land cover change, such as urbanization, (Karl, Diaz, and Kukla 1988) may be valuable components of data for some applications. Identifying and correctly quantifying trends related to large-scale forcing, such as global warming, requires removing both sudden and “creeping” inhomogeneities (Menne and Williams 2009). Understanding local-scale changes in evaporative demand, however, might require climate records that reflect the sum of all changes, including any local warming related to land-cover change due to urbanization, conversion to agriculture, etc. In such cases, homogenized data may, in fact, be inappropriate.

In sum, both practical and scientific considerations should influence users’ choices about which data product to use. The effect that those choices might have on subsequent analyses is often not well characterized. There are a number of open questions about weather and climate in complex topography, how weather and climate variability across large basins influences hydrology, and about how best to use imperfect gridded climate data to better understand natural and managed hydrologic systems. Research efforts to address these questions are on-going. For the time being, users of these products should attempt to assess basic information about the gridded or station data they use and consider how the characteristics of those data might influence their analysis.

4.7 Challenges and opportunities

Challenge

While commonly used gridded climate datasets show very similar variability and trends in precipitation and temperature for the basin, disagreements between the datasets are larger for the sparsely instrumented high-elevation areas in the Upper Basin—the areas that generate the vast majority of the basin's runoff.

Opportunities

- Use other types of measurements, such as streamflow and radar, to constrain the gridded estimates of temperature and precipitation, and add novel observation techniques (e.g., Airborne Snow Observatory; see Chapter 5) to bolster ongoing observations.
- Use numerical weather prediction models (Chapter 7) for spatiotemporal interpolation and validation of observation-based products.

Challenge

It is increasingly understood that the gridded climate datasets have inherent uncertainties and differ from each other, but how those uncertainties and differences manifest in the outputs of typical hydroclimate modeling and analysis tasks needs to be better explored and communicated to users.

Opportunities

- Conduct formal intercomparisons between gridded datasets in the context of specific applications and outputs (e.g., Alder and Hostetler 2019 on the use of different gridded climate datasets for statistical downscaling of GCM data; Chapter 11).
- Application projects can consider including a testing phase in which multiple gridded datasets are tested on a limited portion of the project's domain or analyses.
- Both researchers and users can acknowledge that all data are imperfect, and move away from trying to identify a single "best" product toward greater consideration of the data characteristics that are, and are not, important for their questions and analyses.

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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.

R^2
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


WESTERN WATER ASSESSMENT
A NOAA RISA TEAM
CIRES
University of Colorado Boulder