Climate Change in Colorado

A Synthesis to Support Water Resources Management and Adaptation






A Report for the Colorado Water Conservation Board

Western Water Assessment
CIRES
University of Colorado Boulder
COLORADO
Colorado Water Conservation Board
Department of Natural Resources

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Western Water Assessment, Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado Boulder

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Western Water Assessment

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Executive Summary

This report is a synthesis of climate science relevant for management and planning for Colorado's water resources. It focuses on observed climate trends, climate modeling, and projections of temperature, precipitation, snowpack, and streamflow. Climate projections are reported for the mid-21st century because this time frame is the focus of adaptation strategies being developed by the State of Colorado and other water entities.

Overview

In the past 30 years, Colorado's climate has become substantially warmer. The recent warming trend in Colorado is in step with regional and global warming that has been linked to increasing atmospheric concentrations of greenhouse gases. Annual precipitation, which has high natural variability, has not seen a statewide trend over that period. However, some drought indicators have worsened due to the warmer temperatures.

As greenhouse gases and other human effects on the climate continue to increase, Colorado is expected to warm even more by the mid-21st century, pushing temperatures outside of the range of the past century. The outlook for future precipitation in Colorado is less clear; overall increases or decreases are possible. The risk of decreasing precipitation appears to be higher for the southern parts of the state.

The future warming is projected to generally reduce Colorado's spring snowpack, cause earlier snowmelt and runoff, and increase the water use by crops, landscaping, and natural vegetation. While future increases in annual natural streamflow are possible, the body of published research indicates a greater risk of decreasing streamflow, particularly in the southern half of the state.

Summit Lake Park, along Mount Evans Scenic Byway.
Photo: Creative Commons, Matt Wright.

Observed climate trends in Colorado (Section 2)

- Statewide annual average temperatures have increased by 2.0°F over the past 30 years and 2.5°F over the past 50 years (Figure ES-1). Warming trends have been observed over these periods in most parts of the state.

- Daily minimum temperatures in Colorado have warmed more than daily maximum temperatures during the past 30 years. Temperatures have increased in all seasons.

- No long-term trends in average annual precipitation have been detected across Colorado, even considering the relatively dry period since 2000.

- Snowpack, as measured by April 1 snow-water equivalent (SWE), has been mainly below-average since 2000 in all of Colorado's river basins, but no long-term (30-year, 50-year) declining trends have been detected.

- The timing of snowmelt and peak runoff has shifted earlier in the spring by 1–4 weeks across Colorado's river basins over the past 30 years, due to the combination of lower SWE since 2000, the warming trend in spring temperatures, and enhanced solar absorption from dust-on-snow.

- The Palmer Drought Severity Index (PDSI) shows a trend towards more severe soil-moisture drought conditions in Colorado over the past 30 years, reflecting the combination of the below-average precipitation since 2000 and the warming trend.

- No long-term statewide trends in heavy precipitation events have been detected. The evidence suggests that there has been no statewide trend in the magnitude of flood events in Colorado.

- Tree-ring records and other paleoclimate indicators

FIGURE ES-1. Colorado statewide annual temperature, 1900–2012

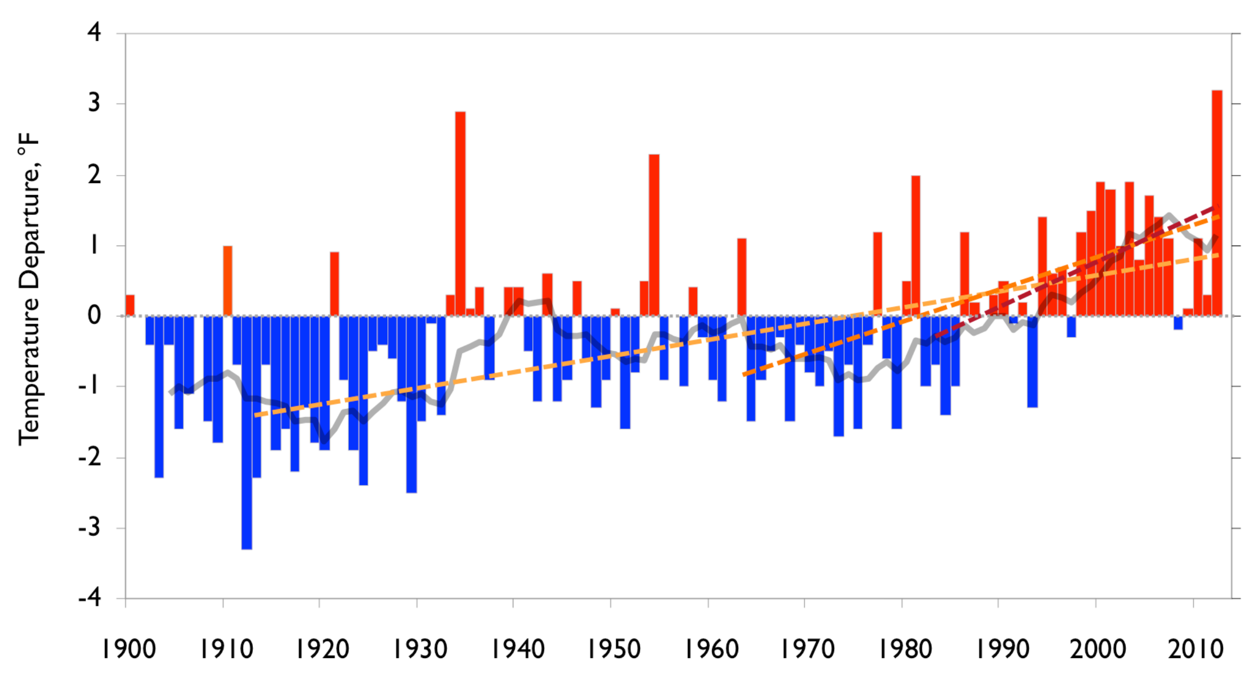

Fig. ES-1. Colorado statewide annually-averaged temperature (°F), 1900–2012. Annual departures are shown relative to a 1971–2000 reference period. The light-orange, orange, and red lines are the 100-year, 50-year, and 30-year trends, respectively. All three warming trends are statistically significant. The gray line shows the 10-year running average. The record shows a cool period from 1900 to 1930, a warm period in the 1930s and again in the 1950s, a cool period in the late 1960s and 1970s, and consistently warm temperatures since the mid-1990s. (Data source: NOAA NCDC; http://www.ncdc.noaa.gov/cag/)

for Colorado show multiple droughts prior to 1900 that were more severe and sustained than any in the observed record.

Linking changes in Colorado to global changes (Section 4)

- The global climate system has warmed since 1900, particularly in the past 30 years, as evidenced by increased surface, atmospheric, and ocean temperatures; melting glaciers and ice sheets; rising sea levels; and increased atmospheric water vapor.
- These global changes have been attributed mainly to anthropogenic (human-caused) influences, primarily the increase in greenhouse gases in the atmosphere to the highest levels in at least 800,000 years.
- In North America, temperatures have increased by about 2°F in the last 30 years, with anthropogenic influences making a substantial contribution.
- In Colorado, temperatures have also warmed by 2°F in the past 30 years. The statewide warming is plausibly linked to anthropogenic influences, but definitive attribution at this spatial scale is difficult.
- Recent variability in Colorado's annual precipitation has not exhibited trends that might be attributed to anthropogenic climate change.
- Anthropogenic climate change may have increased the severity of recent drought conditions in the western U.S., due to the influence of the warming on snowpack, streamflow, and soil moisture.

Projections of Colorado's future climate and implications for water resources (Section 5)

- All climate model projections indicate future warming in Colorado. The statewide average annual temperatures are projected to warm by +2.5°F to +5°F by 2050 relative to a 1971–2000 baseline under a medium-low emissions scenario (RCP 4.5;

FIGURE ES-2. Projected annual temperature and precipitation changes for the western U.S. under RCP 4.5 for 2050

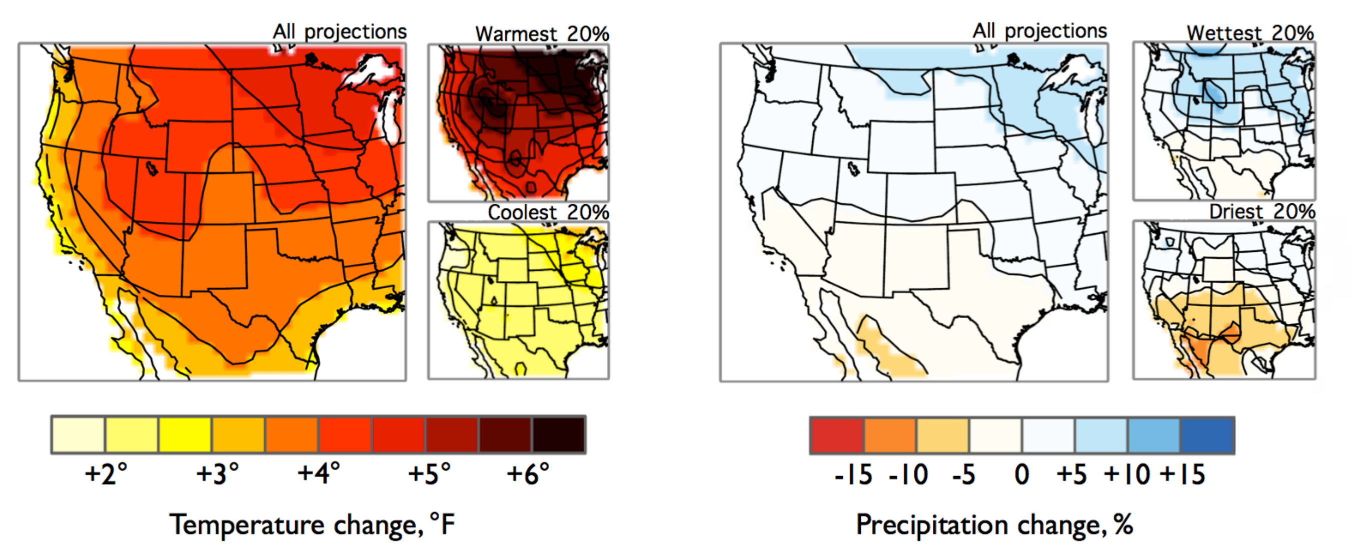

Fig. ES-2. Projected changes in annual average temperature and precipitation by 2050 (2035–2064) over the western US from an ensemble of 37 climate models under RCP 4.5, a medium-low emissions scenario. The large maps show the average change for all of the models (n=37), and the small maps show the average changes for the highest 20% (n=8) and lowest 20% (n=8) of the models, based on the statewide change for Colorado. For Colorado, all models show substantial warming, but there is less agreement about the direction of precipitation change. See Figure 5-1 for an expanded version that also shows seasonal changes. (Data source: CMIP5 projections re-gridded to 1-degree grid, Reclamation 2013; http://gdo-dcp.ucllnl.org/)

Figure ES-2). Under a high emissions scenario (RCP 8.5), the projected warming is larger at mid-century (+3.5°F to +6.5°F), and much larger later in the century as the two scenarios diverge.

- Summer temperatures are projected to warm slightly more than winter temperatures. Typical summer temperatures by 2050 are projected under RCP 4.5 to be similar to the hottest summers that have occurred in past 100 years.
- Climate model projections show less agreement regarding future precipitation change for Colorado. The individual model projections of change by 2050 in statewide annual precipitation under RCP 4.5 range from -5% to +6% (Figure ES-2). Projections under RCP 8.5 show a similar range of future change (-3% to +8%).
- Nearly all of the projections indicate increasing winter precipitation by 2050. There is weaker consensus among the projections regarding precipitation in the other seasons.
- In the first projections of future Colorado hydrology based on the latest climate model output, most projections show decreases in annual streamflow by 2050 for the San Juan and Rio Grande basins. The projections are more evenly split between future increases and decreases in streamflow by 2050 for the Colorado Headwaters, Gunnison, Arkansas, and South Platte basins. However, other hydrology projections show drier outcomes for Colorado, and the overall body of published research indicates a tendency towards future decreases in annual streamflow for all of Colorado's river basins.
- The peak of the spring runoff is projected to shift 1–3 weeks earlier by the mid-21st century due to warming. Late-summer flows are projected to decrease as the peak shifts earlier. Changes in the timing of runoff are more certain than changes in the amount of runoff.
- Most projections of Colorado's spring snowpack (April 1 SWE) show declines for the mid-21st century due to the projected warming.
- Most climate projections indicate that heat waves, droughts and wildfires will increase in frequency and severity in Colorado by the mid-21st century due to the projected warming.

Incorporating climate change information into vulnerability assessment and planning (Section 6)

- Colorado water entities have been at the forefront of incorporating climate change into long-term planning, and their experience can inform future efforts by others.
- Observed records of climate and hydrology are still fundamental to assessing future climate risk, but should be supplemented with information from climate model projections and paleoclimate records.
- Planning approaches that explore multiple futures, rather than assuming a single future trajectory, are more compatible with climate projections and may improve preparedness for a changing climate.
- The uncertainty in projections of precipitation and streamflow for Colorado should not be construed as a "no change" scenario, but instead as a broadening of the range of possible futures, some of which would present serious challenges to the state's water systems.

1

Introduction

1-1. About this report

This report is a thorough revision of a report produced in 2008 by the CIRES Western Water Assessment at the University of Colorado in conjunction with the Colorado Water Conservation Board (CWCB) (Ray et al. 2008; hereafter referred to as the 2008 Report). The 2008 Report synthesized the current science on the physical aspects of climate change relevant to evaluating future impacts on Colorado's water resources. It presented scientific analyses to support future studies and state efforts to develop a water adaptation plan. The development of the report was a direct response to recommendations in then-Governor Ritter's Climate Change Action Plan (Ritter 2007), and its release was timed to support the Governor's Conference on Drought and Climate Risk in October 2008.

The 2008 Report covered five areas:

- The observed record of Colorado's climate (since 1900)
- A primer on climate models, emissions scenarios, and downscaling
- The attribution of significant climate trends and events to climate change
- Projections of Colorado's climate for the mid-21st century
- Implications of the changing climate for water resources

The technical information and graphics in the 2008 Report were based on research and data that had been gathered for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) in 2007, reports produced by the U.S. Global

The Black Canyon of the Gunnison River. Photo: Creative Commons, Tim Engleman.

Change Research Program in the mid-2000s, and other scientific studies specific to Colorado and the Rocky Mountain region. The report authors conducted additional Colorado-specific analyses.

The feedback from users of the 2008 Report indicates that it was successful in helping water resource managers better understand the past, current, and projected future climate in Colorado, and apply that information to their planning. The information was also used by stakeholders outside of the water management community, reflecting the broad need for state- and region-specific climate information.

The six years since the release of the 2008 Report have seen the release of many new research papers and applied studies documenting observed climate variability and climate change in Colorado, and projecting future climate and its impacts. These include efforts focused on projecting future water resources, such as the CWCB's Colorado River Water Availability Study Phase I (CWCB 2012), the Joint Front Range Climate Change Vulnerability Study (Woodbury et al. 2012), and the Colorado River Basin Water Supply and Demand Study (Reclamation 2012). In May 2014 the National Climate Assessment (NCA) issued the third comprehensive report on climate change and its impacts in the U.S. (Melillo et al. 2014). The Climate Assessment for the Southwest (Garfin et al. 2013), which covered Colorado and five other states, was a comprehensive regional assessment that also served as a technical input to the NCA. At the global level, in fall 2013 the IPCC released the Physical Science section of the Fifth Assessment Report (AR5; IPCC 2013), which presents projections from the latest generation of climate models.

The results in these newer studies and reports do not significantly diverge from the 2008 Report's key findings about the character and impacts of past climate variability and projected future climate change for Colorado. But they do add important nuance and detail, and shed further light on important aspects of the climate system. Also, some climate-related water impacts that we now understand to have statewide importance were not addressed in the 2008 Report, such as dust-on-snow events and bark beetle epidemics.

In 2013 the CWCB partnered with the Western Water Assessment to undertake a revision of the 2008 Report. This revision again presents scientific analyses to support water resources management and planning. The report focuses on observed trends, modeling, and projections of hydroclimate variables—including temperature, precipitation, snowmelt, and runoff—that determine both water supply and demand for the state. The geographic scope of the document does not end at the state's borders, because of Colorado's role as the headwaters for the West, and the importance of climate processes that extend well beyond the state. The climate projections focus on the mid-21st century[1], because this is a key planning horizon for the State's adaptation strategies and offers a direct comparison with the projections in the 2008 Report. Some of the figures show projections for earlier and later periods.

While this second edition closely follows the overall structure of the 2008 Report, we have expanded the scope and enhanced the content in nearly all areas, especially these sections:

- Establishing the global context for Colorado's climate (Section 1-2)
- Practical definitions of weather, climate variability and climate change (Section 1-3)
- The processes influencing Colorado's current climate (Section 2-1)
- Observed snowpack and streamflow trends (Section 2-4)
- Observed climate and weather extremes (Section 2-6)
- The paleoclimate of Colorado (Section 2-7)
- Downscaling approaches used in recent studies (Section 3-5)
- Linking observed changes in Colorado to global changes (Section 4; formerly titled "Climate attribution")

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[1] Specifically, the projections shown in Section 5 focus on a 30-year future period (2035–2064) centered on 2050.

- Projections of Colorado's future climate (Sections 5-1 and 5-2)
- Projections of Colorado's future hydrology (Section 5-3)
- Approaches for using climate information in vulnerability assessment and planning (Section 6-2)

As in 2008, this updated report supports other statewide water and climate planning processes. Some of the content of this report has already been integrated into the Colorado Climate Change Vulnerability Study, commissioned by the Colorado Energy Office and to be released later in 2014. The Colorado Water Plan, the draft of which will be released in December 2014, will also draw from this report to inform statewide water planning efforts into the future.

Our understanding of climate and climate change is always improving; like the 2008 Report, this updated report is a snapshot of the evolving state of the science, not a final statement. The information reported here provides a basis for planning now, with the understanding that planning documents and processes will need to be updated as the science progresses.

Like the 2008 Report, this document takes advantage of the most recent efforts to synthesize climate science at regional to global scales. The statements within this report that include an expert assessment of the likelihood and certainty of that statement have been taken from these other synthesis reports. Apart from those syntheses, this report also references over 100 studies published in peer-reviewed journals.

Water managers in Colorado have a long history of adapting to changing circumstances, including changes in economies and land use, increasing environmental concerns, and population growth. Climate change will also affect the decisions made about how Colorado uses and distributes its water. While this report provides a scientific basis to support further studies of water resource impacts and adaptation efforts, the assessment of the sensitivities and vulnerabilities of specific water systems in Colorado is beyond the scope of this report. Since the 2008 Report was released, there have been several new vulnerability assessments focused on water resources. The Colorado Climate Change Vulnerability Study describes vulnerabilities to the water sector, along with other sectors. Section 5-3 and Section 6 of this report describe some of these assessment efforts, as part of a broader discussion of using climate projections in vulnerability assessment, planning, and adaptation.

Organization of the report

The key findings of this report are summarized at the beginning of each section. Most of the key findings are also collected in the Executive Summary that precedes Section 1.

Section 2 describes the climate of Colorado, the observing systems and data available for study, and presents the observed climate variability and trends in Colorado since 1900 that are relevant to water resources. Section 3 provides an overview of climate models and guidance on how to interpret their output. Section 4 links the observed changes in Colorado to global changes and describes the attribution of observed climate conditions to anthropogenic climate change. Section 5 describes the latest climate model projections for Colorado and the surrounding region, presenting a picture of Colorado's potential climate futures. It also presents recent projections of hydrology for the state's river basins and summarizes the implications for Colorado's water resources. Section 6 provides guidance on using the findings of the report in vulnerability assessment and long-range planning for water resources.

In each section, one or more sidebars provide additional detail about specific topics that are relevant to that section. A glossary at the back provides definitions of many key climate terms, which are generally italicized in the text on first use. Supplemental information is available at http://wwa.colorado.edu/climate/co2014report/.

1-2. The global context for Colorado's climate

Changes in Colorado's climate are occurring in a global context. We know that the global climate has changed throughout Earth's history, but we also know that there are novel and rapidly changing conditions today. Carbon dioxide (CO_2), a potent *greenhouse gas*, has increased by 40% from 280 parts per million (ppm) in the pre-industrial era to 400 ppm today, a level that the earth has not seen in at least 800,000 years, due primarily to the burning of fossil fuels. Other greenhouse gases, such as methane (CH_4) and nitrous oxide (N_2O), have also increased dramatically in the past century due to human activities. While some human changes to the earth's climate system such as the emission of aerosols have a cooling effect, the overall anthropogenic (human-caused) influence, or *forcing*, has been to add heat to the climate system.

This anthropogenic warming was first predicted over a century ago when Swedish chemist Svante Arrhenius linked the physical properties of greenhouse gases such as CO_2—first described in the 1830s—with the observations of their increasing levels in the atmosphere (Arrhenius 1896). His prediction from basic physics was later shown to be consistent with paleoclimate studies that found that past periods of higher CO_2 levels had warmer temperatures globally. The observed warming trend over the 20th century, in the context of increasing greenhouse gas concentrations, led to a consensus within the climate science community by the mid-1990s that the warming was likely human-caused and would continue as long as greenhouse gas concentrations in the atmosphere increased. The evolution of global climate models (GCMs) during that time provided sophisticated tools to simulate the earth's climate system under different conditions. This period also saw improved observations of the oceans, and the first satellite measurements of the energy budget of the planet. These observations, along with climate model experiements, strongly suggest that the warming is largely anthropogenic in nature and cannot be explained by natural causes of climate variability, such as changes in the sun's energy output. Projections made by the climate models show a future climate by the end of the 21st century that is different from any experienced by human civilization. To summarize, the current scientific understanding about the recent and ongoing changes in global climate is based on multiple, consistent lines of evidence, including fundamental radiation physics, paleoclimate records, historical and recent observations, and simulations from climate models.

Today, it is an observational fact that the earth's climate system has warmed in the past century; average temperatures at the earth's surface have increased by 1.6°F since 1900 and 0.8°F since 1980 (IPCC 2013). Over 90% of the additional energy accumulated in the climate system since 1980 has gone into warming the oceans, and the global sea level rise of about 0.7 feet since 1900 reflects the thermal expansion of water from this warming as well as increasing melt from mountain and polar glaciers and the Greenland and Antarctic ice sheets. Other global and hemispheric trends in the past several decades that are consistent with the observed warming include a reduction in northern hemisphere spring snow cover, the loss of 75% of the volume of summer Arctic sea ice since 1979, and increasing water vapor in the atmosphere as evaporation has increased. The latest IPCC report found it *extremely likely* (>95% likelihood) that more than half of the observed increase in global surface temperature since 1950 was anthropogenic in nature, primarily from increasing greenhouse gas concentrations (IPCC 2013). (For a more thorough treatment of the scientific evidence for anthropogenic climate change, we direct readers to the FAQs [Walsh et al. 2014b] from the latest National Climate Assessment, available at http://nca2014.globalchange.gov.)

Colorado's climate has evolved within these global climate trends. Like nearly every other part of the globe, Colorado has warmed over the past century, particularly since the 1980s, as detailed in the next chapter. Figure 1-1 (following page) shows how the path of Colorado's observed temperatures since 1900 has closely followed the path of nationwide and global temperatures. Because of the relatively small size of Colorado compared to the U.S. and the Earth's surface, natural variability has had more influence on decade-to-decade changes in Colorado's climate, as is clearly seen in Figure 1-1. Section 4 discusses in more depth the linkage between changes in global climate and observed changes in Colorado's climate.

Figure 1-1. Colorado, U.S, and Global Temperatures, 1895–2012

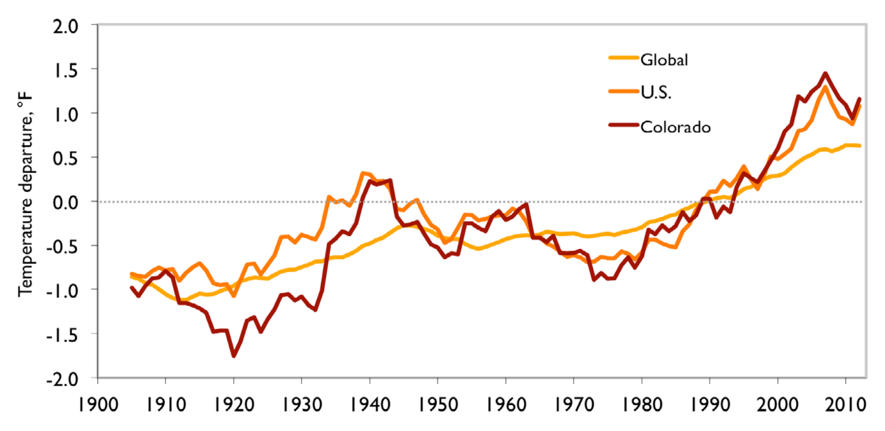

Fig. 1-1. Observed average annual surface temperatures (°F) for Colorado, the U.S., and the globe from 1895–2012, smoothed with 10-year running averages to emphasize longer-term variability and trends. The temperatures are shown as departures from a 1971–2000 baseline. The overall trajectories of temperature of the three records are similar, although there is more variability and a larger recent warming trend at smaller spatial scales. (Data source: NOAA NCDC).

1-3. Weather, climate, climate variability, and climate change

Before examining Colorado's climate and climate trends in Section 2, we will provide working definitions of *weather, climate, climate variability* and *climate change*. The weather is the always-fluctuating state of the atmosphere at a particular location and point in time, e.g., 15°F and overcast in Fort Collins at noon on February 4, 2014. Weather also refers to near-term future state of the atmosphere, including the position and impacts of air masses, fronts, and individual storm systems.

The climate is the statistical description of the aggregate of weather conditions over a longer time period, usually 30 years or more. This description typically focuses on the average daily, monthly, or annual conditions. For example, in Fort Collins in February, the average monthly temperature is 33°F (based on the period 1971–2000), corresponding to an average daily high of 46°F and a low of 20°F. Climate also encompasses the average precipitation, winds, humidity, atmospheric pressure, and cloudiness. To be complete, a description of climate should also include the range of conditions that have occurred over time, including extremes, and the characteristics of the variability within that range over time, as described below. Climate also encompasses atmospheric, oceanic, and cryospheric (snow and ice) processes that act over long periods (years to decades) and are not easily perceived at the timescale of weather (minutes to days), though they can have a large influence on global weather patterns.

Climate variability refers to fluctuations above and below the average conditions over time, on monthly, annual, and longer timescales. These fluctuations are called *anomalies* or *departures*. For example, during the period of 1971–2000, the February monthly-averaged temperature in Fort Collins ranged from 22°F (in 1989), a departure of 11°F below the long-term average, to 39°F (in 1992), a departure of 6°F above the long-term average. Climate variability occurs naturally due to the complex interactions of the atmosphere, oceans, land surface, and land and sea ice. Some of the climate processes that produce variability in Colorado, such as El Niño-Southern Oscillation (ENSO), are described in Section 2-1. Variations in the output of the sun, such as the 11-year solar (sunspot) cycle, and periodic large volcanic eruptions that cause brief cooling, also add to the natural variability. We have sufficiently long instrumental climate records in most parts of the world, including Colorado (Section 2-3), to adequately describe the range of natural variability, augmented by paleoclimate records which extend back hundreds or even thousands of years (Section 2-7).

Climate *change* refers to a persistent change, lasting decades or longer, in the average or range of climate conditions. Statistical tests can be used to determine whether the change lies outside of what would be expected from the observed variability in climate; i.e., whether it is *statistically significant*. The statistical *detection* of a change, however, does not assign a cause to that change. A climate change could be due to natural climate variability or anthropogenic forcings (e.g., greenhouse gases), or a combination of the two. The *attribution* of a climate change to its likely causes is more challenging than initially detecting the change. Section 4 describes the methods used in climate change attribution.

In the media and public conversations, "climate change" is often used as shorthand for "anthropogenic climate change."[2] In this report we distinguish the two concepts, and when we are referring to climate change due mainly to human causes, we try to use the latter term. The rapid buildup of anthropogenic greenhouse gases in the atmosphere makes them stand out among the diverse set of influences acting on climate globally and locally. But we can't assume that any particular change in a climate variable is due to greenhouse gases; natural variability and other factors need to be considered.

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[2] "Global warming" is also often used as a synonym for anthropogenic climate change. While the rise in globally-averaged surface temperature is an indicator of climate change on a global scale, "global warming" doesn't adequately convey the many other aspects of the changing climate.

2

The Observed Record of Colorado's Climate

Key points

- Colorado's climate reflects its mid-continental location, high elevations, and the complex topography of the mountains, plains, and plateaus. The topography leads to differing influences of weather and climate processes in different parts of the state, and large variations in climate over short distances.
- Statewide annual average temperatures have increased by 2.0°F over the past 30 years and 2.5°F over the past 50 years. Warming trends have been observed over these periods in most parts of the state.
- Daily minimum temperatures in Colorado have warmed more than daily maximum temperatures during the past 30 years. Temperatures have increased in all seasons, with the largest trend in summer, followed by fall, spring, and winter.
- No long-term trends in average annual precipitation have been detected across Colorado, even considering the relatively dry period since 2000.
- Snowpack, as measured by April 1 snow-water equivalent (SWE), has been mainly below-average since 2000 in all of Colorado's river basins, but no long-term (30-year, 50-year) declining trends have been detected.
- The timing of snowmelt and peak runoff has shifted earlier in the spring by 1–4 weeks across Colorado's river basins over the past 30 years, due to the combination of lower SWE since 2000, the warming trend in spring temperatures, and enhanced solar absorption from dust-on-snow.

The original D1 weather station (12,264'), Niwot Ridge Long-Term Ecological Research Site. Photo: Jeff Lukas.

- The Palmer Drought Severity Index (PDSI) shows a trend towards more severe soil-moisture drought conditions in Colorado over the past 30 years, reflecting the combination of the below-average precipitation since 2000 and the warming trend.

- No long-term statewide trends in heavy precipitation events have been detected. The evidence suggests that there has been no statewide trend in the magnitude of flood events in Colorado.

- Tree-ring records and other paleoclimate indicators for Colorado show multiple droughts prior to 1900 that were more severe and sustained than any in the observed record.

Observations are the basis for understanding past and recent climate variability, detecting climate change, modeling future climate, and evaluating future climate scenarios. This section begins with a brief overview of the climate of Colorado, then provides background on how observations are made and the challenges in analyzing observations, and then presents the variability and trends in Colorado's climate record since 1900.

This section presents the results of analyses performed by the authors, and results from previously published studies. The results of these observational studies must be taken in the context of the period over which data are analyzed. Colorado's climate record is punctuated with notable climate events and variability, including the Dust Bowl drought years (1930s), a relatively cool period in the 1960s and 1970s, and the relatively warm and dry period since 2000. These variations can influence the results of analyses, depending on the length of the period being analyzed and the start and end dates. Therefore, we explicitly state the time period being analyzed. The new trend analyses performed for this report were performed with 30-year, 50-year, and 100-year periods, all ending in 2012, except for snowpack trends, which end in 2013. The 2008 Report also analyzed 30-year, 50-year, and 100-year trends, but for periods ending in 2006.

2-1. The climate of Colorado

Colorado's central location on the North American continent determines many aspects of the state's climate. Colorado's location in the mid-latitudes (37°N–41°N) leads to a prominent seasonal cycle that strongly influences which climate processes are most active at different times of the year. Upper-level winds (above 18,000') that direct the movements of air masses, fronts, and storms move generally from west to east at these latitudes, with these winds aloft being strongest in the winter and weakest in mid- to late summer. The location of the strongest core of upper-level winds (the jet stream) over western North America also varies both seasonally and on shorter timescales. When the jet stream is positioned over or near Colorado, which is most likely to occur in winter, both the frequency and intensity of storm systems affecting the state are greater (Lareau and Horel 2012).

Colorado's interior location, far from the moderating impacts of humid maritime air masses, means that the state experiences frequent sunshine, low humidity, and rapid and large variations in temperatures. Because Colorado straddles the Continental Divide along the highest crest of the Rocky Mountains, when moisture does reach the state there is almost always orographic (terrain-driven) lifting to produce clouds and precipitation. Moisture typically arrives on the prevailing westerly winds from late fall through winter into early spring, shifting to more frequent intrusions of moist air from the south and east during spring and summer. With the lifting, higher precipitation occurs along windward upslopes and little precipitation occurs on the leeward downslopes, with dry rainshadows extending downwind of the mountains. These patterns induced by the topography change seasonally in a predictable manner but can also vary with every individual storm. Across the seasons, because westerly flow is dominant, the western slopes of the state's mountain ranges are generally wetter than the eastern slopes.

Colorado's complex topography—mountains, valleys, plateaus, and rolling plains—acts to influence temperature, pressure, wind and precipitation patterns, which can all vary dramatically over very short distances (Figure 2-1). Generally, temperatures cool predictably with increasing elevation (by ~3.5°F

FIGURE 2-1. Average annual temperature and precipitation for Colorado, 1950–1999

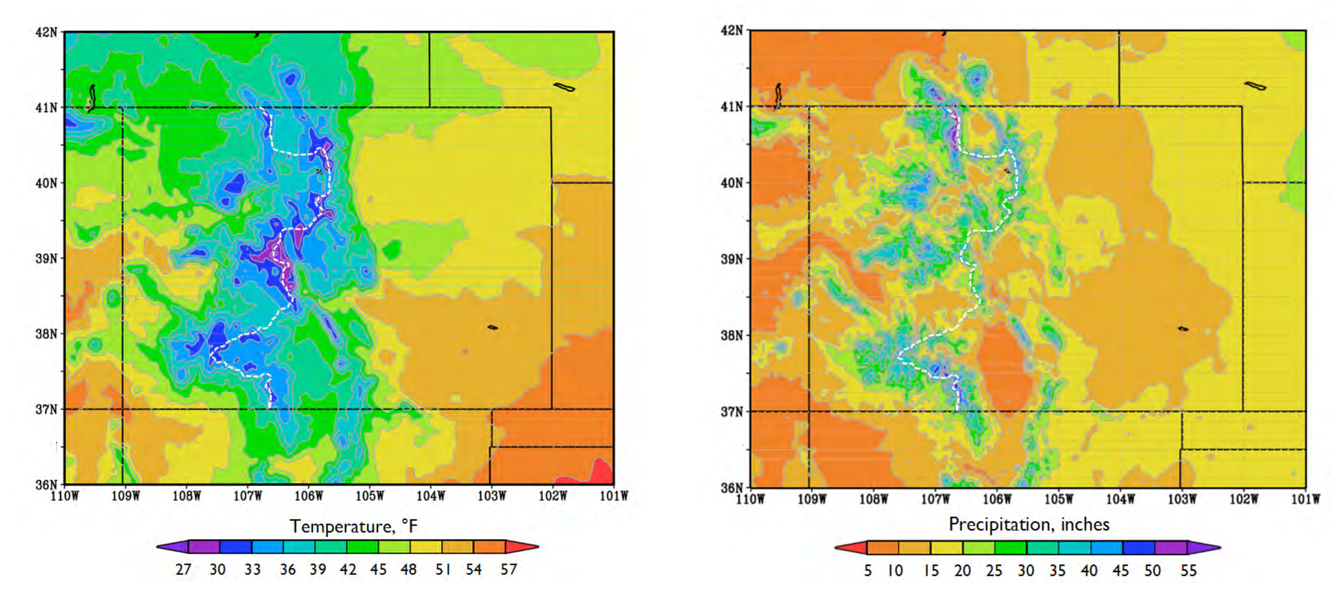

Fig. 2-1. Annual average temperature (left) and precipitation (right) over the period 1950-1999. The spatial variability in both temperature and precipitation across Colorado is strongly controlled by topography and elevation, with the mountains being cooler and wetter than other areas. The dashed white line shows the Continental Divide. (Data source: PRISM[3] Climate Group, Oregon State University)

per 1000’ of elevation gain), with the most reliable gradients occurring in daytime, especially during the warm season. But the ground quickly loses heat by thermal radiation on clear nights and local topography directs the flow of air. The denser cooling air drains down from slopes and ridges and settles into low spots. These cold pools form in many river bottoms: the Gunnison River near Gunnison, the Rio Grande near Alamosa, the White River near Rangely, and the South Platte River near Greeley. This effect is most dramatic when the valleys are covered with fresh snow; in a year with deep and early snows, temperatures can be 6–10°F below average over the entire winter season (Doesken 1992). Conversely, below-average snow cover can lead to warmer temperatures by inhibiting the formation of cold pools.

Across the state, January is typically the coldest month of the year and July the warmest, with a 40°–50°F difference between average mid-winter and mid-summer temperatures (Figure 2-2). Temperatures vary widely from day to day and week to week, especially during the cooler months from mid-autumn to late spring when frequent storm systems affect Colorado. Winter temperatures are more variable, on a daily to monthly basis, than summer temperatures, and daytime maximum temperatures are more variable than nighttime minimum temperatures. The least variability occurs in summer minimum temperatures. The variation in temperature from year to year in the high mountains is determined by the occurrence of persistent atmospheric ridges and troughs—regions of high and low atmospheric pressure, respectively. East of the mountains, the interplay among subtropical, Pacific, and polar continental air masses determines which years are warmer or colder than average (Pielke et al. 2003).

Topography also plays an important role in precipitation processes and patterns (Redmond 2003), even on Colorado’s eastern plains. Precipitation typically increases with elevation in all seasons, but especially in winter when nearly all moisture falls as snow. Areas above 9,000’ along and west of the Continental Divide receive the most winter precipitation and annual precipitation in the state (Figure 2-1). The wettest mountain areas are the Park

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[3] PRISM (Parameter-elevation Relationships on Independent Slopes Model) accounts for the effects of topography and elevation on temperature and precipitation in order to interpolate climate data between weather stations and create spatially consistent climate data over a regular grid (Daly et al. 1994, Daly et al. 2008).

Range around Steamboat Springs, which is favored in northwesterly flow, and the eastern San Juan Mountains around Wolf Creek Pass, favored in southwesterly flow. On average, Colorado's southern mountains experience fewer individual storm events than the northern mountains, but the southern storms tend to be more moisture-laden. During spring, occasional slow-moving storms bring moisture from the Gulf of Mexico into Colorado from the south and east. A small number of these upslope events contribute a large fraction of the annual precipitation to the eastern side of the Continental Divide, especially the northern Front Range. In all mountain ranges, most of the annual total comes from cold-season precipitation (Figure 2-2).

In the summer, most precipitation statewide comes from convective processes that generate frequent, sometimes daily, thunderstorms. Thunderstorms typically develop over high terrain by early afternoon. Over the Front Range and Plains, these storms typically move eastward as the day progresses. These convective processes depend on the presence of moist air masses, which most often reach Colorado from the south and east. Southerly moisture flow is associated with the North American Monsoon system (Adams and Comrie 1997) and has the greatest

FIGURE 2-2. Average monthly temperature and precipitation for eight Colorado stations

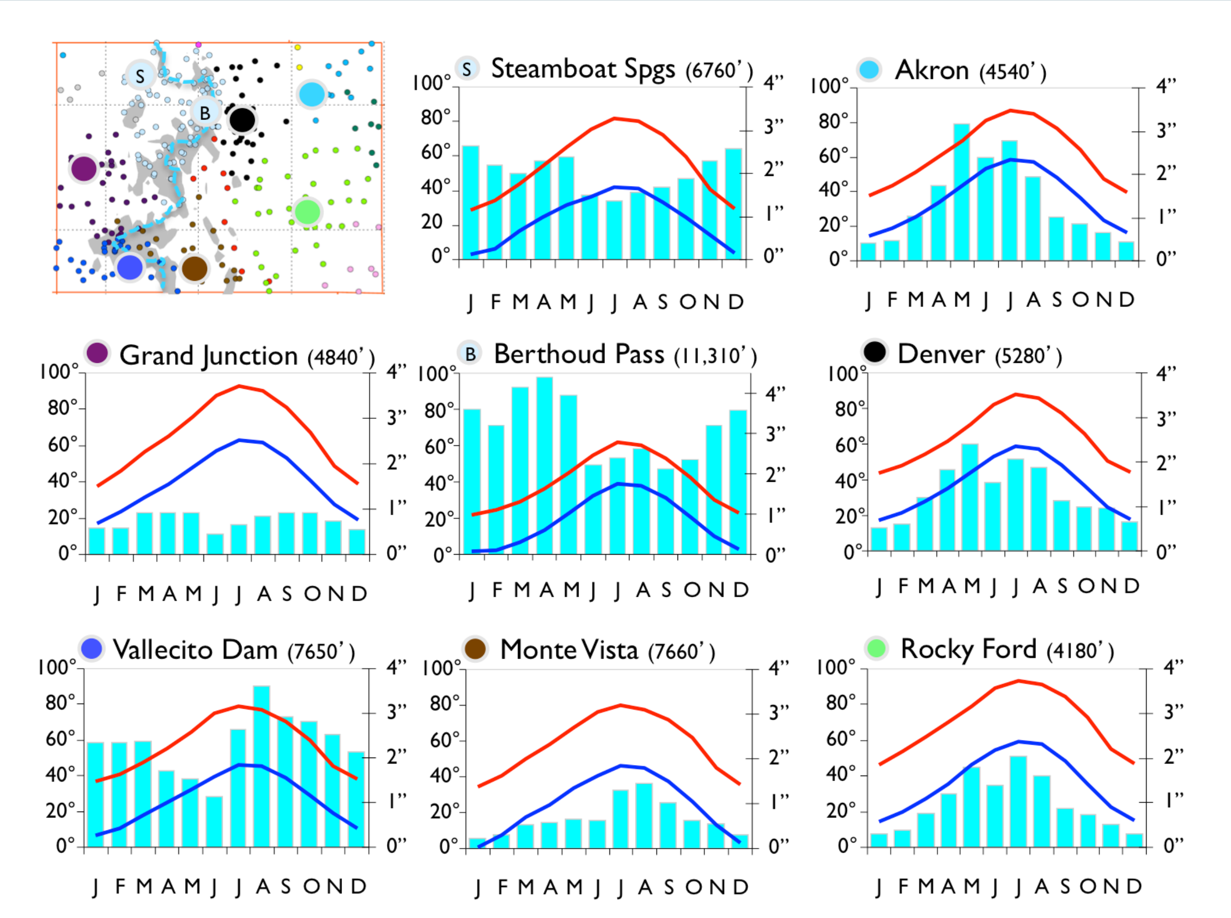

Fig. 2-2. Monthly temperature and precipitation, averaged over 1971–2000, at eight Colorado COOP stations selected to represent areas with different seasonal climate patterns (colored dots in map, upper left). On the graphs, the red line shows the mean daily maximum temperature for each month; the blue line shows the mean daily minimum temperature, in degrees F (left-hand vertical scale). The blue bars show the mean monthly precipitation, in inches (right-hand vertical scale). The differences in seasonality across the state reflect the different climate processes having more or less influence, depending on elevation and relationship to topography. On the inset map, the small colored dots represent stations with seasonal climate patterns similar to the eight selected stations (large dots). See Figure 2-7 for further explanation. The gray shading indicates areas above 10,000'. (Data source: Western Regional Climate Center, http://wrcc.dri.edu)

FIGURE 2-3. Multivariate ENSO Index (MEI), 1950–2013

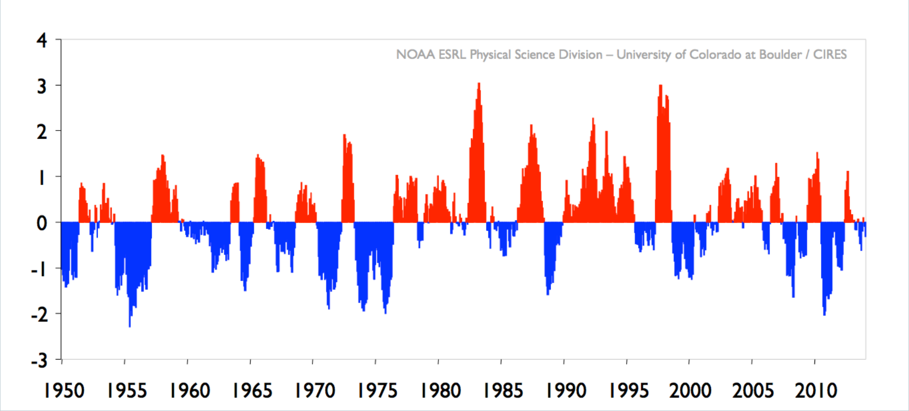

Fig. 2-3. Time series of the Multivariate ENSO Index (MEI) from January 1950 through December 2013. El Niño-like conditions are shown in red, La Niña-like conditions are shown in blue. Since 2000, there have been no strong El Niño events (MEI greater than +1.5 for at least 3 months), and neutral or La Niña conditions have been prevalent. (Data source: K. Wolter, http://www.esrl.noaa.gov/psd/enso/mei)

impact on the southern and central mountains. The Front Range and eastern Colorado receive most of their summer moisture from lower-level easterly and southeasterly flow from the Gulf of Mexico. The upper-level westerly flow is weaker in summer and the strongest jet stream winds are well to the north of Colorado. Across Colorado, the length of the active summer thunderstorm season varies considerably from year to year. With little precipitation coming in winter, eastern Colorado's precipitation regime is dominated by spring and summer precipitation. The lower elevations of southern and central Colorado also receive a significant proportion of their annual precipitation from late summer storms (Figure 2-2).

Since many of the same processes influence both temperature and precipitation, the two variables are often closely related in space and time. This is most clearly seen in the spatial variability of temperature and precipitation across Colorado; the coldest areas also tend to be the wettest (Figures 2-1 and 2-2). It is also seen in the daily and monthly variability during the warm season (May–October). The weather patterns associated with above-average temperatures (e.g., persistent high pressure) also lead to below-average precipitation, while weather patterns associated with below-average temperatures also lead to above-average precipitation. A feedback mechanism often reinforces the relationship: once vegetation and soils dry out during a summer dry spell, the sun's energy can go directly into heating the soil and adjacent air, rather than evaporating water, raising temperatures further. Thus summer drought periods are often much hotter than normal. In the cold season, the situation is more complicated. High pressure is often associated with below-average precipitation and below-average temperatures from Arctic air masses, while low-pressure systems may bring copious moisture from the Pacific Ocean along with relatively mild maritime air.

These many influences on Colorado's climate, when aggregated and averaged, produce the long-term climatic conditions to which we are accustomed, as reflected in the 30-year normals (see Sidebar 2-1). But hidden within those long-term averages are sequences where the year-to-year fluctuations can be enormous, as described in the following sections. It is this natural variability that has driven the historical vulnerabilities of water supplies and the uses of water resources such as agriculture.

Much of the month-to-month and year-to-year natural variability is essentially random, as the chaotic fluid motions in the earth's atmosphere and oceans act to maintain a dynamic global equilibrium in energy and moisture. But the enormous heat storage capacity and slower movement of the oceans also leads to patterns or modes of variability that are slower-acting, having detectable and predictable influences on weather and climate over vast regions for months to years.

El Niño-Southern Oscillation (ENSO)

The best known of these global modes of variability, and the most important for Colorado and the western U.S., is El Niño-Southern Oscillation (ENSO). ENSO influences precipitation across Colorado, with different tendencies according to region and season (Wolter and Lukas 2010).

The key features of ENSO are changes in the sea-surface temperatures of the eastern tropical Pacific Ocean, the atmospheric pressure difference between eastern Pacific high pressure and western Pacific low pressure (the 'Southern Oscillation'), and the preferred location of tropical thunderstorms. These processes drive changes in the atmospheric circulation outside the tropics, such as the position of the jet stream and storm tracks over western North America. The Multivariate ENSO Index (MEI; Figure 2-3) monitors these effects in an integrated manner, and the MEI record since 1950 shows the characteristic 2- to 7-year timescale of the oscillation between the two phases of ENSO: the El Niño (warm-phase) events and La Niña (cold-phase) events.

FIGURE 2-4. Correlations between seasonal precipitation for Colorado and Multivariate ENSO Index (MEI), 1956–2005

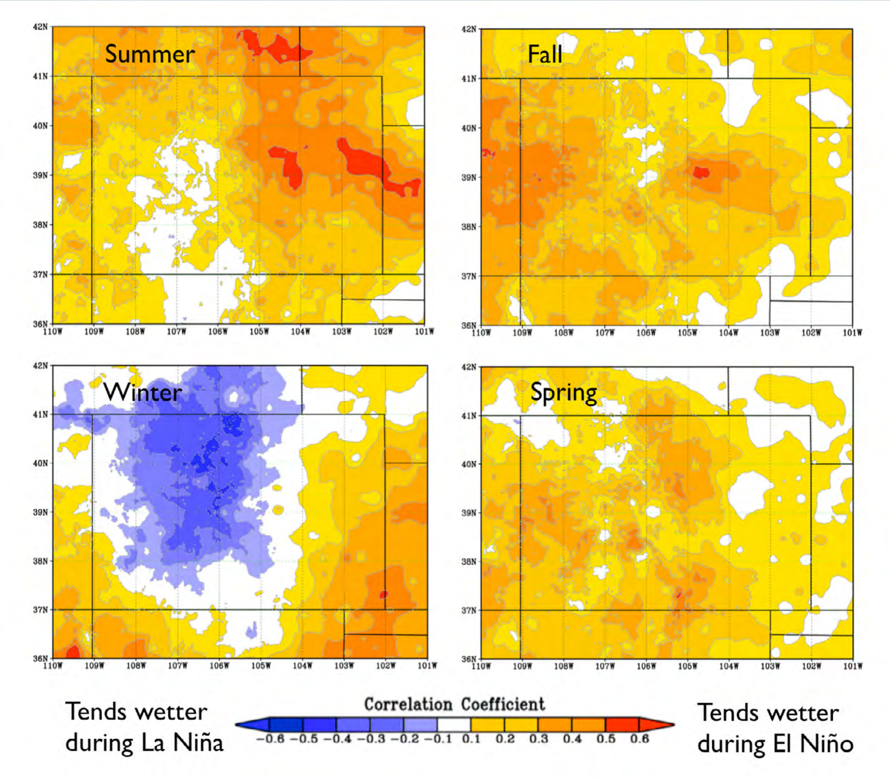

Fig. 2-4. Correlations between the Multivariate ENSO Index (MEI) and precipitation in Colorado for each season, 1956-2005. Orange colors indicate a tendency towards wetter conditions during El Niño (positive MEI) and drier during La Niña (negative MEI); and blue indicates a tendency towards wetter conditions during La Niña and drier during El Niño. In all seasons but winter, El Niño tends to lead to above-average precipitation across Colorado; in winter, the mountains tend to be wetter with La Niña. (Source: PRISM gridded climate data; MEI: http://www.esrl.noaa.gov/psd/enso/mei. Analysis by K. Wolter.)

Once an El Niño or La Niña event is established, often during summer, it tends to persist into the following calendar year. Thus, ENSO events impart "memory" and seasonal predictability to the climate system. In fact, the ENSO state is the main source of predictive skill for seasonal precipitation forecasts for Colorado and western North America. ENSO has a more consistent year-round effect on climate variability to our southwest (Arizona, New Mexico) and to the northwest (Washington, Oregon, Idaho). Those two regions form a "dipole" in which El Niño events typically lead to wet conditions for the Southwest and dry conditions for the Northwest, with the reverse for La Niña events. Colorado, being in the middle of the dipole, has more seasonally variable ENSO impacts.

Figure 2-4 shows how the spatial pattern and strength of the ENSO "footprint" in Colorado changes through the seasons. The colors indicate the correlation between seasonal precipitation from the PRISM gridded dataset and the MEI, from 1956–2005. Orange colors indicate areas that tend to be wetter in that season during El Niño, while blue colors indicate areas that tend to be wetter during La Niña. El Niño is often wet in the summer, fall, and spring across Colorado. During winter (December–February), the wet tendency with El Niño is limited to southeast Colorado and the Four Corners, while higher elevations in northern and central Colorado tend to be dry. La Niña events, conversely, tend towards drier conditions in the orange areas, and wetter in the blue. Since the winter months are often the wettest time of year in our mountains, a wet La Niña winter can balance out typically dry La Niña conditions during the rest of the year. Nevertheless, averaged across the state, El Niño is associated with more precipitation overall, and El Niño events have been instrumental in ending long-lasting droughts such as the Dust Bowl and 1950s drought.

Longer-term climate oscillations

The Pacific Decadal Oscillation (PDO) is the principal pattern of sea-surface temperature variability in the northern Pacific (Mantua et al. 1997), and has been found to have statistical associations with moisture conditions in Colorado and the surrounding region (Goodrich 2007). However, PDO is not a single well-defined physical phenomenon like ENSO, and it appears that much of the variation in the PDO is actually ENSO variability being expressed in the northern Pacific over longer time scales (Newman et al. 2003; M. Newman, personal communication). Thus, any relationship since the 1970s between the phase of the PDO and Colorado being in either a relatively dry or wet state is likely to have been driven as much by clusters of La Niña (dry) or El Niño (wet) events, as by conditions in the northern Pacific that are independent of ENSO.

A similar slowly-varying sea-surface temperature and pressure oscillation in the north Atlantic Ocean is named the Atlantic Multidecadal Oscillation (AMO; Schlesinger and Ramakutty 1994). The positive (warm) phase of the AMO has been found to be statistically associated with increased risk of drought in a region that includes Colorado (Hidalgo 2004, McCabe et al. 2007). A study using climate models found that the combination of negative PDO phase and positive AMO phase is the least favorable for moisture in the interior U.S. (Schubert et al. 2009). However, the physical mechanism by which the AMO actually affects conditions in the interior West is not clear, unlike with ENSO (Nowak et al. 2012). While the phases of the AMO and PDO may be indicators of enhanced drought risk for our region, both should be used cautiously.

2-2. Observing and interpreting Colorado's climate

Describing the patterns of Colorado's climate in both time and space requires a long-term, extensive network for observing atmospheric variables. The earliest instrumental weather observations in Colorado came from some of the early forts built on the western frontier. In 1870, the organization that later became the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) established more weather stations in Colorado, including Denver, Pueblo, and Pikes Peak. In the 1880s the Colorado State Legislature authorized the creation of the Colorado Weather Service, with a goal of better defining the weather and climate of Colorado. This network of dozens of urban and rural weather stations later became Colorado's portion of the nationwide NWS Cooperative Observer (COOP) Network. NOAA's National Climatic Data Center (NCDC), which maintains the national archive of COOP data, in the early 2000s deployed a special climate observing network called the Climate Reference Network (CRN), including six stations in Colorado, with the express purpose of detecting a nationwide signal of climate change.

There are now over 500 weather stations in Colorado that measure and report at least temperature and precipitation daily to a publicly accessible data archive. Of these, about 200 are COOP stations that measure and report daily high and low temperatures, precipitation (rain and the melted water from snow and ice), snowfall, and total snow depth. Average daily temperature is computed as the mean of the minimum and maximum temperatures. Some weather stations report additional information such as wind, humidity, and cloud cover.

It is important to note that observing weather is not the same as monitoring climate. With the exception of CRN, none of these weather observing networks in Colorado and across the U.S. were established and maintained with the goal of detecting long-term climate trends. Changes in instrumentation, station locations, time of measurement and other factors create steps, or inhomogeneities, in the records and affect the interpretation of long-term trends. Station moves can result in slight differences in the local climate being observed, and may create a spurious trend. Of the roughly 200 active COOP stations in Colorado, only two (Fort Collins and Rocky Ford) are "original" stations that were established in the 1880s in nearly the same location that they are in today. The widespread

Sidebar 2-1. The changing normal

A climate normal, or the average conditions over a set baseline period, is routinely used for placing recent or current climate conditions into a longer context. Whenever you see a reference such as "percent of average precipitation", the normal is embedded in that value. The standard practice in the meteorological community is that a 30-year period, encompassing three full decades, is used as the normal. The normal is typically updated every decade, so the most current 30-year normal is 1981–2010.

This practice has been adopted by most providers of hydroclimatic information for Colorado and the region. Others may use a longer-term average as the baseline for monitoring current conditions. Key providers who use the standard 30-year normal include the NOAA National Climatic Data Center (climate monitoring); Regional Climate Centers (RCCs; climate monitoring); the NRCS Colorado Snow Survey (snowpack monitoring and water supply forecasts), and the Colorado Basin River Forecast Center (CBRFC; hydrologic monitoring and streamflow forecasts)

Between 2011 and 2013, all of these providers changed their baselines for calculation from the previous normal (1971–2000) to the new 1981–2010 normal. When the 30-year normal was updated to the new one, the decade of the 1970s was replaced in the baseline period with the 2000s. Statewide Colorado precipitation, averaged over the decade, was very similar between the 2000s and the 1970s. But the 2000s were warmer than the 1970s over most of the world and the US, including Colorado. Thus the new 1981–2010 normal is warmer than the previous one—and so for hydroclimatic variables like streamflow and drought indices that are affected by temperature, the new normal is also drier.

According to the CBRFC, the 1981–2010 streamflows now used to compute the percent of average are lower than the previous normal throughout the Colorado River Basin; for example, the 1981–2010 unregulated April-July inflows to Lake Powell were 11% lower than the 1971–2000 inflows. In fact, the new normal for Lake Powell inflows is lower than any of the seven previous normals, beginning with 1911–1940. So the coming years' conditions will appear to be cooler and have greater flow than under the old normal, because they will be compared to a warmer and lower-flow baseline.

In this report, we explicitly state the normal being used as a baseline for metrics like "percent of average" and "departure from average." Since the historical period for the climate model runs ends in 2005, the 1981–2010 normal crosses over into the projected "future" period. Thus for the analyses of projected future changes (Section 5) it is more appropriate to use the older 1971–2000 normal as the observed baseline for comparison. In Section 2, we elected to also use the 1971–2000 normal for most of the analyses and graphics, to keep the baseline consistent and to facilitate comparisons between the observed trends and projected future trends.

transition from glass to electronic thermometers in the 1980s nationwide resulted in a cold shift, or cold *bias*, of about 0.5°F compared to observations made prior to the change. An even larger cold bias can occur when the daily observing time is changed from the afternoon to the morning (Pielke et al. 2002), as has widely occurred in recent decades. Land-use changes that affect local temperature are also common in Colorado and elsewhere, including urban heat island effects and altered irrigation patterns, which impact temperatures during the growing season (Pielke et al. 2002). These changes are not always well-documented (Pielke et al. 2007). An extensive discussion of the records at selected Colorado climate stations is provided in Pielke et al. (2002). Because of these issues, as well as local variability in weather patterns, trends at individual stations will not necessarily reflect trends over larger areas.

There are two complementary approaches to selecting and quality-controlling station records for climate analysis so the results are not unduly influenced by the non-climatic factors described above. The first is to select only the longest and highest-quality station records, with relatively fewer station moves and changes in instrumentation and no obvious breakpoints in the record, and use these records without adjustments. The second is to use a broader set of station records and apply well-established procedures to account for and adjust for observational bias, including instrumentation changes and station location. The methods used to improve observational datasets have been reviewed and vetted by the scientific community. The advantage of the second approach is that many more stations can be used, and averaged together to more robustly represent larger regions. Section 2-3 presents results from both approaches: analyses of unadjusted records from selected individual stations, and also analyses from composites of adjusted records, and comparisons between the two.

2-3. Variability and trends in Colorado temperature and precipitation since 1900

Trend analysis uses statistical methods to analyze records spanning a period of time in order to assess whether or not there is a detectable trend that clearly emerges from the year-to-year and longer-term variability. When a detectable trend is identified, this indicates a change (see Section 1-3). For the analyses performed for this report, linear regression analysis was used to determine whether the slope of a trend line was different than zero at >97.5% likelihood.

Section 2-3 describes variability and trends in Colorado's climate since 1900. These analyses are based on data from the NWS COOP Observing Network described in Section 2-2, using both unadjusted records from individual COOP weather stations and adjusted COOP records as composited into NCDC's official climate division and statewide averages.

Analysis of selected high-quality, unadjusted COOP stations records

In 2008, in collaboration with the Western Water Assessment (WWA), the Colorado Climate Center categorized each station in Colorado according to suitability for trend analysis and detection. The Colorado Climate Center developed a website specifically to view temperature and precipitation variations and trends for the best long-term datasets at stations in Colorado, including the data shown in Figures 2-5 and 2-6 (accessed via http://ccc.atmos.colostate.edu).

To represent local differences in climate variability and trends in Colorado using the most fundamental data sources, for the 2008 Report nine stations were selected from 38 "better quality" stations throughout Colorado (Figures 2-5 and 2-6). Since all of these stations are still in operation, they were used again for this report, with the records updated through 2012. All nine stations have 90-year or longer records for both temperature and precipitation, and relatively few identified problems with station relocation, instrument changes, and missing observations, according to analysis by the Colorado Climate Center and the WWA. Stations in Denver, Colorado Springs, and the central mountains were relocated too frequently or had other problems limiting their use in long-term analysis. The temperature records for the nine selected stations show the annual departures from the 1971–2000 average (Figure 2-5), and the precipitation records (Figure 2-6) show the annual values, as well as the 1971–2000 average.

The nine stations show similar variability in temperature (Figure 2-5) on decadal timescales since 1900: a very cool period from 1900 to 1930, warm periods in the 1930s and again in the 1950s, a cool period in the 1960s and 1970s, variable conditions in the 1980s, and a very warm period since the mid-1990s (Figure 2-3). The annual variability is also similar among the records, with 1934, 1954 and 2012 consistently among the five warmest years, and 1913, 1929, and 1951 among the five coolest. The temperature for each year generally falls within 2°F of the long-term average for that station. At seven of the nine stations, the warmest running 10-year period on record ends in 2005 or later, indicating that the temperatures since the mid-1990s exceed those of earlier warm periods. For the remaining two stations, the warmest period ends in 1938 and 1943, respectively.

Linear regression analysis was used to identify trends in the temperature record that were statistically significant (>97.5% likelihood). Of the total of 27 linear trends for temperature examined (30-, 50-, and 100-year time periods, at nine stations), 18 are increasing, 1 is decreasing (the 100-year trend at Lamar), and 8 are

FIGURE 2-5. Annual temperature at nine long-term observing stations, 1900-2012

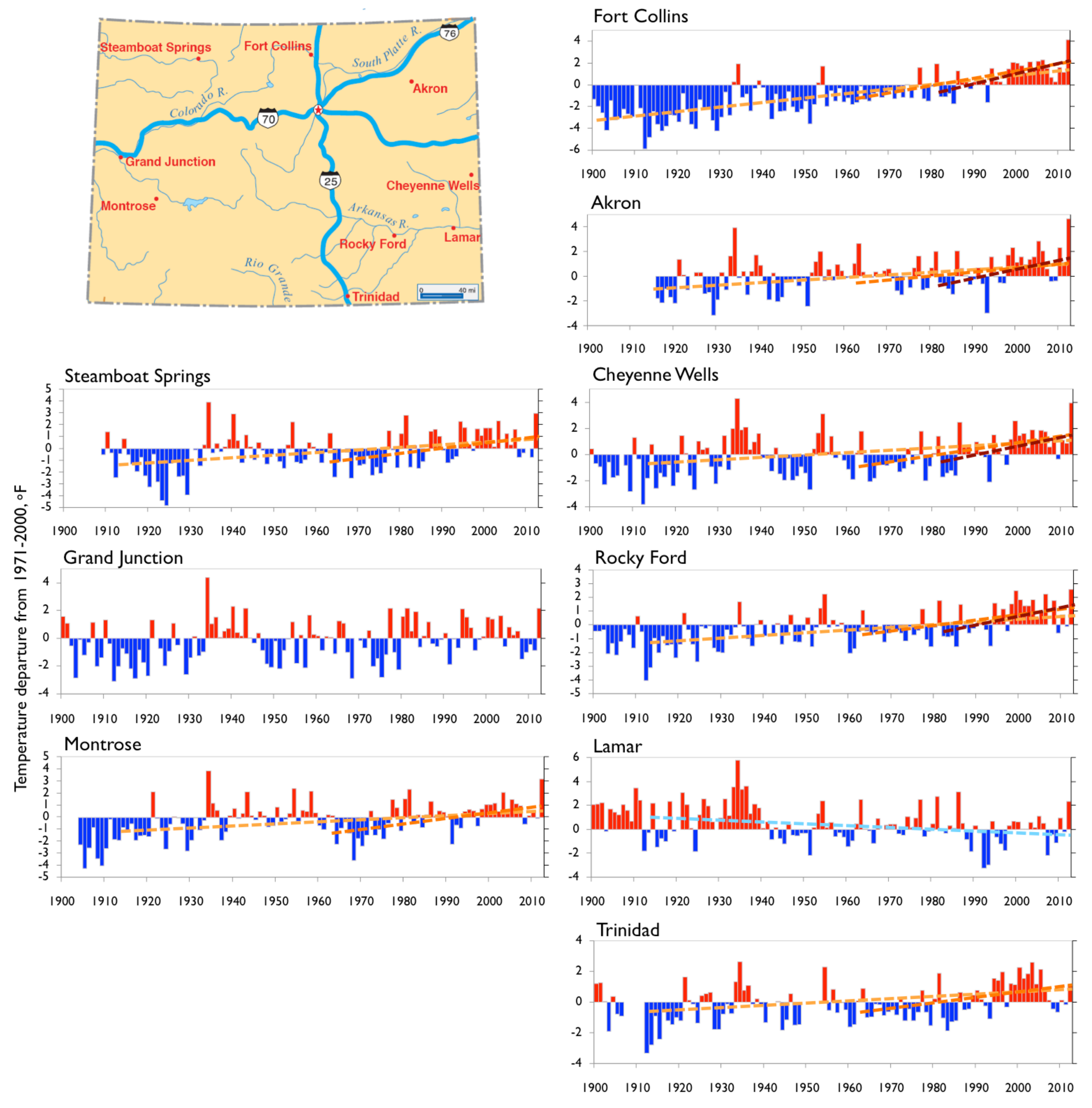

Fig. 2-5. Annually averaged temperature, 1900–2012, expressed as a departure (°F) from the 1971–2000 average, at nine long-term observing stations in Colorado. Station locations are shown on the map of Colorado (top left). Those linear trends through 2012 that are statistically significant (>97.5%) are shown with yellow or blue (100-year), orange (50-year) and dark red (30-year) lines. Of the 27 total trends examined, 18 are increasing, 1 is decreasing (100-year trend at Lamar), and 8 are not statistically significant (not shown). (Source: NOAA NCDC; analysis by K. Wolter)

not statistically significant (Figure 2-5). These results are very similar to the results of the trend analysis conducted for the 2008 Report, which examined the same nine stations, and in which the periods for the trend analysis were shifted six years earlier, so that all periods ended in 2006. That analysis found that 19 of 27 trends were increasing, 1 was decreasing, and 7 were not significant. In contrast, no significant

FIGURE 2-6. Annual precipitation at nine long-term observing stations, 1900–2012

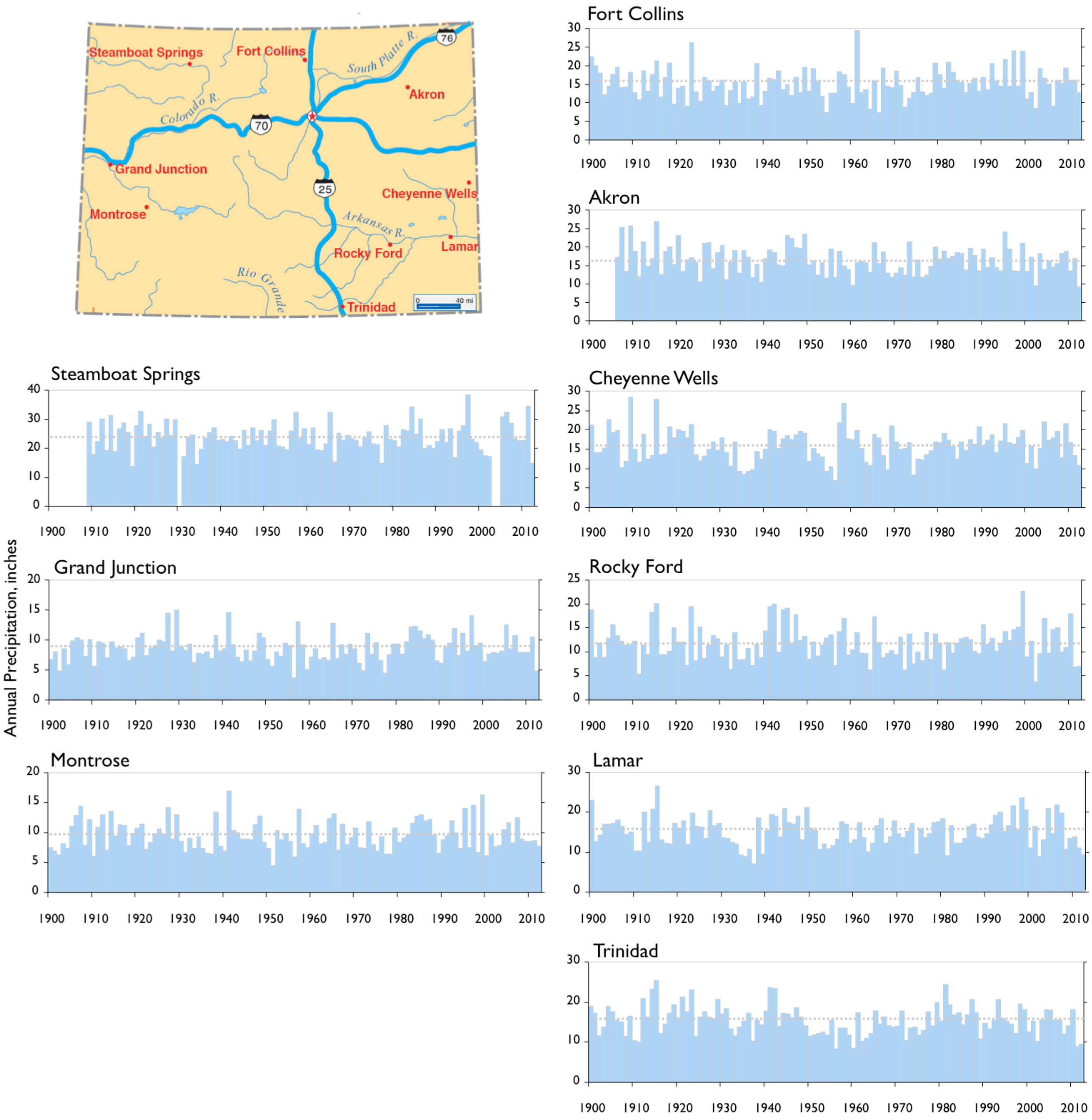

Fig. 2-6. Water year precipitation (inches) at nine long-term observing stations in Colorado, 1900–2012. Station locations are shown on the map of Colorado (top left). The 1971–2000 averages are shown with the gray dashed lines. The linear trends (30-, 50-, and 100-year) through 2012 are not significant at any of the nine stations. The records share much decadal-scale variability, such as the droughts of the 1930s, 1950s, and the early 2000s. (Source: NOAA NCDC; analysis by K. Wolter)

long-term trends in annual precipitation (Figure 2-6) were detected over the three time periods for any of the nine stations. The year-to-year and decadal-scale variability dominates the records; annual precipitation ranges three-fold to four-fold at all locations, from half the long-term average in a dry year up to double the average in a wet year (Figure 2-6). Examination of the coefficient of variation (CV) indicates there have been no consistent increases or decreases in the magnitude of year-to-year variability over the length of the nine records.

FIGURE 2-7. Annual temperature for nine alternate climate divisions, 1913–2012

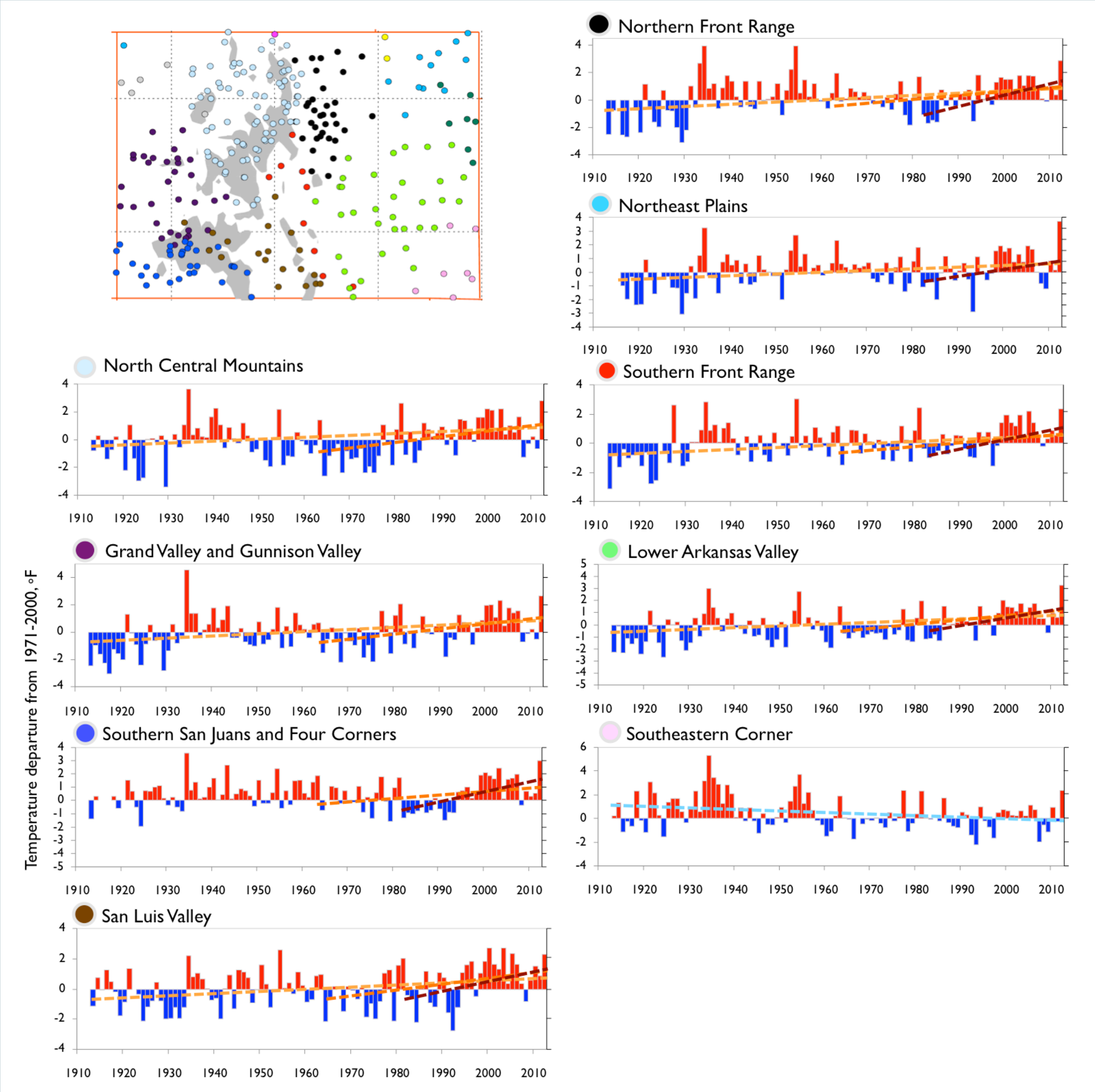

Fig. 2-7. Annually averaged daily temperature, 1913–2012, expressed as a departure (°F) from the 1971–2000 average, for nine alternate climate divisions (Wolter and Allured 2007) with multiple stations in Colorado. Station locations are color-coded to the divisions, as shown on the map of Colorado (top left). The linear trends through 2012 that are statistically significant (>97.5%) are shown with yellow or blue (100-year), orange (50-year) and dark red (30-year) lines. Of the 27 total trends examined, 20 are increasing, 1 is decreasing (100-year trend for Southeastern Corner), and 6 are not statistically significant. The gray shading on the map shows mountain areas over 10,000′ in elevation. (Source: NOAA NCDC for individual station records; analysis by K. Wolter)

Regional analysis from unadjusted COOP records

Climatic trends at individual stations (Figures 2-5 and 2-6) may not necessarily be representative of climate over larger areas, such as a river basin, because of local processes affecting those stations. For this reason, climatologists often assess long-term regional variability by grouping observing stations together. These groupings can be more reliable indicators of regional differences in trends and variability than individual stations.

The NOAA National Climatic Data Center's (NCDC) five official climate divisions group Colorado climate data into regions by river basins, but as NOAA acknowledges, the divisions are not necessarily representative of the complex regional climates in the state. An alternate set of climate divisions was developed by Wolter and Allured (2007). These alternate divisions are based on groups of observing stations that vary in a similar manner from year to year, reflecting similar underlying regional climate processes. This procedure resulted in nine primary climate divisions in Colorado, each having at least seven stations within the state. Sufficient data are available to construct time-series of temperature for all nine climate divisions back to 1913, although the San Luis Valley division is based on only a single station before 1950. The averages calculated from the better-quality observing records within each division can help to detect regional temperature trends by eliminating local processes that are not indicative of regional climate at each observing station.

Temperature trends were computed for these alternative climate divisions for the same time periods (30-, 50-, and 100-year periods; Figure 2-7) as for the nine-station analysis. Most of the nine divisions have statistically significant warming trends over the past 100 years (7 of 9), the past 50 years (7 of 9), and the past 30 years (6 of 9). Over the past 30 years (1983–2012), the strongest warming trends are in southwest Colorado (+2.8°F), the San Luis Valley (+2.5°F), and the northern Front Range (+2.4°F). The Southeastern Corner (pink circles) climate division, which includes the Lamar station noted in the nine-station analysis, is the only division to have a significant long-term cooling trend (over the past 100 years) and to have no significant warming in either the past 50 or 30 years. Only two stations, Holly and Lamar were used

FIGURE 2-8. Statewide annual temperature, 1900–2012

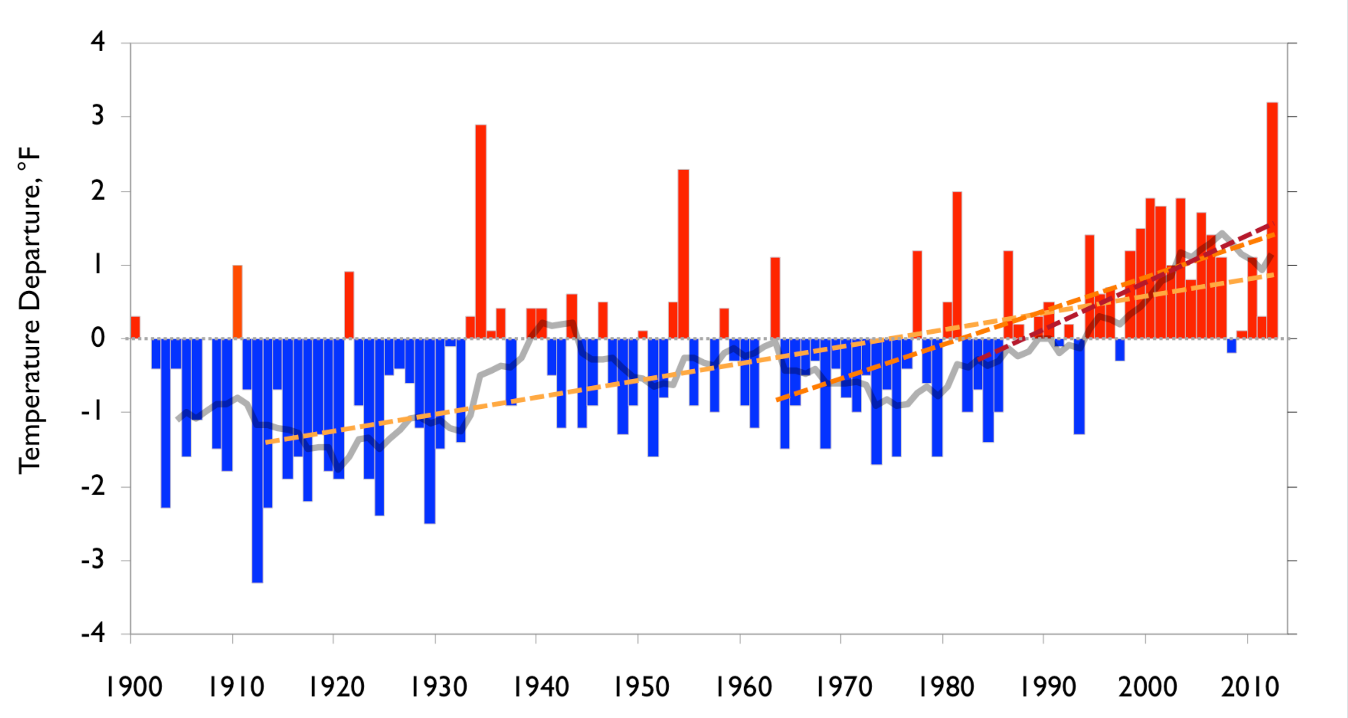

Fig. 2-8. Colorado statewide annually-averaged temperature (°F), 1900–2012. Annual departures are relative to a 1971-2000 reference period. The dashed yellow, orange, and dark-red lines are the 100-year, 50-year, and 30-year trends, respectively. All three warming trends are statistically significant. The gray line is the running 10-year average. The record shows a cool period from 1900 to 1930, a warm period in the 1930s and again in the 1950s, a cool period in the late 1960s and 1970s, and consistently warm temperatures since the mid-1990s. (Data source: NOAA NCDC; http://www.ncdc.noaa.gov/cag/)

to compute the divisional average. Pielke et al. (2002, 2007) discuss problems with the observational record at these stations, including changes in observation time that may have introduced a cold bias.

Statewide analysis from adjusted COOP records

A final approach to examining trend and variability in Colorado's temperature and precipitation is to use the official statewide averages from the new "nClimDiv" dataset from NOAA NCDC, in which individual COOP records are first adjusted to account for changes in station location, instrumentation, and time of observation as described in Section 2-2, then interpolated to a 5-km (3-mile) grid similar to that used for PRISM data, and then averaged over the grid to represent divisional or statewide values.

The statewide average temperature for Colorado since 1900 is shown in Figure 2-8. Colorado's climate since 1900 shows a cool period from 1900 to 1930, a warm period in the 1930s and again in the 1950s, a cool period in the 1960s and 1970s, and a general warming trend since about 1970. Since 1994, 18 of 20 years have been warmer than the 1971–2000 average. The temperature has increased by +2.5°F in the past 50 years (1963–2012) and by +2.0°F in the past 30 years (1983–2012). Both of these warming trends are statistically significant, as is the 100-year (1913–2012) warming trend (+2.2°F).[4] The statewide warming shown here and in the previous figures is consistent with the regional warming that has been observed across the western U.S. (Hoerling et al. 2013).

The effect of the NCDC station adjustment on the statewide trends can be discerned by comparing the data shown in Figure 2-8 with an average of the nine climate division records shown in Figure 2-7. The average of the nine climate divisions has increased by 1.5°F in the past 50 years and 1.8°F in the past 30 years. These trends are smaller than those in the adjusted statewide data, but are still statistically significant.

Using the NCDC statewide data, we can also examine the trends in daily minimum and maximum temperatures, and also in the average temperatures by season. The daily minimum temperatures (nighttime lows) averaged across Colorado have warmed more than daily maximum temperatures (daytime highs) during these periods. This pattern is consistent with U.S. and global trends (Hoerling et al. 2013, Walsh et al. 2014a). Statewide temperatures in the past 50 years have increased in all seasons, with the largest trend in spring (3.4°F), followed by summer (2.4°F), winter (2.3°F), and fall (1.8°F). Over the past 30 years, temperatures have also increased in all seasons, although with a different ordering in the seasonal changes: the largest trend has been in summer (2.5°F), followed by fall (2.5°F), spring (2.2°F), and winter (1.6°F).

Temperature trends with elevation

Temperature tends to decrease as elevation increases, and temperature strongly influences hydrologic processes such as evapotranspiration, snowpack accumulation, and timing of snowmelt. An elevation-dependent response in the overall observed warming trend for Colorado—consistently lesser or greater warming at higher elevations—would have important implications for water resources. There are physical reasons to expect greater warming at high elevations as global temperatures increase (Rangwala and Miller 2012). But the sparseness of long-term observations at elevations above 10,000' in Colorado limits our ability to reliably determine whether elevation-dependent warming is actually occurring. At present, there is no consistent and robust observational evidence that higher-elevation regions in Colorado are warming at a different rate than lower-elevation regions.[5]

2-4. Snowpack and streamflow

All of Colorado's major rivers, and all streams with headwaters above about 8,000', have a snowmelt-

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[4] Compared to the previous NCDC divisional dataset, the nClimDiv dataset released in March 2014 has better data coverage prior to 1930, and because it uses grid-based spatial averaging, there can be differences in the statewide and divisional values for all time periods. In the previous NCDC dataset, the Colorado statewide warming trends were as follows: 30-year: 1.9°F; 50-year: 2.6°F; 100-year: 2.0°F.

[5] The 2008 Report reported the results from Diaz and Eischeid (2007), who analyzed the temperature record in the PRISM dataset, and found larger warming trends at high elevations, as shown in Figure 2-6 in the 2008 Report. However, this finding is no longer believed to be robust, in part because of the scarcity of observed data in PRISM for regions above 10,000'. Additional analyses since 2008 also point to the Diaz and Eischeid (2007) finding being affected by discrepancies in temperature observations from the high-elevation SNOTEL network incorporated into the PRISM dataset.

dominated hydrology. The majority of the annual flow originates as meltwater from a mountain snowpack which accumulates from late fall into the spring and typically peaks in April or May. The rapid melt of the snowpack creates a pronounced peak in streamflow, typically in May or June. In this section we describe the observed variability and trends in Colorado's snowpack and streamflow.

Snowpack

Snow-water equivalent (SWE) describes the total amount of water stored as snow; that is, the amount of liquid water that would result if the snowpack were melted down. April 1 SWE has a close relationship with April–July streamflow in Colorado and elsewhere in the West, and is a better measure for hydrologic monitoring than total snowfall or snow depth. SWE is measured at SNOTEL (SNowpack TELemetry) sites and snow courses across the West by the Natural Resources Conservation Service (NRCS). Similar to weather station data, snow data are subject to non-climatic influences, including local weather-modification efforts (cloud-seeding) and changes in vegetation over time that affect snow deposition at the site (Julander and Bricco 2006). Thus, as with other climate data, trend analyses based on multiple sites are more representative of basin-wide conditions than those based on a single site.

Several studies have assessed trends in April 1 SWE across the West from 1950 to the early 2000s using a combination of snow course and SNOTEL data (Hamlet et al. 2005, Mote et al. 2005; Regonda et al. 2005). While declining SWE was detected in other parts of the West over that time period, Colorado was found to have had no overall trends. Hamlet et al. (2005) concluded that those stations reporting increased SWE were associated with modest upward precipitation trends, and that widespread warming, rather than precipitation trends, caused the downward trends in SWE. The warming was also linked to the overall regional trend towards a greater proportion of cool-season precipitation falling as rain rather than snow, though there have been no consistent rain vs. snow trends for Colorado (Knowles et al. 2006). Colorado has colder climate and generally higher elevations than the regions with the largest downward trends in April 1 SWE: the Cascades, northern Sierra Nevada, and northern Rocky Mountains. Accordingly, the snowpack in Colorado appears to be less vulnerable to the impacts of the observed West-wide warming trend than other regions.

A more recent study by Clow (2010) assessed trends in Colorado's snowpack between 1978 and 2007. The period examined by Clow was constrained by the choice to use only SNOTEL records, which begin in the late 1970s. Over this shorter period, Clow found that there were significant downward trends in April 1 SWE in all 14 of the Colorado "snowpack regions" that he delineated. Winter precipitation significantly declined over this period in 11 of the 14 regions, suggesting that lower precipitation was largely driving the downward SWE trends, although warming springtime temperatures may have also been a factor.

A new analysis conducted for this report assessed the variability and trend in Colorado's April 1 SWE over the full length of the available observations (snowcourse and SNOTEL), which extend back to the late 1930s for three of Colorado's eight major river basins, and back to 1961 for the other five basins. Note that while April 1 SWE is a useful overall measure of snowpack, it may not reflect more subtle changes in the seasonal evolution of snowpack, such as the effects of dust-on-snow (see Sidebar 2-3).

The time-series of April 1 SWE (Figure 2-9) shows that in many years the eight basins track each other closely, especially in severe drought years such as 1977, 1981, 2002, 2012, and 2013. Over the entire April 1 SWE record, neighboring basins tend to correlate strongly. There are greater differences between the more northerly and southerly basins, reflecting the tendency of the winter storm tracks to favor either the north or south in some years. There also tends to be larger year-to-year variability in the southern basins. Thus, Figure 2-9 shows the eight basin records in two groupings, northern and southern. Of the long-term trends (30-year, 50-year) in April 1 SWE examined across all eight basins, no trends are statistically significant. The difference between this result and that of Clow (2010) is likely due to the different statistical approach; the Regional Kendall test used by Clow is more sensitive in detecting trends than linear regression (Clow 2010).

FIGURE 2-9. April 1 Snowpack through 2013 for Colorado's major river basins

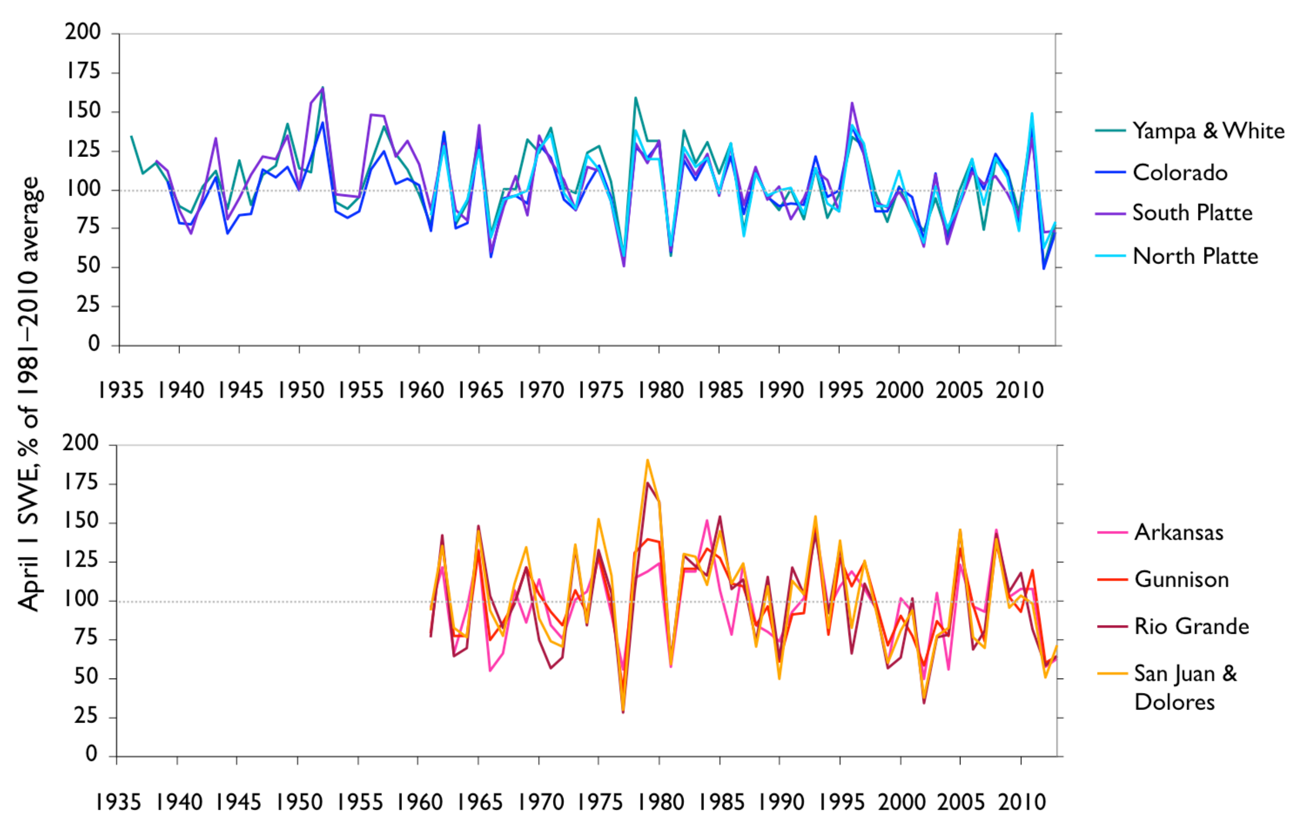

Fig. 2-9. April 1 Snow Water Equivalent (SWE) through 2013 for each of Colorado's eight major river basins, grouped by northern (top) and southern (bottom) basins. The start dates of the basin records, ranging from 1936 to 1961, are based on when multiple snow courses were established. Of the trends (30-year, 50-year, 70-year) examined for each basin, only one trend is statistically significant (70-year trend for South Platte Basin; decreasing). (Source: NRCS Colorado Snow Survey; analysis by K. Wolter)

Streamflow

The variability in surface water supply in Colorado, as represented by annual streamflow, very closely follows the variability in precipitation and snowpack with respect to the sign of the departure above or below average. However, evapotranspiration and related factors affect the conversion of precipitation to runoff so that the year-to-year variability of streamflow is greater than that of precipitation. For example, if the April 1 SWE in a given year is 90% of average (departure of 10% below average), the resulting April–July runoff will typically be closer to 80% of average (departure of 20% below average) (Vano et al. 2012). Figure 2-10 shows long-term records of naturalized[6] annual (water-year) streamflow for four river basins in Colorado through 2012, expressed as percentage of the average flow for 1971–2000. All four records show considerable year-to-year variability—a three- to six-fold difference between the lowest and highest annual flows—and decadal variability. All four records show the same multi-year droughts and wet periods, reflecting the large-scale influence of the weather patterns that determine Colorado's mountain precipitation and snowpack for a given winter. We did not detect significant long-term trends, however, in these four streamflow records. This

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[6] Naturalized streamflow, also known as natural, undepleted, or virgin streamflow, is a gaged streamflow record that has been corrected for human alterations of the natural hydrology, principally upstream diversions and augmentations, and reservoir storage and evaporation.

Sidebar 2-2. Beetles, climate and water

Engelmann spruce killed by spruce beetle infestation near Wolf Creek Pass, January 2013. The death of trees in the forest canopy alters key hydrologic processes, including snow accumulation, snowmelt, and water uptake by vegetation. (Photo: Eric Gordon, Western Water Assessment)

Since 2000, bark beetle epidemics have caused extensive tree mortality across 4 million acres of forested watersheds in Colorado (Pugh and Small 2011). Most of this acreage is in lodgepole pine forests infested by mountain pine beetle, but spruce beetle and pinyon ips beetle have also affected broad areas.

While bark beetles are native to Colorado's forests and have periodically erupted in epidemics every several decades, the epidemics in Colorado in the last 15 years are historically unprecedented in their scale. They are also part of continental-scale bark beetle epidemics that have occurred since the mid-1990s throughout western North America, from British Columbia to New Mexico. The synchronous timing of these widespread outbreaks of bark beetles has been attributed to the overall warm and dry conditions which have promoted beetle over-wintering survival and reproduction and reduced the trees' resistance to beetle attacks (Raffa et al. 2008, Bentz et al. 2010). A field study in Colorado's Front Range found that the emergence of mountain pine beetles from infested trees in 2009 and 2010 occurred 4–6 weeks earlier than in the 1970s, allowing for a longer season for infestation and, in some cases, a second round of reproduction in the summer (Mitton and Ferrenburg 2012).

In Colorado, most of the beetle-affected watersheds lie at higher elevations and produce substantial annual runoff from snowmelt (Section 2-4). Studies of tree harvesting and previous beetle infestations in Colorado have shown that widespread tree mortality leads to a significant increase in total runoff, and also earlier peak runoff, as the removal of the canopy causes changes in snow accumulation, snowmelt, and water uptake by trees. This led to the expectation that more runoff and earlier runoff would occur with the most recent infestation (Pugh and Gordon 2012).

However, three separate studies have failed to detect consistent changes in observed total runoff in Colorado in basins impacted by the post-2000 mountain pine beetle mortality (Stednick and Jensen 2007, Somor et al. in revision, K. Elder personal communication). The Western Water Assessment has recently conducted comprehensive hydrologic modeling of four affected Colorado watersheds to simulate the impacts of both bark beetle infestation and dust-on-snow (see Sidebar 2-3). The results show an increase in simulated annual runoff, of 5–10%, due to the effects of beetle infestation alone, consistent with the expectations described above (Livneh et al., in preparation). The mechanism for this increase is the combination of reduced canopy interception of snowfall (which leads to less sublimation loss) and reduced warm-season transpiration from beetle-killed areas, leaving more moisture available to run off into the streams. The modeled changes in runoff timing were negligible, due to the offsetting effects of increasing snow accumulation and faster melt.

In summary, it is plausible that a beetle "signal" in runoff in Colorado is actually occurring. But it is not large enough to be detected amid the high interannual variability in precipitation and runoff, which creates a very "noisy" background from which to tease out a trend due to the beetle infestations. The ongoing spruce beetle infestation in the San Juans expanded from 2010 to 2013 (photo, above), and given the deeper snowpacks in the high-elevation spruce-fir forests, changes in runoff may be detectable in the near future.

is consistent with the findings of Murphy and Ellis (2014), who did not find persistent long-term trends in streamflow in the three basins within Colorado they examined: the Yampa River, the Animas River, and the Upper Gunnison River. It is plausible that the recent warming has tended to reduce the fraction of annual precipitation reaching streams and rivers by increasing evapotranspiration (Hoerling et al. 2013), but this

FIGURE 2-10. Annual streamflows through 2012 for four major river basins

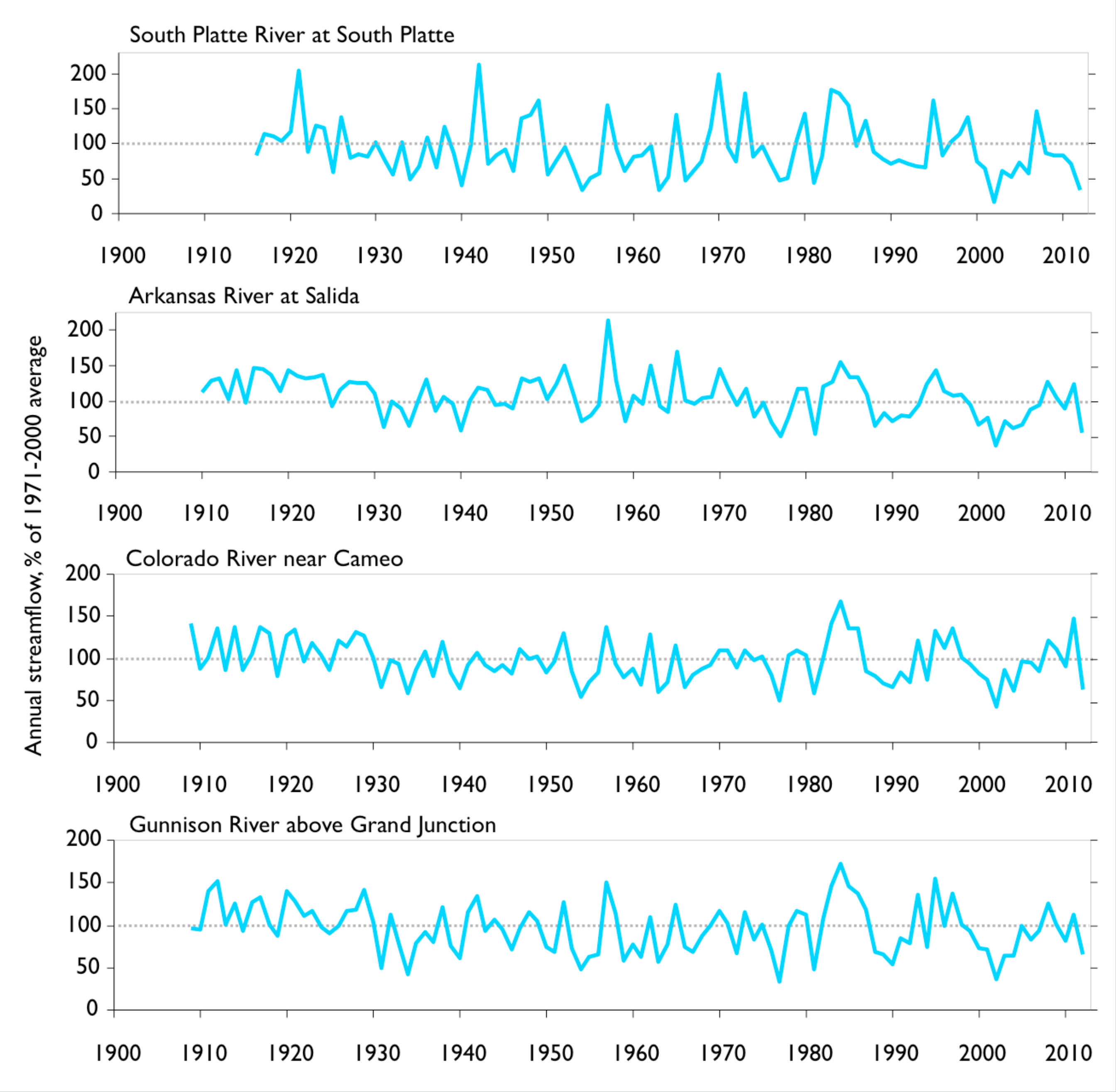


Fig. 2-10. Naturalized annual (water-year) streamflows through 2012 at four long-term (>95-year) stream gages representing runoff over four major river basins both east and west of the Divide. The range between the lowest and highest annual flows is three-fold to six-fold. Note that the gages have very similar year-to-year and decadal variability. The yellow dotted line shows the 1971–2000 average flow. 2002 is the lowest or second-lowest annual flow on record at all four gages. There are no significant long-term trends. (Data sources: South Platte: Denver Water; Arkansas: Colorado Springs Utilities through 2003, with 2004–2012 estimated from CDWR gaged flows; Colorado and Gunnison: Colorado Water Conservation Board through 2006, and 2007–2012 estimated from Reclamation natural flows and USGS gaged flows for the same gages)

effect has not been large enough to cause detectable trends in annual streamflow.

Regarding changes in the variability of streamflow over time, Pagano and Garen (2005) found increases in April-September streamflow variability for the White River at Meeker (1943-2002) and also an increase in the year-to-year persistence of high and low flows. A similar analysis of the four century-long water-year streamflow records shown in Figure 2-10, performed for this report, is in agreement their results. Comparing the 50-year periods before and after 1960, the coefficient of variation (CV) has increased by 10–20% at all four gages, indicating an overall increase in variability. The year-to-year persistence of high and low flows, as indicated by lag-1 autocorrelation (AR1), has also increased at all four gages since 1960, although this measure is much more variable over time than CV.

For many uses of water in Colorado, the timing of runoff can be as important as the runoff quantity, because of strictly timed diversion rights, specific crop water needs, and other factors. From 1950–2000, shifts to an earlier onset and peak of the spring runoff were not consistent across Colorado and were smaller (5–10 days) than in other regions of the West (Stewart et al. 2005, Regonda et al. 2005). More recent analyses, however, that include most or all of the generally dry and warm 2000–2010 period have detected larger shifts towards earlier spring runoff onset and peak runoff across Colorado (Clow 2010, Fritze et al. 2011, Hoerling et al. 2013), with the magnitude of the shift depending on the start date of the analysis. Clow (2010) found that the pervasive shifts to earlier snowmelt and runoff timing in Colorado from 1978–2007, of roughly 1–4 weeks, were best explained by a combination of the downward trends in SWE from 1978–2007, and the warming trend in spring temperatures over that same period. Clow (2010) also noted the potential impact of dust deposition on snowpack in changing snowmelt and runoff timing; this impact is explored further in Sidebar 2-3.

2-5. Drought

Drought is a simple concept: a period of drier-than-average conditions lasting from weeks to years. But defining the onset of drought, its severity, and its spatial patterns is more challenging. Droughts begin

Sidebar 2-3. Dust-on-snow: impacts on hydrology

In 2013, as in many recent years, the late-spring snowpack in the mountains of southwestern and central Colorado was a pink-red to brownish color, from a heavy deposition of desert dust (photo, next page). The dust's visual impact reflects physical changes that have already impacted the hydrology in the state's river basins, especially on the Western Slope.

Soil surfaces in the Colorado Plateau and Great Basin are naturally resistant to wind erosion thanks to physical and biogenic soil crusts, but these crusts are easily disturbed by land uses such as grazing, oil and gas exploration and drilling, agriculture, and off-road vehicle use. Once disturbed, soil particles can then be picked up by strong winds and transported hundreds of miles from the source. Dust-deposition events in Colorado occur with large-scale storms that produce strong southwesterly winds over the source regions, most frequently in late winter and spring. The dust layers from each event are buried by subsequent snows. As the snowpack compacts and melts down in late spring, the layers emerge and are concentrated at the snow surface.

Sediment cores from alpine lakes in the San Juan Mountains of Colorado tell us that dust deposition increased six-fold in the mid-1800s, coinciding with increased settlement and grazing (Neff et al. 2008). The deeper parts of the cores show no spikes of deposition corresponding to the several "megadroughts" prior to 1800 (see Section 2-7), further indicating that human disturbance rather than severe drought is the key factor in causing elevated dust emissions. The deposition decreased somewhat after the late 1800s, but leveled off in the late 20th century at about five times the natural background levels, due to continued disturbance. Dust deposition now appears to have increased in our region since the late 1990s, due to both increasing aridity in the dust source areas and increasing human disturbance of the soils (Brahney et al. 2013).

Field studies beginning in the mid-2000s have demonstrated that dust deposition in the snowpack alters the energy balance of snowmelt, enhances melt rates, and advances the timing of spring runoff (Painter et al. 2007, Painter et al.

Sidebar 2-3. Dust-on-snow: impacts on hydrology (cont'd.)

2012, Skiles et al. 2012). Using hydrologic models, two recent studies have quantified the likely impact of recent dust loading on both the timing and amount of runoff across the upper Colorado River Basin (Painter et al. 2010, Deems et al. 2013). Moderately dusty years like 2005 through 2008 are estimated to cause snowmelt and the peak of spring runoff to occur about three weeks earlier compared to with the pre-1800s dust levels. The extreme dust loading that occurred in 2009, 2010, and 2013—several times more than in 2005–2008—is estimated to cause melt and runoff to occur another three weeks earlier, or a total of six weeks earlier than in the pre-historic hydrology.

The modeling has also indicated that moderate dust loading has reduced runoff from the Upper Colorado River Basin by about 5%, or 800,000 acre-feet, compared to pre-1800s conditions. In the model, as the snowpack melts out earlier, more evapotranspiration occurs from soils and vegetation, reducing runoff. Extreme dust loading only increases that loss to 6%, because meltout occurs so early that the sun angle is too low to drive much additional evapotranspiration.

Dust-covered late-spring alpine snowpack in Senator Beck Basin, upper Uncompahgre River Basin north of Silverton, on May 16, 2013. The dust that has coalesced on the snow surface reflects the "extreme" dust deposition that occurred over the winter of 2012–2013, the highest since measurements began at Senator Beck Basin in 2004–2005. Dusty snow absorbs more solar radiation, causing faster melt and earlier peak runoff. (Photo: Jeff Deems, CIRES)

This dust-caused shift and reduction in runoff has likely been present in many years since the early 1900s, so the moderate dust impact is partly embedded in what we consider 'normal'. But the spatial and year-to-year variability in dust loading, and resulting impacts on the hydrograph, complicates the forecasting, storage, and allocation of runoff. The fact that three of the last five years through 2013 have seen "extreme" dust loading may indicate a trend towards increasing alteration of hydrology.

For the snowmelt processes on the receiving end of the dust, the interaction of the projected future warming with the dust-on-snow effect is complex, according to the modeling by Deems et al. (2013). Runoff timing is strongly affected by dust under all warming scenarios, meaning that dust reduction efforts could enhance snowpack longevity even under a markedly warmer climate. The amount of annual runoff shows the opposite: warming reduces snowpack amounts much more strongly than dust-induced evaporation losses, such that moving from moderate dust to extreme dust in a 2050 climate has no additional effect on runoff volume, at least averaged across a 20-year period. A warmer future climate would also lead to drier soils in the dust source region, reducing vegetation cover and allowing for greater dust emissions.

It may be possible to at least partly reverse dust-on-snow impacts in Colorado with management and policy changes. Researchers are currently working to determine how improved land-use practices might reduce the amount of dust that is mobilized and ultimately deposited in the snowpacks of Colorado and the West, with funding from water management agencies in the Colorado River basin.

CWCB and many other water management agencies are supporting the Colorado Dust-on-Snow (CODOS) dust monitoring program conducted by the Center for Snow and Avalanche Studies, in order to anticipate yearly impacts on snowmelt and runoff. See http://www.codos.org/#codos for more information.

as meteorological drought (a deficit in precipitation) and if they persist for more than a few weeks, they can also manifest as agricultural drought (soil moisture deficit) and hydrologic drought (reduced runoff). The severity of agricultural and hydrologic drought is a function not only of the precipitation deficit, but also increased evapotranspiration caused by warmer-than-average temperatures—which in summer are strongly associated with periods of low precipitation.

The indicators used to monitor and describe drought in Colorado and the West can be divided into those that (1) only reflect the precipitation deficit, such as percent of normal precipitation and Standardized Precipitation Index (SPI); and those that (2) reflect both the precipitation deficit and the effects of warmer temperatures that typically accompany drought. The latter set includes snowpack (e.g., percent of normal April 1 SWE), streamflow (e.g., percent of normal April–July runoff), reservoir storage, and the Palmer Drought Severity Index (PDSI; Palmer 1965). The drought indices that reflect the effects of both precipitation and temperature may be more useful in a warming climate.

PDSI represents the balance of water inputs to the soil, based on observed monthly precipitation, and water losses from the soil, based on observed monthly temperature. Thus PDSI is often used as an indicator of agricultural drought. This soil-moisture balance calculation accounts for the "memory" of water storage within the soil, so PDSI for a given month or season actually reflects the previous nine to twelve months of weather conditions (Palmer 1965; Alley 1984). Thus, while summer PDSI captures moisture anomalies that peak during the three months of summer, it also incorporates the weather of the previous fall, winter, and spring, i.e., the antecedent moisture.

The record of Colorado statewide summer PDSI from 1900–2013 (Figure 2-11) shows the annual and decadal variability also seen in the observed records of precipitation, snowpack, and streamflow that were described earlier. For much of the first three decades of the 20th century, Colorado and the West experienced relatively little drought. Sustained and severe drought emerged in Colorado and the Great Plains during the 1930s (the "Dust Bowl"), with lesser drought episodes in the 1950s and the mid-1960s. The period from 1965–1999, while not as wet as the early 20th century, saw less drought than the previous three decades, with short droughts in 1977 and 1981, and also in the early 1990s. Since 2000, Colorado has experienced an extended dry period, with few years of above-average summer PDSI and two particularly severe drought episodes: 2000–2003, including the record extreme conditions of 2002; and 2012–2013.

There is a statistically significant trend of decreasing statewide summer PDSI (i.e., more drought) over a 30-year period (1983–2012), but no trend over a 50-year period or 100-year period. The recent downward trend reflects both the persistently below-average precipitation since 2000, and the warming trend which has caused these recent PDSI values to be even lower than they

FIGURE 2-11. Statewide summer Palmer Drought Severity Index, 1900–2013

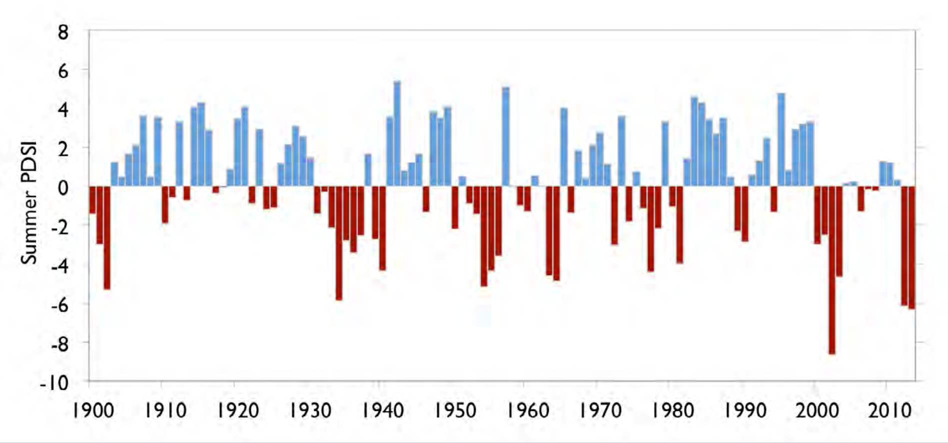


Fig. 2-11. Colorado statewide summer (June–August) Palmer Drought Severity Index (PDSI), 1900–2013. The multi-year droughts in the 1930s, 1950s, and 2000s stand out. Since 2000 the three lowest statewide summer PDSI values on record have occurred: 2002, 2013, and 2012. There is a significant decreasing trend (i.e., increasing drought severity) over the 30 years from 1983 to 2012. (Data source: NOAA NCDC; http://www.ncdc.noaa.gov/cag/)

would have been in the absence of warming.

Other studies indicate that the recent warming in our region may have exacerbated the recent drought conditions and drought impacts. A nationwide study found an increase in the severity of droughts over the period 1925–2003 in the southwestern United States, including the Western Slope of Colorado (Andreadis and Lettenmaier 2006). They qualitatively attributed the increased drought severity in that region to the increase in observed temperatures and the resulting increase in evapotranspiration. Similarly, Breshears et al. (2005) compared the early 2000s drought in the Southwest to the 1950s drought, in terms of vegetation impacts, and found that greater warmth had been a key factor in the recent drought's more severe impacts. Munson et al. (2011) concluded that over the previous 20 years, increasing temperatures in the southwestern US had led to both reduced cover of perennial grasses and increased emission and transport of dust from the Colorado Plateau (see Sidebar 2-3).

FIGURE 2-12. Statewide heat wave index, 1900–2012

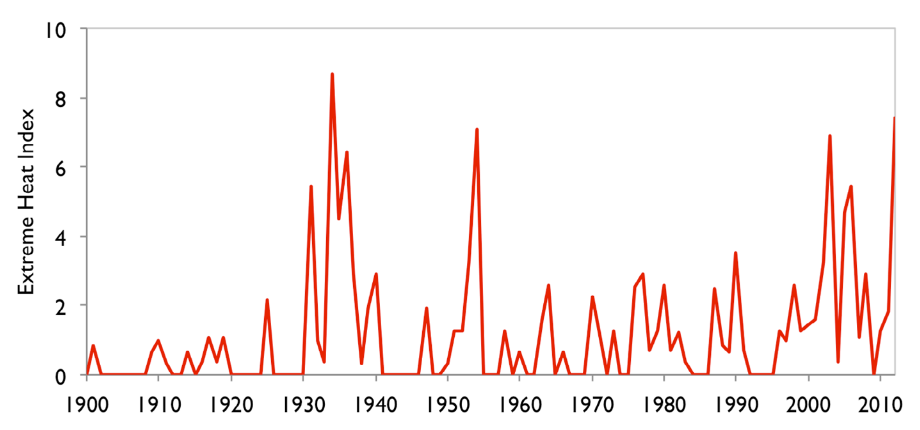


Fig. 2-12. Index of heat wave occurrence for Colorado, 1900–2012, based on 12 long-term observing stations across the state. There are increasing trends in heat waves over the past 50 years and 30 years. The most recent 10-year period (2003–2012) had the second-highest average index, after the period 1931–1940. (Data source: Kunkel et al. 2013b)

2-6. Other climate and weather extremes

Climate and weather extremes have received increasing attention recently, and rightly so. Rare extreme events cause the vast majority of societal costs related to climate and weather (Peterson et al. 2008). Thus it is important to understand whether the occurrence of extreme events has changed historically, and whether we should expect their occurrence to change in the future. But it is critical that we consider different types of extreme events individually, since they have different relationships with broad-scale atmospheric patterns and processes, and will respond differently to anthropogenic climate forcing. Blanket statements such as "extreme weather is getting worse" are difficult if not impossible to evaluate. Below, different types of extreme events are listed, followed by descriptions of observed variability and trends in those extremes in Colorado and the surrounding region.

Heat waves

Multi-day extremes of high temperature have a straightforward link to a warming climate; as temperatures warm in general, we would expect the number of days above a given temperature threshold to increase. Over the six-state Southwest region, there has been an increasing trend in heat waves since 1900, although the heat-wave frequency in the 2000s is not markedly higher than the 1930s (Hoerling et al. 2013). Heat waves are defined as the *n* hottest 4-day periods observed at each station over the entire record, where *n* is the station record length in years divided by 5. Thus, these are events that would be expected to occur no more often than every five years. For Colorado, this same index, based on 12 long-term stations, shows significant increasing trends in heat waves over the past 50 years and 30 years (Figure 2-12; Kunkel et al. 2013b). The heat wave occurrence averaged over 2003–2012 is the second-highest of any 10-year period, after 1931–1940. This highlights the unusual nature of the 1930s, and indicates that the most recent heat waves in

Colorado are not yet outside of the range of historical variability.

Cold waves

Conversely, as the climate warms overall, we would expect the number of cold days below a given threshold to decrease. The Extreme Cold Index for Colorado represents the occurrence of severe cold waves; these are the very coldest 4-day periods at each of 12 stations, such that they have occurred once every five years or less frequently. The occurrence of cold waves shows a decreasing trend over the past 30 years, but no trend over longer periods (Figure 2-13, Kunkel et al. 2013b). This is consistent with the regional trend in cold waves over the six-state Southwest region (Hoerling et al. 2013). Overall, the intrusion of deep Arctic air masses into the U.S. has become less frequent in recent decades (Peterson et al. 2013).

FIGURE 2-13. Statewide cold wave index, 1900–2012

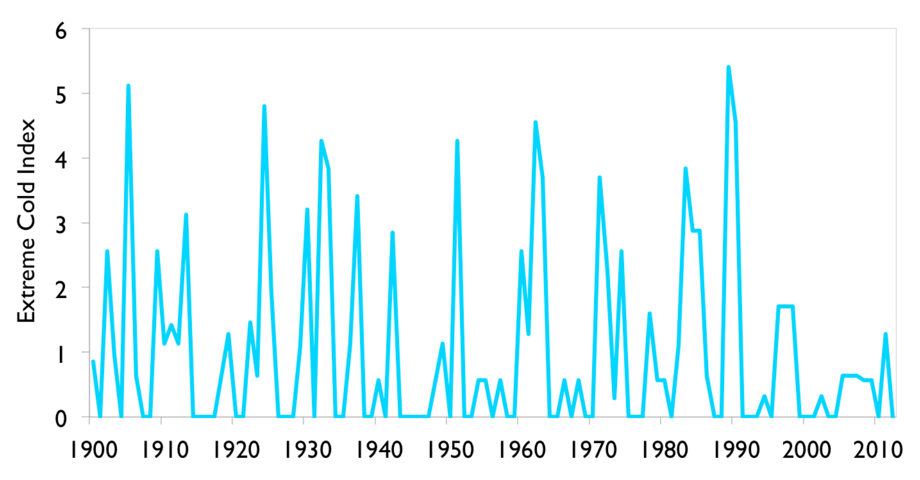


Fig. 2-13. Index of cold wave occurrence for Colorado, 1900–2012, based on 12 long-term observing stations across the state. There is a decreasing trend in cold waves over the past 30 years. (Data source: Kunkel et al. 2013b)

FIGURE 2-14. Statewide length of frost-free season, 1900–2012

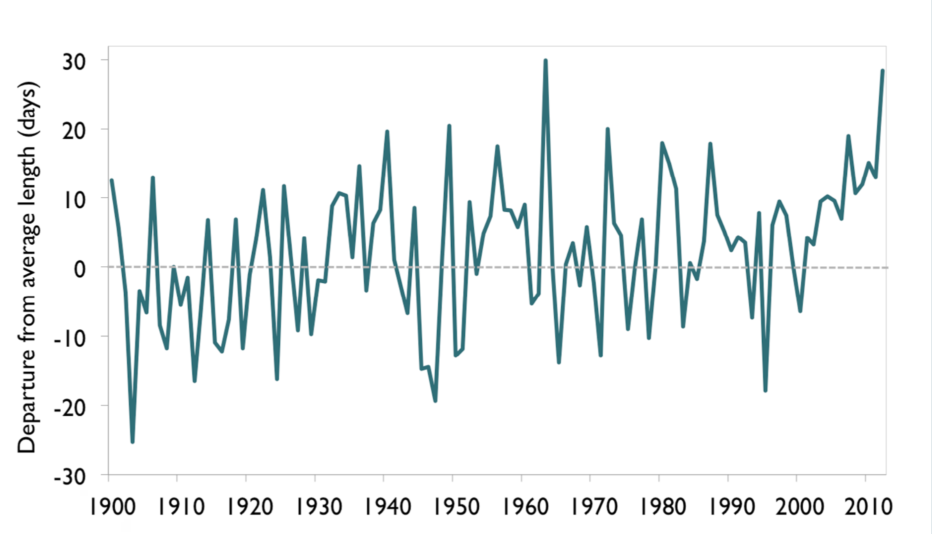


Fig. 2-14. Length of frost-free season, expressed as a departure from the 20th-century (1901–2000) baseline, based on 12 long-term observing stations across the state, 1900–2012. There is a significant increasing long-term trend in the frost-free season, consistent with the overall warming trend. (Data source: Kunkel et al. 2013b)

Frost-free season

The frost-free season is the period between the last frost in spring and the first frost in fall, with frost defined as the minimum temperature falling below 32°F. The length of the frost-free season has important implications for agriculture, as it is strongly correlated with the growing season and partly dictates what crops and varieties can be grown in a given area, and likewise constrains urban landscaping. The frost-free season also has some influence on wildfires (see below), as a growing season that extends further into spring allows more grass and other fine fuels to grow prior to their drying and curing during the summer fire season. A statewide averaged frost-free season length for Colorado, based on 12 long-term observing stations across the state, shows significant increasing 100-year and 30-year trends, consistent with the warming trend in annual temperatures (Figure 2-14, Kunkel 2013b). The 50-year trend is not statistically significant.

Heavy precipitation events

Warmer temperatures tend to cause more water vapor will be evaporated and held in the atmosphere. Globally, there has been an increase in water vapor of 3–5% since the 1970s (IPCC 2013). Whether this increased water vapor is translated into more frequent heavy or extreme precipitation events depends on a complex interplay of factors at different spatial scales. Heavy and extreme precipitation events may not necessarily show the same trend over time as total annual precipitation.

In the United States, heavy precipitation events—those occurring once every year or less often—have increased in the past 50 years in some regions, especially the Northeast and the Midwest (Peterson et al. 2013, Walsh et al. 2014a). The six-state Southwest region, however, has experienced no detectable trends in 1-day heavy precipitation events or 5-day heavy precipitation events (Hoerling et al. 2013).

The same indices of heavy precipitation events for Colorado, based on daily precipitation records from 12 long-term observing stations, also show no statistically significant trends over the past 30, 50, or 100 years. The threshold for 1-day events varies by station but is generally 1”–2” of precipitation in 24 hours for western Colorado, and 2”–3” in 24 hours for eastern Colorado. About half of these events occurred in summer (June–August), about one-third in spring (March–May), and most of the rest in fall. A different index, based on the proportion of annual precipitation coming in the largest 1% of all precipitation events, also shows no trend for Colorado since 1900 (Kunkel 2013b). In summary, there are no clear trends in heavy precipitation events for Colorado, and like annual precipitation, there is considerable variability at annual and decadal time scales. (Including the September 2013 Front Range rainfall event in the trend analyses would not change this conclusion.)

Floods

While the occurrence of flooding is usually dependent on heavy precipitation, the trends in flood events may not necessarily track the trends in heavy precipitation events as expressed in the indices described above. Additional factors such as precipitation intensity, soil moisture and snow conditions, and basin topography are also important in determining the occurrence and severity of flooding. And while many floods are immediate responses to precipitation events, whether flash floods from individual thunderstorms or larger-scale flooding, Colorado can also experience flooding from rapid spring melting of the mountain snowpack, without any additional precipitation.

The evidence in Colorado is limited, but suggests there has been no increase in flood events over the past 100 years. Two recent studies have together assessed eight long-term near-natural streamflow records in Colorado for trends in annual peak daily discharges (i.e., the highest discharge observed in each year), as part of national analyses (Villarini et al. 2009, Hirsch and Ryberg 2012). No increasing trends over time in annual peak discharges were detected at any of the eight Colorado gages. Because both of these analyses included all annual peak discharges over the period of record, neither study necessarily speaks to trends in less frequent and more severe floods, such as the September 2013 flood event in eastern Colorado (see Sidebar 4-2).

Wildfires

The ignition of wildfires and their intensity and size are strongly influenced by climate and weather conditions prior to and during the fire season (Littell et al. 2009). In the Southern Rockies ecoregion, which covers all of Colorado’s forested mountain regions and extends slightly into Wyoming and New Mexico, variation in spring and summer precipitation accounted for most of the year-to-year variability in wildfire area burned from 1977–2003, with drier conditions of course being associated with more fire (Littell et al. 2009). Non-climatic factors also affect both ignitions and fire behavior. These include changes in forest and land management (e.g., fire suppression) and resulting changes in fuel loads, and increasing human activity and development within forests and other fire-prone vegetation types.

Since 2000, Colorado has experienced its three largest wildfires since at least 1930, topped by the 140,000-acre Hayman Fire in 2002, and also the five most destructive wildfires in terms of structures destroyed, topped by the 2013 Black Forest Fire (over 500 homes). A recent analysis found that Colorado large fires (>1,000 acres) that burned on National Forest lands have greatly increased since 1970, with 6 large fires in the decade from 1970–1979, 11 from 1980–1989, 7 from 1990–1999, 35 from 2000–2009, and 19 in just the three years 2010–2012 (Climate Central 2012). This increasing trend in large fires in Colorado is consistent with trends across the western United States. Westerling et al. (2006) found that the increasing trends in the area burned by wildfires and the length of the fire season across the West since 1970 were strongly correlated with increasing spring and summer temperatures, and earlier snowmelt. However, the strongest relationships were found in the Northern Rockies, with weaker relationships in the Southern Rockies, including Colorado. In summary, it is very plausible that the increase in large wildfires in Colorado since 2000 is at least partly due to climate factors, including both the overall warming trend and the very low precipitation during the summer fire season in several recent years.

2-7. The Paleoclimate of Colorado

Since observed climate records for Colorado are at most 125 years in length, and often much shorter, it can be helpful to get a longer perspective on natural climate variability and put the observed climate variations and trends into context. Paleoclimate studies use environmental indicators, or *proxies,* to reconstruct the climate prior to the beginning of instrumental records. For reconstructing the past one to two millennia of climate in Colorado, the most useful proxies are the annual growth rings of trees (tree rings), which can reflect either temperature variability or moisture variability, depending on the species, elevation, and location. Other paleoclimate proxies in Colorado and the surrounding region, such as ice cores, glacier size and movement, sand dunes, and lake sediments, provide information that complements and supports the tree-ring data.

Temperature

There are relatively few high-resolution (annual or near-annual) paleotemperature records for the past two millennia for Colorado and the surrounding region. All of these paleotemperature records indicate that the modern period, since about 1950, has been warmer than at any time since at least 1400. Most, but not all, of these records also agree that the modern period was also warmer than the period known as the Medieval Climate Anomaly (MCA) from c. 900–1350 AD, or any other period in the past 2000 years (Hoerling et al. 2013). Global climate model (GCM) experiments using paleo-proxy-derived estimates of past solar variability and volcanic activity also suggest that recent warmth in the southwestern United States exceeds the warmth of the MCA (Stevens et al. 2008; Woodhouse et al., 2010).

Precipitation, streamflow, and drought

Colorado and the surrounding region have yielded an unusually rich resource for reconstructing past hydrologic conditions: hundreds of highly moisture-sensitive tree-ring records from 300–2000 years long. Most of these records are based on Douglas-fir, ponderosa pine, or pinyon pine, all of which are abundant and live up to 900 years in Colorado. Other useful species include bristlecone pine, limber pine, and juniper, all of which can live over 1000 years. Dead wood may persist on the ground for many hundreds of years and can be used to extend the tree-ring records based on living trees.

These site-level tree-ring records are closely correlated with observed (post-1900) records of moisture-related variables in Colorado, including summer PDSI (Woodhouse and Brown 2001, Cook et al. 2009), seasonal and annual precipitation, April 1 snow-water equivalent (Woodhouse 2003; Pederson et al. 2011), and naturalized annual (water-year) streamflow (Woodhouse and Lukas 2006, Meko et al. 2007). By calibrating the tree-ring data with an observed record over their period of overlap, we can use the resulting statistical model to reconstruct that variable prior to the observed record. Here, we focus on the reconstructions of naturalized annual streamflow, since the past changes streamflow match those in the other moisture-related variables. Over 30 stream gages in Colorado, representing all seven of the state's water divisions, have been reconstructed using tree rings. Three of these reconstructions are shown in Figure 2-15, along with a reconstruction for the Colorado River at Lees Ferry, Arizona, which captures all of the runoff from western Colorado. These reconstructions as shown range from 370–1000 years long.

FIGURE 2-15. Tree-ring reconstructed streamflows for four major Colorado river basins

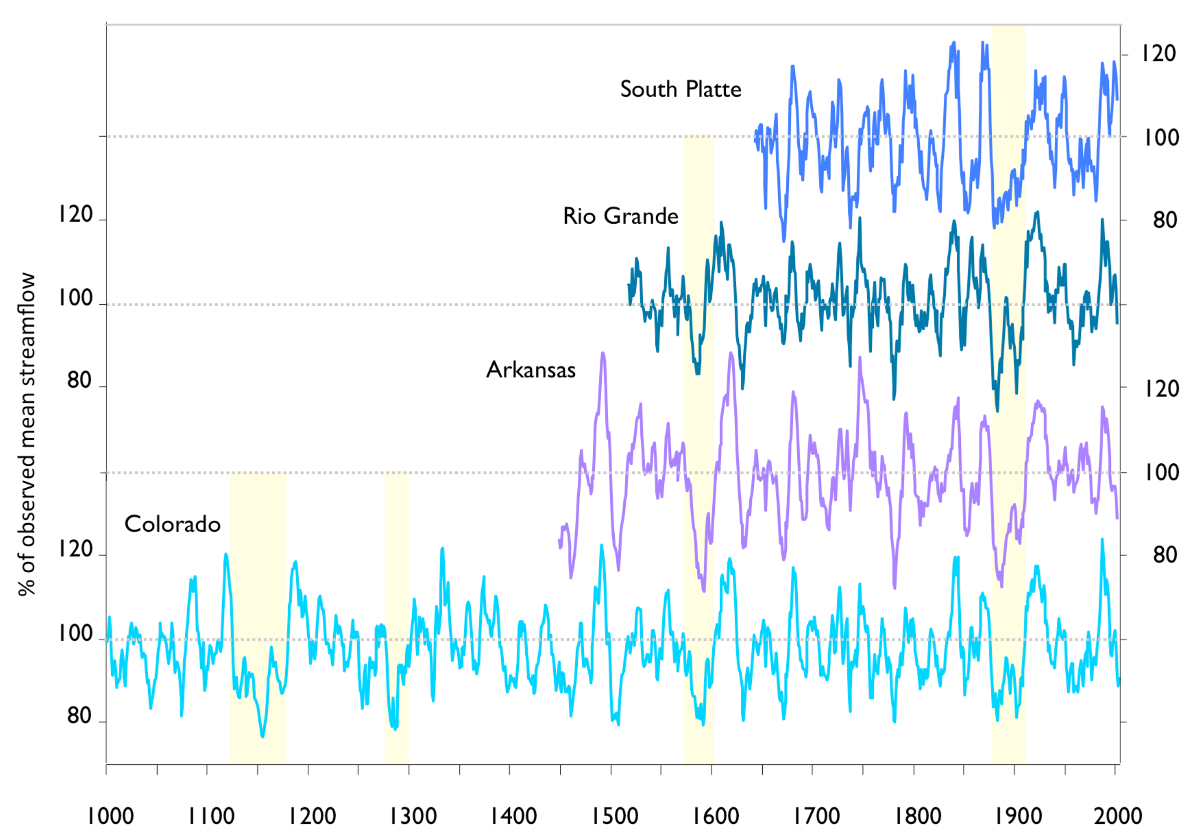


Fig. 2-15. Tree-ring reconstructed water-year streamflows as % of observed mean, showing the 10-year running average, for four gages representing major Colorado basins: the Colorado River at Lees Ferry, AZ (762–2005, here shown from 1000–2005), the South Platte River at South Platte, CO (1634–2002), the Rio Grande at Del Norte, CO (1508–2002), and the Arkansas River at Salida, CO (1440–2002). All four records show the occurrence of droughts prior to 1900 that were more severe and sustained than any modern droughts. The yellow shading highlights several notable multi-decadal paleodroughts, in the mid-1100s, the late 1200s, the late 1500s and the late 1800s. The 20th century was unusual in having two persistent wet periods and no droughts longer than 10 years. (Data: TreeFlow web resource; http://treeflow.info)

Collectively, these paleodrought records tell us that the most severe multi-year droughts observed during the past century in Colorado, such as the 1930s, 1950s and the early 2000s, were exceeded in severity and duration by several paleodrought events during the preceding 2000 years. The four records show very similar decadal-scale variability; all four show severe, sustained droughts in the late 1500s and late 1800s that have no analog in the post-1900 record. These pre-historic droughts were driven by natural variability in precipitation, and thus could recur in the future, independent of any changes in the climate. The most severe and sustained paleodroughts, sometimes called *megadroughts*, occurred during the relatively warm Medieval Climate Anomaly (MCA) from c. 900–1350 AD. These megadroughts were likely caused by persistently cool (La Niña-like) conditions in the tropical Pacific Ocean (Seager et al. 2008), which tends to lead to both below-average precipitation and above-average temperatures in our region. Severe and sustained paleodroughts also occurred during other times, the late 1500s megadrought (Stahle et al. 2000), and the early 2nd century megadrought (Routson et al. 2011). The paleo-records also indicate that the 20th century overall experienced less drought than most of the preceding 4–20 centuries (Barnett and Pierce 2009). The 20th century was also unusual in having two persistent wet periods. Thus, the observed record of Colorado's streamflow, typically used as the baseline for water planning, is not representative of natural variability over a longer period.

3

A Primer on Climate Models, Emissions Scenarios, and Downscaling

Key points

- Global climate models are complex, computer-based, mathematical representations of the Earth's climate system based on fundamental scientific principles. About 30 research centers worldwide have developed climate models, using the same fundamental principles but different representations of some climate processes.

- In the current generation of model projections (CMIP5), the models have generally increased in spatial resolution and complexity. They have improved in their ability to simulate temperature at regional scales, such as over Colorado, but they have not improved in their simulation of precipitation at regional scales.

- The CMIP5 projections represent incremental improvement in climate modeling, and do not invalidate the results of analyses done with the earlier set of model projections (CMIP3) that were featured in the 2008 Report.

- The average of all available models is consistently more accurate in simulating past climate than any individual model. However, the range of projections across all of the different models captures the uncertainty regarding the future trajectory of the climate, and so the range should be emphasized in planning.

- Representative Concentration Pathways (RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5) have been adopted by the international climate science community to replace the previous set of emissions scenarios (SRES) in representing future trajectories of

Aerial view of downtown Denver. Creative Commons, X-Weinzar.

greenhouse gases and other climate forcings. These span from RCP 2.6 (low), which assumes strong carbon mitigation, to RCP 8.5 (high), which assumes no mitigation.

- RCP 4.5, and RCP 6.0 have similar climate change implications out to 2050; RCP 2.6 has lesser effects on climate, and RCP 8.5 has greater effects. The four RCPs increasingly diverge after 2050 in their effects on climate.
- The global climate models can not represent the complexity of Colorado's topography, since the grid of the highest-resolution global models is about 40 miles on a side, or the length of a typical Colorado mountain range.
- Downscaling methods are used to translate the climate model output to the scales that are relevant processes to Colorado's natural resource managers. Many sets of downscaled projections are now available for Colorado, but each dataset has different strengths and weaknesses.

Global climate models are the principal tools used by climate scientists to quantitatively explore potential future climates, globally and regionally. They have improved significantly in the past few decades and now provide realistic simulations of many of the physical phenomena, broad-scale patterns, and statistical characteristics of the historical and current global climate. The simulations of future climate for a given region, including the projected changes in temperature and precipitation, differ widely among the different climate models, mainly reflecting the scientific uncertainty regarding some key climate processes. While this wide range of results can make interpretation and use of the model output challenging, they can still provide useful information for long-term planning.

In Section 3-1, we describe the inner workings of a climate model. Section 3-2 describes the CMIP model intercomparison program, the source of the model projections used in this report (Section 5) and in other climate assessments. Section 3-3 describes the emissions scenarios that are used to represent potential future pathways of greenhouse gases that are expected to be the main driver of climate change over the next century and longer. Section 3-4 describes how climate models are evaluated and the sources of differences among the models, and discusses the credibility of the model projections. Section 3-5 summarizes the process of downscaling the outputs of the global models so they can be applied to scales more relevant to resource management. Section 3-6 comments on the recent and likely future progress in climate modeling.

3-1. Anatomy of a climate model

Global climate models (GCMs) are complex, computer-based, mathematical representations of the Earth's climate based on fundamental scientific principles. Many different climate processes are represented in the global climate models (Figure 3-1). Precipitation, wind, cloudiness, the ocean currents, air and water temperatures, the amount and type of vegetation, the concentration of greenhouse gases (GHGs) and atmospheric aerosols (fine particles)—these and other

FIGURE 3-1. Components and processes in a global climate model

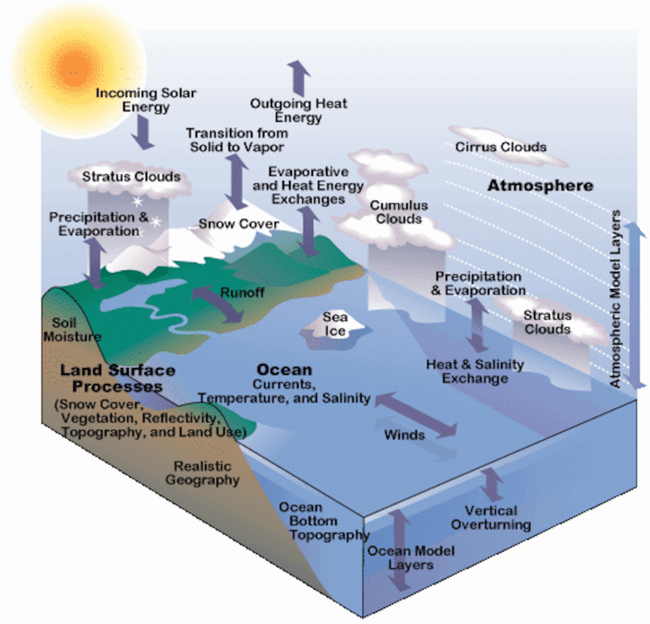


Fig. 3-1. Major climate system components and processes represented in a typical global climate model, the NCAR-based Community Climate System Model (CCSM). (Image credit: University Corporation for Atmospheric Research)

variables evolve in time and space governed by physical, chemical, and biological processes. All of these processes are expressed as mathematical equations derived from scientific laws, empirical relationships, and observations.

Two types of global climate models are commonly used for long-term projections: atmosphere-ocean general circulation models (AOGCMs), and the newer and more comprehensive Earth System Models (ESMs). AOGCMs simulate the atmosphere, ocean, sea-ice, and the land-surface energy and water balance, as well as the interactions among these components. ESMs include additional model components that simulate the sources and sinks of carbon dioxide, methane and other atmospheric trace gases along with the detailed evolution of these chemicals in the atmosphere.

How climate models operate

Climate models share many features with weather forecast models. Both types of models have at their cores the equations for fluid (air and water) dynamics and the first law of thermodynamics, the conservation of energy. They both include mathematical representations of many of the atmospheric processes shown in Figure 3-1 that are important to the daily weather. In fact, they both simulate weather on hourly or finer time scales. But compared to global climate models, weather forecast models have smaller spatial domains, higher spatial resolution, and much shorter forecast periods (days vs. years). Weather models do not need to simulate the ocean circulation, which doesn't influence weather on short time scales. Climate models cover the entire Earth at a relatively lower spatial resolution, include the ocean circulation, and are used to simulate decades to centuries. Another important difference is in the way the models are run. Weather forecast models are regularly updated with the latest atmospheric observations, because the accuracy of these starting observations (the initial conditions) is a large factor in determining the skill of the weather forecast for the next several days. In contrast, climate models are initialized with starting observations, but are not periodically updated with observed data. Instead, they run freely in time to simulate the past and make long-term projections of future climate. They generate their own sequences of weather, thus simulating natural climate variability, using only solar variations, greenhouse gas emissions or concentrations, and other slowly changing *forcings* as inputs.

Climate models are marched forward at discrete time intervals, called *timesteps*. Timesteps can range from a few minutes to an hour. As a result, the climate models simulate many aspects of the weather, and climate averages are computed from the simulated weather data just as they are from observed weather data.

In the spatial dimensions, climate models typically divide the globe—the atmosphere and the oceans—into a grid in the horizontal and vertical, creating gridboxes (Figure 3-2). The finer

FIGURE 3-2. Global climate model grid

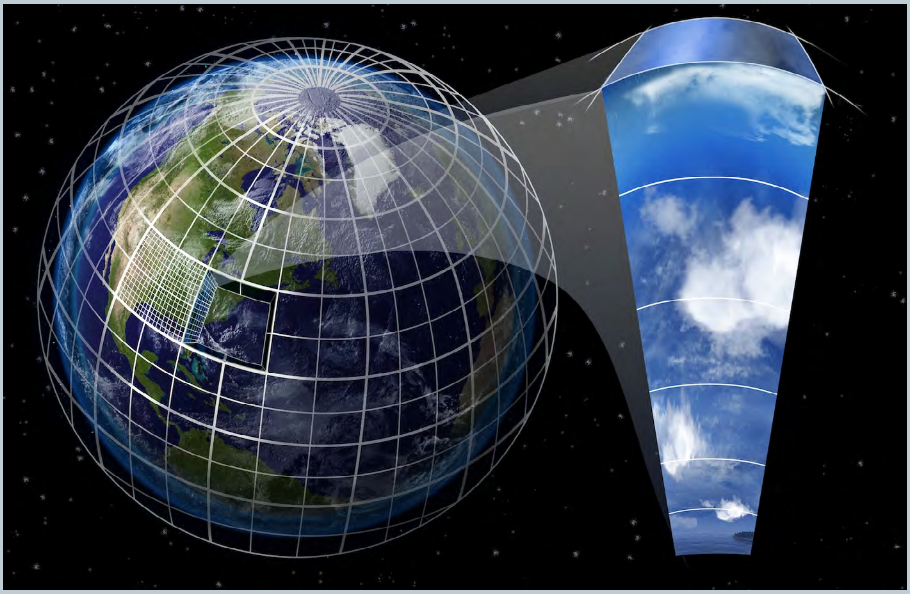


Fig. 3-2. The model grid for the atmosphere component of a global climate model. The grid for a typical climate model in the CMIP5 ensemble analyzed for this report is about 100 miles on a side in the horizontal, similar to the finer grid shown over the eastern US in the figure, with 25–40 layers of varying thickness in the vertical. The processes that take place at scales smaller than one gridbox are represented through parameterization: generalized values based on observations. (Image credit: Nicolle Rager Fuller, National Science Foundation)

the grid, the higher the spatial resolution, and the more computer power required to run the simulations. The clearest indicator of improvement in climate models over time is the increasing spatial resolution of the models; a typical model now has gridboxes measuring under 100 miles on a side (Table 3-1; Figure 3-4).

Many climate processes, such the formation of clouds and thunderstorms, take place at spatial scales much smaller than a model gridbox. Climate models don't ignore these processes; instead they account for the influence of these sub-grid-scale processes by using numerical factors (*parameters*) that have been generalized from observations to the gridbox scale, a procedure called *parameterization*. The choice of the methods used in parameterization can have a sizable impact on a model's climate simulations, and is one of the main causes of differences among the climate models. The parameterization of cloud formation and of cumulus convection (thunderstorms) stand out for their large impact on model results, and also for the wide range of parameters used by different modeling groups, which reflects the scientific uncertainty about how to best represent these processes.

Global climate models also represent surface hydrologic processes such as evapotranspiration, snowpack and soil moisture evolution, and river routing. In general, the hydrologic components of the current generation of climate models are much more detailed than previous generations. The main advantage of the hydrology output from climate models is that all of the key hydrologic processes are simulated into the future in a physically consistent and integrated manner. However, the robustness of these simulations is limited by the coarse spatial scales at which the models are run. Because the model grid cannot capture the full height of mountain ranges, the contribution of snow to the water cycle is underestimated. In addition, most of these models are not calibrated to specific basins. These limitations are particularly apparent in the western U.S. due to the complex topography, importance of snowpack to runoff, and a lack of detailed observations of soils and other drivers of sub-surface water flow.

Consequently, for most assessments of future hydrologic impacts for this region, only the basic climate outputs (temperature and precipitation changes) are extracted from the climate models, downscaled, and then run through much finer-scale stand-alone hydrologic models (e.g., VIC, SAC-SMA) that are calibrated for the basins of interest (see Section 5-3 and Figure 5-19). The stand-alone hydrologic models simulate all of the processes represented in the global climate models.

3-2. Model intercomparison: The CMIPs

In the 1990s the global community of climate modelers recognized the need for standardized sets of climate model runs, with consistent inputs, time periods for simulation, and historical and projected trajectories of greenhouse gases. These sets of model runs are designed around scientific hypotheses that can be tested within the framework of the climate models. These efforts evolved into the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project (CMIP). The third phase, called CMIP3, was carried out to support the IPCC's Fourth Assessment Report (AR4; IPCC 2007), while the current phase, called, CMIP5 supports the IPCC Fifth Assessment Report (AR5; IPCC 2013).

Compared to CMIP3, CMIP5 has more participating modeling centers and models, generally higher-resolution models, and more individual projections of future climate. These and other differences are summarized in Table 3-1. A much larger archive of model output is available for the CMIP5 models compared with CMIP3, with daily output available for most runs, and even 3-hourly output for some variables. This difference is significant, because it allows for the development of downscaled data for use in hydrologic models and other climate-impact models directly from the archived CMIP5 daily model output, without having to first disaggregate the monthly model output, as with CMIP3. Daily model output also facilitates the computation of many commonly used climatic indices that are based on daily data, such as extremes of daily precipitation, heat indices, and growing season length.

CMIP5 also includes a separately generated set of decadal climate predictions. Many stakeholders have expressed interest in climate forecasts with a 5- to 10-year time horizon for climate variables such as onset or persistence of long-term regional drought. The decadal predictions have been analyzed for their skill based on "retrospective forecasts" starting from 1960.

Unfortunately, the results do not indicate the ability to make skillful decadal forecasts over North America using the global climate models.

While the CMIP5 model output is quickly becoming the *de facto* standard for climate projections, we must emphasize that CMIP5 represents only incremental progress in modeling from CMIP3, and does not invalidate the results of analyses done with the earlier set of models. The CMIP3 and CMIP5 model ensembles have very similar projections for mean temperature and precipitation changes over much of the globe, including most of North America, and a similar range of uncertainty. The projections for Colorado differ in detail between the CMIP3 and CMIP5 model ensembles, but not in their larger messages (see Sidebar 5-1). It is also important to note that it took the climate science community several years to comprehensively examine and diagnose the results of the CMIP3 models, and that process is still ongoing for the CMIP5 models. Thus, while we have reason to believe the CMIP5 output is better than CMIP3 in some respects, at this stage the CMIP3 output has been more fully vetted.

3-3. Emissions scenarios: In the driver's seat

Emissions scenarios represent how greenhouse gas emissions might unfold over the next century and longer. The emissions determine the accumulation of greenhouse gases (GHGs) in the atmosphere. The IPCC has developed a suite of scenarios called Representative Concentration Pathways (RCPs) for use in the CMIP5 climate projections, which replaced the SRES scenarios (e.g., B1, A1B, A2) that were used for the CMIP3 projections.

The RCPs use a new methodology intended to make the climate modeling based on the scenarios less time-consuming. Their purpose is the same as before: to create a standard set of scenarios that represent a broad range of trajectories of GHG emissions and other human impacts to the climate system that are themselves driven by trends in demographic, socioeconomic, technological, and political factors. Since those underlying trends cannot be predicted

TABLE 3-1. Key characteristics of CMIP3 and CMIP5 model projections

Characteristic	CMIP3	CMIP5
Emissions scenarios	SRES B1, A1B, A2	RCP 2.6, 4.5, 6.0, 8.5
Historical climate	1880–2000	1850–2005
Projection period	2001–2100	2006–2100+
# Modeling centers	16	30
# Models	22	55
# Model simulations (projections)	120	250
Range of spatial resolutions (average gridcell size)	60–300 miles (median: 160 miles)	40–160 miles (median: 90 miles)
Time-scale of archived data	Monthly	Daily and monthly
Decadal prediction	No	2010–2035
Selected climate assessments using these projections	IPCC AR4 (2007) Climate Change in Colorado (2008) Climate Assessment of the Southwest (2013) The 3rd National Climate Assessment (2014)	IPCC AR5 (2013–2014) Climate Change in Colorado (2014) The 3rd National Climate Assessment (2014)
Selected hydrology studies based on these projections	Colorado River Water Availability Study – Phase I (2012) Colorado River Basin Water Supply and Demand Study (2012) Joint Front Range C. C. V. Study (2012)	Colorado River Water Availability Study – Phase II (ongoing)

Table 3-1. Key characteristics of the Coupled Model Intercomparison Project (CMIP), Phase 3 (CMIP3) model projections featured in the 2008 Report, and the Phase 5 (CMIP5) model projections featured in this report. (Source: CMIP)

with any confidence, there have been no probabilities assigned to any one of these RCPs being the actual future path.

Each CMIP5 model projection uses one of four concentrations pathways: RCP 2.6, RCP 4.5, RCP 6.0, or RCP 8.5 (Figure 3-3). The numbers refer to the strength of their *radiative forcing* in watts per square meter (W/m^2)— how much extra energy is trapped in the climate system by added greenhouse gases and other human-caused changes—by the year 2100, compared to pre-industrial (~1750) levels. As with the SRES scenarios, the divergence among the RCPs by 2050 is much less than the end of the century (Figure 3-3). The projected increase in global average temperature by 2100 closely corresponds to the radiative forcing of each RCP.

RCP 2.6 (low) assumes immediate and large (~70%) reductions in GHG emissions from today's levels, such as through major policy intervention, and its climate forcing has peaked by 2050 with CO_2 levels at about 435 parts per million (ppm) as compared to the current 400 ppm (as of spring 2014). After 2050, the forcing trajectory of RCP 2.6 is below the other RCPs and also below B1, the lowest of the main SRES scenarios. RCP 4.5 (medium-low) assumes large reductions in GHG emissions that are less drastic and take effect later than in RCP 2.6, with CO_2 at about 475 ppm at 2050 and rising. At 2050 the forcing of RCP 4.5 is slightly above RCP 6.0 and similar to B2, but after 2070 it levels out so that it is below RCP 6.0 and more similar to B1. RCP 6.0 (medium-high) assumes moderate reductions in emissions, and its forcing is very similar to RCP 4.5 at 2050 and continues to climb throughout the 21st century, on a path slightly below A1B. RCP 8.5 (high) assumes no reduction in emissions, so it can be considered a "business as usual" scenario. RCP 8.5 has greater forcing than the other RCPs at 2050, with CO_2 at about 530 ppm, and the gap increases over the 21st century. By 2100 RCP 8.5 is above the high A2

FIGURE 3-3. Radiative forcing of RCP and SRES emissions scenarios, 2000–2100

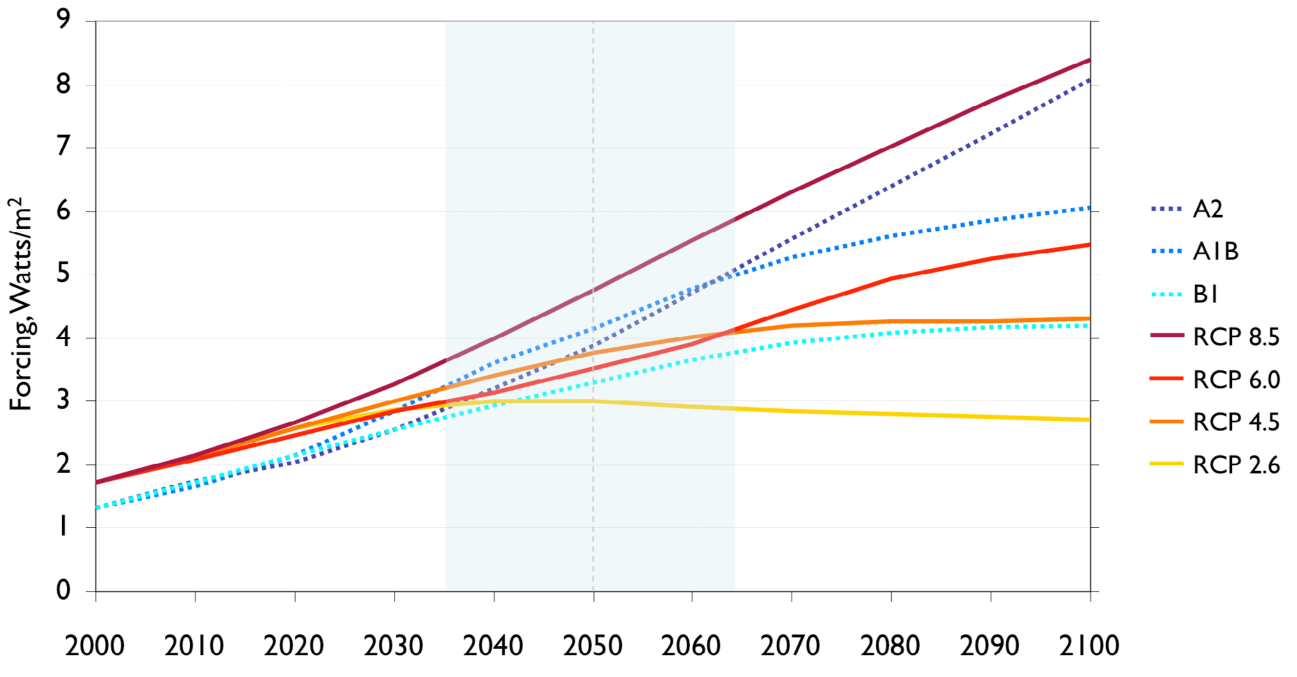


Fig. 3-3. Radiative forcing of the Representative Concentration Pathways (RCPs) used to drive the CMIP5 climate models and the SRES emissions scenarios used for the CMIP3 climate models, from 2000–2100. Over the 2050-centered analysis period (2035-2064; blue shading) used in this report, the three SRES scenarios and RCP 4.5 and RCP 6.0 have similar radiative forcing, and thus similar projected global temperature increases. RCP 8.5 is higher, and RCP 2.6 is lower. All of the RCPs and SRES scenarios diverge markedly after 2050. (Data source: SRES: IPCC 2000; RCP: IIASA RCP Database; http://tntcat.iiasa.ac.at:8787/RcpDb/)

scenario, with CO_2 levels around 950 ppm.

Note in Figure 3-3 that the range of climate forcings across the four RCPs is larger than that across the main three SRES scenarios, so that assessments that combine results from all four RCPs will tend to show greater overall uncertainty (i.e., a larger range in modeled future climate) by the end of the 21st century compared to studies that used SRES B1, A1B and A2.

In this report we will focus primarily on climate projections using RCP 4.5 and RCP 8.5, mainly because there are more individual climate model projections available in the CMIP5 archive for those two RCPs than for RCP 2.6 and RCP 6.0. Together, RCP 4.5 and RCP 8.5 cover most of the total range of the RCPs at 2050. (Over the 2050-centered analysis period, the forcing of RCP 4.5 and RCP 6.0 are almost identical.) The forcing of RCP 4.5 at 2050 is also the closest analogue to the A1B SRES scenario, which was the focus of the 2008 Report.

3-4. Climate model evaluation and credibility

Why do climate scientists have confidence that the climate models can credibly simulate the future climate? The first reason is that the models are based on fundamental and well-understood scientific principles such as fluid dynamics and the laws of thermodynamics. The second reason, closely related to the first, is that the models are able to replicate the major features of the earth's climate, such as the jet streams and their seasonal movement, mid-latitude cyclonic storms, the north-south Hadley circulation, ENSO, and most ocean currents. The third reason is that the models have been successful at simulating trends in global and continental-scale temperatures over the past century, a period over which the climate forcings have changed, and also at simulating the state of global climate when the forcings and other conditions were very different than the last century, such as the Last Glacial Maximum (LGM) 20,000 years ago. The improvements seen in the models over the past two decades in simulating historical climate and paleoclimate have come through better understanding and representation of the climate processes in the model (Figure 3-1).

Despite the improvement in climate models, they still have significant biases (systematic errors) in their simulation of the observed climate, which become larger as one moves from the global scale to regional scale. While these biases are typically corrected before the data are used in hydrologic modeling, it is important to evaluate and understand them. In this section we describe the evaluation of models with respect to (1) how well the models simulate the climate of the recent past, both globally and regionally, and (2) how well the models simulate specific climatic phenomena such as ENSO and the Pacific Decadal Oscillation that influence Colorado's climate. We also note where the CMIP5 output used in this report has improved over the CMIP3 data used in the 2008 Report, and where it has not. A more detailed discussion of climate model evaluation is presented in IPCC (2013), Chapter 9.

Simulating the characteristics of the observed climate

Model evaluation first considers the accuracy of the model's simulation of the climate of the late-19th and 20th centuries. These "historical" simulations include known forcing factors such as variations in solar output, emissions of volcanic and industrial aerosols (fine particles suspended in the air), and changes in greenhouse gas concentrations. The historical runs produce natural variability of the climate from year to year and decade to decade, and the characteristics of this variability are examined along with the average simulated climate.

Climate model simulations are judged by how well they reproduce climate statistics rather than on matching the timing of individual historical events. This is because climate models do not receive inputs of observational data to periodically reset the model, as would happen with a weather forecast, but instead run freely through time. Consequently, while the simulations cannot reproduce the observed weather on any specific day, they should reproduce climatological averages (i.e., normals) and other statistics of the weather. Likewise, while the historical simulations cannot reproduce the timing and features of a specific longer-lived climate event such as the 1997–98 El Niño, they should show El Niño and La Niña events that resemble the ones that have occurred, in terms of magnitude, duration, and recurrence interval.

The historical simulations show a climate response to

Sidebar 3-1. Why climate model projections differ from each other

An inescapable characteristic of climate model projections is that different projections show different future changes in temperature, precipitation, and other climate variables for a given region or location. The future change from a given model projection can differ from other projections due to any or all of the following factors:

- The particular emissions scenario used to drive the model
- The model's representation of key climate processes, which varies between models
- The simulation of natural variability unique to each projection
- If the projection is downscaled, the methodology used to downscale the model output

The first factor is the most obvious, since the emissions scenarios (i.e., RCPs) are deliberately constructed to represent a broad range of future anthropogenic influences on climate. For temperature, the effect of the emissions scenario is predictable and consistent: a higher pathway (e.g., RCP 8.5 vs. RCP 4.5) leads to yet warmer projected temperatures, both globally and regionally. For projected precipitation change, the influence of the RCP is more variable and may be difficult to discern.

If we look only at projections driven by a single emissions scenario, we still find a large range in both projected temperature and precipitation change. The main reason is that the different climate models have different approaches to represent key climate processes and patterns. This reflects that our observations and understanding of these processes are not complete enough to have confidence in a single methodology for including them in climate models, or the coarse scale of the climate models inhibits accurate simulation, or both. Thus, different modeling groups use different approaches to represent these processes.

The third factor is the unique simulation of natural climate variability in each projection. As described in Section 3-4, climate models do not attempt to replicate the actual events and sequences of historical climate; instead, they generate a simulated climate history that captures the key characteristics of historic natural variability. As a model is run out into the future, it likewise projects a sequence of climate variability that, because of the randomness inherent in the climate system, does not match the sequences produced by other models. Because natural variability has a multi-decadal phase (see Section 2), analyses of projected change that compare the averages across two periods will inevitably include some amount of natural variability.

The fourth factor comes into play if the climate projection is downscaled (see Section 3-5). The downscaling procedure, whether statistical or dynamical, can shift the future change in temperature and/or precipitation from that shown in the underlying global climate model output (see Sidebar 3-2). The direction and amount of this shift will differ among downscaling approaches and with the region being downscaled.

It is difficult to generalize about these factors' contributions to the overall range of model output, and thus to our uncertainty about future climate. The importance of the factors will vary by both spatial scale and the future time frame of the projection. But for temperature change for Colorado by the mid-21st century, the emissions scenario and the GCM's representation of key processes tend to be most important. For precipitation change, the emissions scenario is less important, and the GCM's representation of key processes and simulation of natural variability are more important.

the known natural and anthropogenic forcing factors, resulting in periods of global warming in the early and late 20th century and slight cooling in the mid-20th century, matching the observed record (see Figure 4-1, lower left). The modeled response to large volcanic eruptions—a sharp cooling that lasts a few years—also agrees closely with the observed temperature response.

Spatial resolution complicates model evaluation, particularly in mountainous regions like Colorado. In these areas, local climates are influenced by details of topography and elevation that are not captured by the climate models. Because of their coarse spatial grid, climate models depict a highly smoothed representation of mountain regions, including the Rocky Mountains (Figure 3-4). Climate models are evaluated by comparing their output with averages of observed precipitation and temperature over areas that are comparable in size to the model gridboxes. Examined this way, the climate models do simulate the large-scale climate processes affecting mountainous regions, including the typical winter and spring storm tracks. They also broadly reproduce the differences in the seasonal cycle of precipitation as one moves from the Great Plains across the Rockies to the Intermountain West. For this reason, it is possible for further processing of the model output (e.g., downscaling, Section 3-5) to relate these large-scale phenomena in climate models to the detailed topography of the state, resulting in an improved representation of variables and processes important to hydrology in Colorado.

At global to sub-continental spatial scales the CMIP5 models do well in their simulation of both surface temperature and precipitation, and have clearly improved over CMIP3 (IPCC 2013). The models still have problems simulating precipitation at sub-continental and regional scales, and have not improved substantially in this regard compared to CMIP3.

For Colorado, we can compare the temperature and precipitation simulated by the climate models with a gridded observational dataset over the period 1950-1999 (Maurer et al. 2002). The CMIP5-modeled climate is on average slightly cooler and considerably wetter than the observed climate over Colorado. These biases are not isolated to Colorado but occur over most of the western U.S. The regional wet bias is likely due to a combination of the under-representation of the height of mountain ranges in the model, and too-strong simulated westerly flow from the Pacific Ocean (McAfee et al. 2011).

All of the CMIP5 models are too wet over Colorado. The ensemble-average bias in statewide annual precipitation is +67%, which similar to the bias seen in the CMIP3 models. The wet bias is similar in each season of the year, indicating that the overall shape of the seasonal cycle in precipitation is reproduced, even though there is too much precipitation overall. The persistent bias in precipitation speaks to the difficulty of simulating precipitation processes.

The mean bias in statewide average annual temperature across the CMIP5 ensemble is about -1°F, with the individual model biases ranging from -7°F to +6°F. The median summer temperature bias is the smallest. For both precipitation and temperature, the greatest range among the models in their individual bias occurs in summer, reflecting the challenges associated with simulating the North American Monsoon, thunderstorms, and the associated fluctuations in soil moisture that have a strong influence on surface temperatures.

That the models have biases in representing the average state of the observed modern climate does not mean that they cannot credibly simulate changes in the future climate. But it does mean that the bias needs to be accounted for before interpreting the projections, either through formal bias-correction of the data (usually performed as part of downscaling; Section 3-5), or by comparing the uncorrected model output for a historical period with the uncorrected output for the future period of interest, and examining the projected change (or *delta*) between the two periods, which effectively cancels out the bias. This simple delta approach to bias correction was used for the projected changes for Colorado described in Section 5-1.

Beyond the averages: Climate phenomena that impact Colorado

Year-to-year climate variability in Colorado arises in part from modes of variability such as ENSO that influence storm tracks and other atmospheric dynamics. The simulation of ENSO has improved in some aspects from CMIP3 to CMIP5; for example, most CMIP5 models capture the characteristic 2- to

7-year timescale for recurrence of ENSO, whereas few CMIP3 models did (IPCC 2013, Sheffield et al. 2013b). But it is less clear that the representation of ENSO's impacts on North America and Colorado has improved. The representation of decadal Pacific variability and its associated climate effects over North America likewise have improved in some aspects since CMIP3 (Sheffield et al. 2013b, Polade et al. 2013).

FIGURE 3-4. Model grids in a GCM compared to an RCM

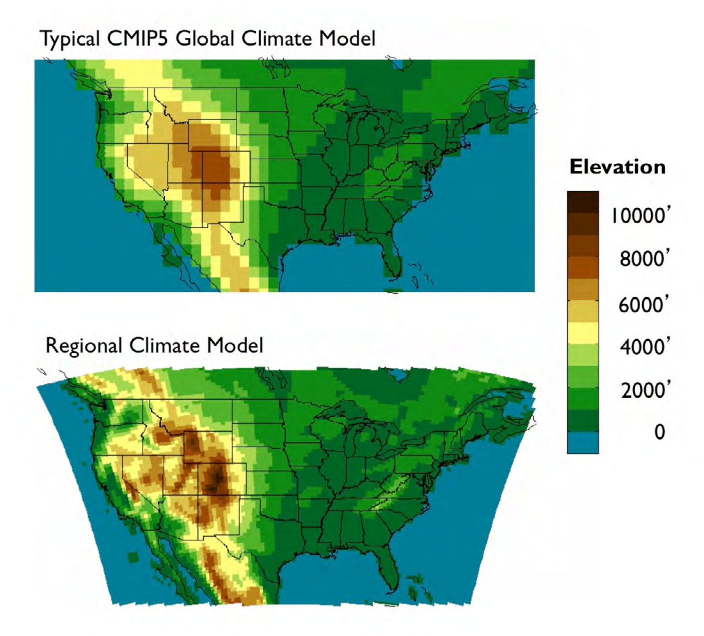


Fig. 3-4. Comparison of the model grids and representation of terrain in a Global Climate Model (GCM) and Regional Climate Model (RCM). The typical GCM in the CMIP5 ensemble (top panel) has gridboxes that are about 100 miles on a side. The WRF regional climate model (bottom panel), used for dynamical downscaling, has gridboxes that are about 30 miles on a side. The smoothed representation of the Rocky Mountains in global climate models reduces the elevations of the mountain peaks. Downscaling methods relate the large-scale climate features that are simulated by GCMs to the small-scale climatic and topographic features of Colorado. The highest-resolution GCMs now have gridboxes about 40 miles on a side.

Climate models capture many important aspects of the seasonal movements of storm tracks over North America (CCSP 2008a), which are a major feature of climate in Colorado. The CMIP5-simulated storm tracks have improved from CMIP3, but are still positioned a little too far south, are weaker, and show fewer storms, compared to observations (Chang 2012).

The North American Monsoon, which is strongest over northern Mexico and southern Arizona, is an important source of moisture for much of Colorado during the summer. Many CMIP5 climate models are now able to simulate the seasonal timing of rainfall over the core area of the monsoon, and the northward progression of monsoon moisture in northern Mexico. However, the models still generally underestimate the amount of monsoon precipitation. Colorado sits at the northern edge of the monsoon system, and the simulation of the monsoon's extension into Colorado has not been specifically evaluated.

Overall, we have more confidence in the model-projected changes in cold-season precipitation than in those for warm-season precipitation.

Is there a "best" model?

When the multiple aspects of evaluation described above are used to judge the climate models, it is difficult to discern the "best" or even "better" models (Mote et al. 2011). For example, a model that has a smaller temperature bias over Colorado may not have a good simulation of ENSO, or vice versa. The authors of a study of projections for California noted that while some models were more capable at simulating particular aspects of 20th-century climate, when several credibility measures were combined, the models tended to perform equally well (Brekke et al. 2008). They also found that screening the models or applying weighting factors to models based on their overall performance had little effect on the resulting distribution of climate outcomes in their study. This is not unexpected, because a model's skill based on historical simulation does not necessarily correlate with the magnitude of future change that the model projects. Accordingly, as long as a large enough sample of climate models is used (Harding et al. 2012), it is not necessary to try to screen the models, and they can be treated more or less equally.

Over the past few decades, the models have progressively improved in their ability to simulate the climate, even as the modeling community has set more demanding goals. They are still, however, imperfect descriptions of the Earth's climate. For most measures of model performance, the average of all the models

SIDEBAR 3-2. The "wettening" in the BCSD downscaled data

Statistical downscaling methods, in correcting the biases of the GCM output and translating the output to finer spatial scales, may have additional effects on the downscaled output. For example, when the Bias-Correction Spatial Disaggregation (BCSD) method described in Section 3-5 was used to downscale the CMIP3 GCM output, it was found that future precipitation changes over the Colorado mountains were slightly wetter, in terms of percent change from the historical period, than those seen in the underlying GCM data (Reclamation 2011). This BCSD "wettening", once translated through hydrologic modeling into runoff, on an annual basis was equivalent to about 6% of the annual average flow at Lees Ferry, or about 1 million acre-feet of flow (Barsugli 2010).

This wettening effect is somewhat stronger in the CMIP5 data downscaled with the BCSD approach over Colorado and the Upper Colorado River Basin. Figure 3-5 shows the "raw" GCM data for 37 CMIP5 projections under RCP 4.5, plotted by their statewide temperature and precipitation change for Colorado (red dots) connected with dashed lines to the corresponding BCSD downscaled output (blue dots). A step in the bias-correction explicitly preserves the trends in the GCM-modeled temperature, so there is very little difference in the temperature changes between the BCSD and the raw GCM data. However, there is no equivalent step for precipitation, and the BCSD procedure shifts the precipitation change in the wetter direction in nearly all cases, with the largest wettening imparted to the GCM runs that already showed an increase in precipitation, i.e., the wet get wetter (Reclamation 2013).

While the details are still being investigated, it appears that BCSD wettening is a consequence of the quantile mapping in the bias-correction step (Reclamation 2013). In matching the distributions of the modeled and observed climate data, the bias-correction effectively amplifies the wettest model months if they were of lesser magnitude than the wettest observed months, relative to average months. There is evidence that the BCSD-induced wettening is an appropriate correction for the GCMs systematically under-representing precipitation variability in our region, in particular the wettest months (A. Wood, personal communication).

Since the wettening is larger in CMIP5 than in CMIP3 and will have proportionately larger consequences for CMIP5-based hydrology, researchers are currently examining the wettening effect to better understand its sources and implications. More broadly, the BCSD wettening illustrates that downscaling methods are not a panacea or magic—they perform a necessary function that enables many user applications, but they have embedded assumptions that may have implications for the projected changes. Comparisons like the one shown in Figure 3-5 can document the effects of the downscaling proceure. In this case, the "dry side" of the risk profile is similar in the GCM and BCSD data, but the risk on the wet side is different. As with any projection dataset, it is important not to fixate on the average of the projections but to consider the range of future possibilities indicated by the models.

FIGURE 3-5. The wettening effect in BCSD downscaled projections

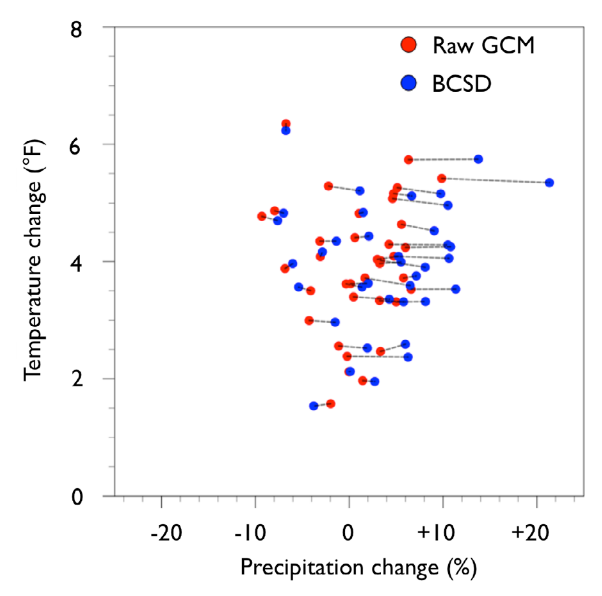


Fig. 3-5. The BCSD downscaled projections are systematically wetter than the corresponding CMIP5 GCM projections. CMIP5 GCM projected temperature and precipitation change for Colorado (red dots) from 1971-2000 to 2035-2064 under RCP 4.5, compared with the BCSD statistically downscaled projections (blue) over the same time period. The dashed lines connect each CMIP5 model projections (n=37) with the corresponding BCSD downscaled projection. (Data source: CMIP5 projections re-gridded to 1-degree grid and BCSD downscaled projections, Reclamation 2013; http://gdo-dcp.ucllnl.org/downscaled_cmip_projections. Analysis by I. Rangwala.)

performs better than a single model (Reichler and Kim 2008, Sheffield et al. 2013a, IPCC 2013). However, the average of all models does not capture the uncertainty, due to incomplete scientific understanding, that is reflected in the range of model output. Consequently, it is very important for planners to consider a range of model projections to assess the robustness of planning options under different future climates (see Sections 5-1, 5-3, and 6).

3-5. Downscaling methods

In order to use the coarse-grid global model output to study climate change impacts in specific regions or basins in Colorado, the model output needs to be related to the detailed topography and climate of the state through a process called downscaling. This process may not necessarily lead to more accurate projections of local future changes in temperature and precipitation than the underlying coarse-scale climate model output. We will describe the two main approaches to downscaling (statistical and dynamical) and several specific methods and datasets that have been used for Colorado. A more complete overview of downscaling methods is found in Fowler et al. (2007).

Statistical downscaling

Statistical downscaling methods use the observed relationship between coarse-scale and finer-scale climate to translate the GCM output into finer, more usable spatial scales. This is less computationally intensive than dynamical downscaling, and so it is feasible to generate downscaled datasets based on large ensembles (>100 projections) of the global model simulations.

The simplest statistical downscaling approach is the delta or "period-change" method. The delta method gets its name from the Greek letter commonly used to denote change. The delta method starts with time series of historical daily or monthly climate data from gridded observations or from individual stations. The change in the monthly climatological average of temperature between a GCM-simulated historical period and GCM-projected future period is calculated across the GCM grid. These changes (deltas) are interpolated from the GCM grid down to the observation locations, and then added to the historical observations to produce the downscaled projections. Similarly, the percent change in precipitation from the GCMs is applied to the precipitation observations.

The delta method incorporates the coarse-scale patterns of climate change seen in the GCMs while preserving the fine-scale spatial detail and time sequences of weather events from the historical data. This method is often chosen because it is simple to implement and to explain. Because water systems are sensitive to the sequence of wet and dry years, and water managers are familiar with how their systems have performed over the historical period, the delta method is attractive since it simulates how historical climate sequences (such as the 1950s drought) would appear in a changed climate. The delta method typically limits the analysis to a comparison of climate during two time periods.

The delta method can also be applied to already-downscaled data, instead of raw GCM output. This is useful for applications where both sophisticated treatment of fine-scale spatial patterns in climate and retention of the historical climate sequences are desirable. This approach was used to generate the climate inputs to the hydrologic models used in the Colorado River Water Availability Study (CRWAS; CWCB 2012) and the Front Range Climate Change Vulnerability Study (Woodbury et al. 2012).

While the delta method inherently corrects for the systematic biases in the GCM output (Section 3-4), a separate bias-correction step must be incorporated into other statistical downscaling methods. Bias-correction calculates the GCM bias based on the difference between the historical GCM simulation and fine-scale observations, and adjusts the historical and projected GCM output accordingly. In contrast to the delta method, which adjusts the observed historical climate sequences, methods incorporating bias-correction retain the simulated future sequencing from the GCM output. The choice of observational dataset is an essential element of a bias-correction method, and results can differ based on this choice, particularly in data-sparse regions.

The Bias-Correction Spatial Disaggregation method (BCSD), developed by a team at the University of Washington (Wood et al. 2004), incorporates bias-correction and statistical downscaling. For the BCSD method, the biases are first computed at a common grid-scale from the GCM-modeled monthly average temperature and precipitation compared to the Maurer et al. (2002) gridded observational dataset. What distinguishes this method from many others is that the biases are computed and adjusted separately for each portion of the distribution of the climate variables through a procedure called “quantile mapping.” In effect, biases are adjusted separately for wet months and dry months, and for warm months and cold months. These bias-corrected GCM data are then spatially disaggregated to the fine-scale grid; that is, the bias-corrected temperature and precipitation in a GCM gridcell are adjusted based on the observed finer-scale climatological pattern of temperature and precipitation within the GCM gridcell.

The BCSD downscaled data has been chosen for use in many hydrologic applications. In these applications, the BCSD climate projections are used as the driving inputs for stand-alone hydrology models calibrated to a specific river basin. This generates a hydrologically consistent set of projections based on the range of climate inputs. The Bureau of Reclamation co-developed a West-wide set of hydrologic projections (Gangopadhyay et al. 2011) used for many subsequent assessments, including the Colorado River Basin Supply and Demand Study (Reclamation 2012). It has been noted that the BCSD downscaled data indicate a wetter future for Colorado and the surrounding region than the underlying GCM output, an effect discussed in Sidebar 3-2.

Many other types of statistical downscaling have been developed. NASA has implemented a variant of BCSD, using 800-meter (0.5-mile) PRISM gridded data as its observational baseline, that does not show the wettening effect described in Sidebar 3-2. The ARRM method is another bias-correction method using a quantile-based correction, applied to daily GCM output. Other methods include “weather analogs” that find observed weather patterns similar to those in the GCMs, (e.g., MACA, BCCA), statistical regression-based techniques, (e.g., SDSM), and stochastic “weather generators” (e.g., K-NN).

Ongoing advances in statistical downscaling include the development of additional datasets that provide daily data (ARRM, BCCA, MACA), and statistical methods that yield more accurate relationships among the downscaled climate variables.

Dynamical downscaling

Dynamical downscaling uses high-resolution regional climate models (RCMs) to simulate fine-scale processes. As their name suggests, RCMs operate much like GCMs but are only able to simulate the climate for a portion of the globe. They typically receive inputs from the global model gridboxes at the boundaries of their domain and then simulate wind, temperature, clouds, evapotranspiration, and other variables on a much finer grid within their domain, effectively nesting the regional model within a “driving” global model (Wigley 2004; Wilby and Wigley 1997). RCM downscaling is computationally intensive, requiring substantial time to run even on supercomputers. As a result, the available ensembles of climate projections using this method are much smaller (typically 3 to 7 individual projections) than those that use statistical downscaling, and may only represent a single underlying emissions scenario. When evaluating RCM output, it is important to know where the driving GCM lies within the larger ensemble of GCMs, in terms of its coarse-scale temperature and precipitation change.

The largest available set of dynamically downscaled data with coverage of Colorado is from the North American Regional Climate Change Assessment Project (NARCCAP; Mearns et al. 2009). This dataset consists of 11 projections downscaled to a 50-km (31-mile) grid resolution from four CMIP3-era GCM simulations. Further downscaling of the NARCCAP output may be needed depending on the application.

As of mid-2014, dynamical downscaling of CMIP5 output has yet not been performed for North America. The CORDEX program has downscaled CMIP5 output to produce RCM simulations at 6-mile (11-km) resolution for many regions of the globe. However, a North American CORDEX program, analogous to the NARCCAP program for CMIP3, has not been funded.

Dynamical downscaling is particularly useful for exploring the spatial details of how particular climate processes may play out in the future. For example, the more detailed representation of the Rocky Mountains in RCMs has allowed the examination of how temperature and precipitation change will vary according to elevation, identifying drying of soils at high elevation in summer as contributing to the projected warming, while the increased moisture in the atmosphere leads to accelerated warming in winter at high elevations (Rangwala et al. 2012, Rangwala et al. 2013).

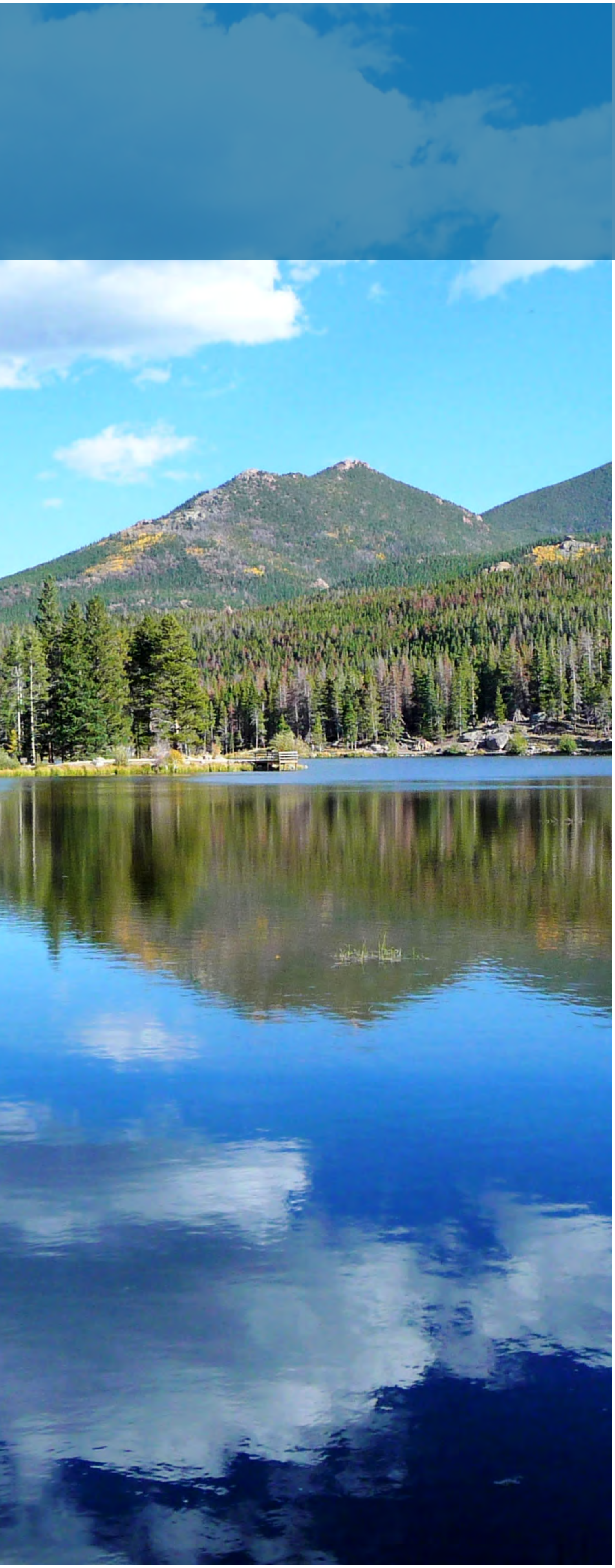
Beyond typical dynamic downscaling, sub-regional modeling allows the study of climate processes at even finer spatial scales. The Colorado Headwaters Project led by NCAR has run a small set of model simulations for the Upper Colorado Basin using a weather forecast model on a 2-km (1.2-mile) grid (Rasmussen et al. 2011, Rasmussen et al. 2014); their results regarding winter precipitation are described in Section 5-1. Mahoney et al. (2012) used the same weather forecast model to further downscale NARCCAP output and study summer convective precipitation, as described in Section 5-4. The advantage of this methodology is the ability to explore processes that can not be depicted by either global or regional climate models.

3-6. Progress in climate modeling

When a group of water resource managers in Colorado and across the country were surveyed five years ago about their needs for climate change information, they identified four areas in which improvement in climate model projections was desired: higher-resolution spatial and temporal scales, greater model agreement about the direction of regional precipitation change, a narrower range of climate projections, and improved shorter time-horizon projections (Barsugli et al. 2009).

Comparing the climate projections in this report (Section 5) with those presented in the 2008 Report, we can say that there has been progress in the first area, in that global and regional models are being run at higher spatial resolution, many more downscaled datasets are available, and more daily data from projections are available. But the other three areas have seen less improvement, and significant progress may not occur for a decade or more (Barsugli et al. 2012). This slow progress reflects not lack of effort but rather the science of climate modeling bumping up against the incredible complexity of the global climate system and the limits of our knowledge. Some uncertainties may eventually be reduced, but others will persist.

The next generation of climate models will likely see incremental progress similar to that between CMIP3 and CMIP5: higher resolution, and better representation of many climate processes. But there is unlikely to be a significant reduction in the range of model projections at global or regional scales under a given emissions scenario.



4

Linking Observed Changes in Colorado to Global Changes

Key points

- The global climate system has warmed since 1900, particularly in the past 30 years, as evidenced by increased surface, atmospheric, and ocean temperatures; melting glaciers and ice sheets; rising sea levels; and increased atmospheric water vapor.
- These global climate changes have been attributed mainly to anthropogenic (human-caused) influences, primarily the increase in atmospheric concentrations in greenhouse gases to the highest levels in at least 800,000 years.
- In North America, temperatures have increased by about 2°F in the last 30 years, with anthropogenic influences making a substantial contribution.
- In Colorado, temperatures have also increased by 2°F in the past 30 years (Section 2-3). The statewide warming is plausibly linked to anthropogenic influences, but definitive attribution at this spatial scale is difficult.
- Colorado's annual precipitation has not exhibited trends that might be attributed to anthropogenic climate change.
- Anthropogenic climate change may have increased the severity of recent drought conditions in the western U.S., due to the influence of the warming on snowpack, streamflow, and soil moisture.

Sprague Lake, Rocky Mountain National Park. Photo: Creative Commons, Daniel Mayer (Mav).

Section 2 described the observed changes in the climate of Colorado over the past century (from instrumental records) and the last millennium (from paleoclimate records) as a baseline for understanding recent trends. Planning for future climate risk, however, also requires exploration of the causes of those trends. If causes can be identified, this allows for the estimation of these trends continuing into the future, through climate model projections and other tools. The process of establishing the principal causes for observed climate phenomena and trends is known as climate *attribution*. This process necessarily begins at the global scale, examining the overall changes to the earth's climate system.

Determining an attribution for an observed climate change requires that first, scientists can demonstrate that the change is consistent with anthropogenic causes (usually in combination with natural variability), and second, that these changes are inconsistent with physically plausible explanations that exclude anthropogenic causes. When attribution is established, a likelihood statement may be assigned that presents the probability that the identified cause resulted in the observed conditions or trends.

Attribution studies use both statistical analyses of past climate relationships and climate model simulations in which cause-and-effect relations are evaluated. The model simulations are compared with the observed record, including estimates of natural variability and trends from climate models, historical observations, and paleoclimate reconstructions of past temperatures. Attribution studies are also used to assess the natural and anthropogenic causes of droughts and other extreme climate events.

4-1. The global picture

Evidence that Earth's climate has changed during the past century is clear. The IPCC Fifth Assessment Report (IPCC 2013) states that the observed warming of the climate system is "unequivocal." This statement is based on observed trends of melting snow and ice; rising sea level; and increasing surface, ocean, and atmospheric temperatures. The most relevant observed trends at global scales include the following (IPCC 2013):

- Global average surface temperatures in the decade 2001–2010 were the warmest of any decade since 1850, having increased by about 1.6°F since 1900 and 1°F since 1950.
- The upper ocean (down to 2300 feet depth) has warmed from 1971 to 2010; due to the high heat capacity of water, ocean warming accounts for more than 90% of the additional energy accumulated in the earth's climate system over that time.
- Over the last 20 years, the Greenland and Antarctic ice sheets have lost ice mass, mountain glaciers have continued to shrink almost worldwide, and summer Arctic sea ice has further decreased.
- Due mainly to the ice sheet and glacier melt, and thermal expansion of sea water, global sea level has risen by 8 inches since 1900, with the rate of increase greater since 1990 than before.
- Globally, water vapor in the atmosphere has increased by 3–5% in the last 50 years, which is an outcome expected from the warming, since warmer air can hold more water vapor.

These observed trends can then be considered in the context of changes in radiative forcings—the natural or human-caused mechanisms which cause the total energy in the global climate system to increase or decrease—as well as natural variability. Trends in the radiative forcings include the following (IPCC 2013):

- The atmospheric concentrations of the long-lived greenhouse gases carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have increased to levels unprecedented in at least the last 800,000 years. Carbon dioxide concentrations have increased by 40% since pre-industrial times, primarily from fossil fuel emissions and secondarily from land use change. Together, these gases now have a positive radiative forcing of +3 W/m^2 [7] compared to preindustrial (~1750) levels.

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[7] W/m^2 = watts per square meter, a measure of the average heat being added over the earth's area by a radiative forcing. A miniature incandescent Christmas-tree bulb puts out 1 watt, thus 1 W/m^2 is equivalent to a miniature Christmas tree bulb burning on every square meter of the earth's surface. As described in Section 3, the names of the new emissions scenarios (e.g., RCP 4.5) indicate the additional W/m^2 of climate forcing by 2100 inherent in that scenario. For comparison, the globally-averaged solar radiation reaching the top of the earth's atmosphere is 342 W/m^2.

FIGURE 4-1. Observed versus modeled global temperature trends

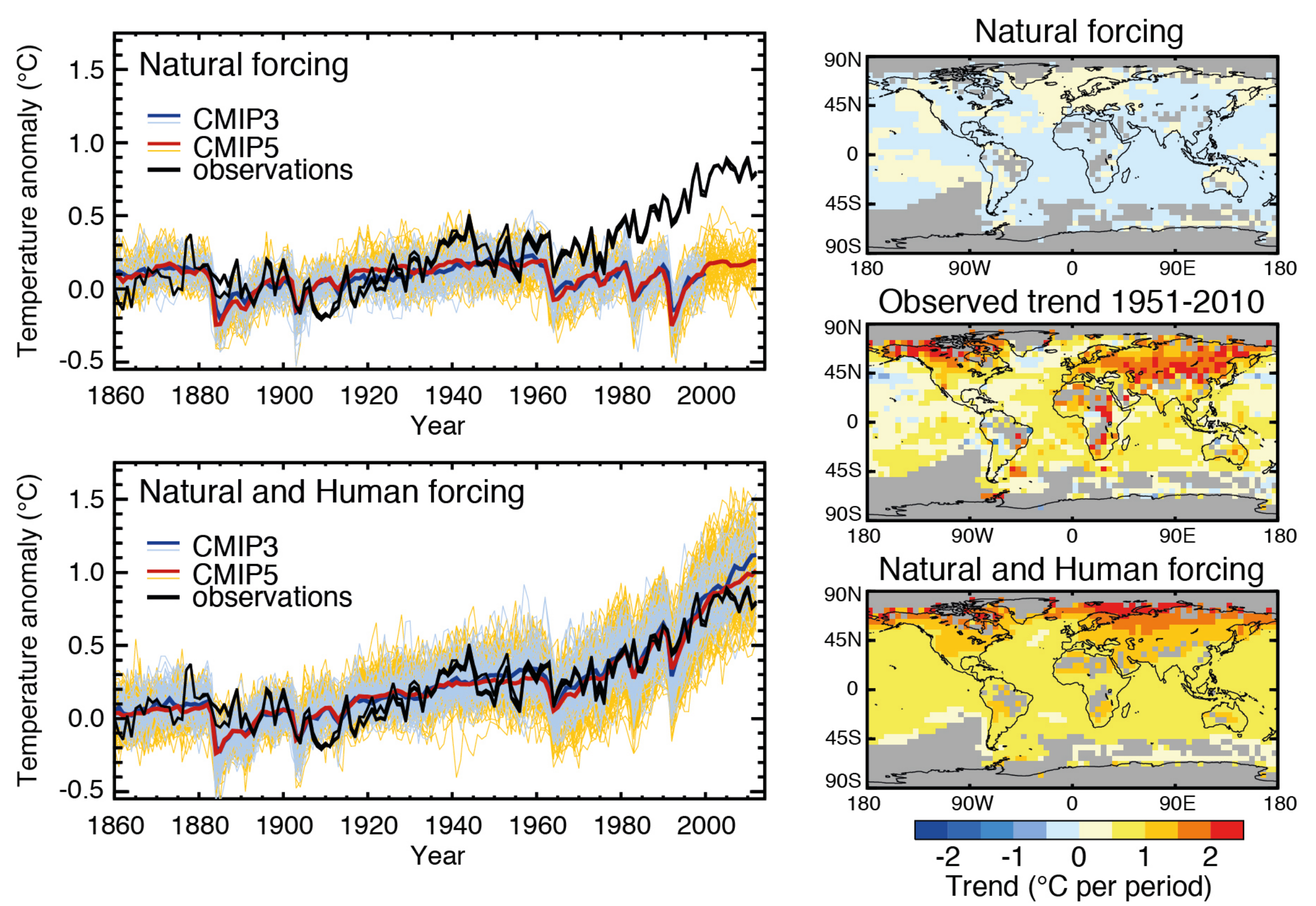


Fig. 4-1. Observed versus modeled global temperature trends, indicating the influence of human forcings. Left: Time series of global and annual-averaged surface temperature change from 1860 to 2010. The top left panel shows results from two ensembles of climate models driven with just natural forcings, shown as thin blue and yellow lines; ensemble average temperature changes are thick blue and red lines. Three different observed estimates are shown as black lines. The lower left panel shows simulations by the same models, but driven with both natural forcing and human-induced changes in greenhouse gases and aerosols. Right: Spatial patterns of local surface temperature trends from 1951–2010. The upper panel shows the pattern of trends from a large ensemble of CMIP5 simulations driven with just natural forcings. The bottom panel shows trends from a corresponding ensemble of simulations driven with natural + human forcings. The middle panel shows the pattern of observed trends from the HadCRUT4 data set during this period. (Image credit: IPCC 2013, FAQ 10.1, Figure 1)

- Human-generated aerosols (dust, sulfur dioxide, soot, black carbon) have also increased but have a net negative radiative forcing (cooling effect), around -1 W/m^2, though with more uncertainty than the greenhouse-gas forcing.

- The total net human-caused radiative forcing from long-lived greenhouse gases, shorter-lived greenhouse gases, and aerosols has increased from about +1.2 W/m^2 in 1980 to +2.3 W/m^2 in 2011, with the preindustrial (~1750) levels as a baseline.

- Natural aerosols from periodic volcanic eruptions can cause a short-lived (1–3 years) negative radiative forcing of up to -3 W/m^2 in large eruptions such as Mount Pinatubo in 1991. During the most recent decade, radiative forcing from volcanic activity has been much smaller, on the order of -0.05 to -0.10 W/m^2.

- Changes in sun's output over the past two centuries have led to a very small increase in solar radiative forcing, about +0.05 W/m^2, though the trend over the last 30 years is downward.

Comparing the sizes of the different radiative forcings, it is clear that at the global scale, the anthropogenic mechanisms (greenhouse gases, aerosols) have been dominant over natural forcings (the sun, volcanoes) in recent decades. Experiments using global climate models allow assessment of the contribution of different forcings. Figure 4-1 shows that both CMIP3 and CMIP5 models run with only natural forcings (upper left) fail to match the observed global warming trend over the past 50 years, while the models when run with both natural and human forcings follow the observed warming trend closely (lower left) and also capture the observed spatial pattern of warming, with greater warming over the subarctic and Arctic regions. This forms the basis of attributing the observed global temperature trends, and other observed trends, to human causes. The most notable attribution statement in the IPCC AR5 report is that it is *extremely likely* (>95% likelihood) that the majority of observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations together with other anthropogenic forcings (IPCC 2013).

4-2. North America and the United States

Analysis of observed climate records indicates that North America has warmed by about 2°F since 1980. The greatest warming has occurred over the northern and western portions of the continent. The warming trend between 1950 and 2012 in the Western United States is clear. The time series of annual North American-averaged temperatures (Figure 4-2, upper right) shows that every year since 1997 has been warmer than the 1971–2000 baseline. However, the rise in temperature has not been constant; year-to-year fluctuations have been superimposed on an increasing trend.

The observed warming of North American mean surface temperature is greater than the overall global warming because land heats up faster than the ocean surface and because high-latitude areas have warmed more than low-latitude areas.

SIDEBAR 4-1. The recent slowdown in global surface temperature warming

Since about 2000, the observed global surface temperatures have not risen as fast as between the mid-1980s and the late 1990s, or as fast as projected by the average of the climate models, as shown in in the lower left of Figure 4-1, where the observations (black line) sits below the average of the CMIP5 models (red line) and the average of the CMIP3 models (blue line). Some have seized on this slowdown or hiatus to claim that global warming has "stopped." But measurements of ocean heat content as well as satellite observations of the earth's radiation balance show that excess heat continues to accumulate in the global climate system at a rate similar to that before 2000. Global sea level rise, which integrates many of the effects of warming, continues at the same rate as in the 1990s. So why is global surface temperature—which is based on thousands of land-surface and sea-surface measurements—showing a recent slowdown in warming?

A large part of the explanation involves the natural variability of the oceans, which store much more heat (>90% of the global total) than the land surface and the atmosphere combined. The very strong 1997–98 El Niño event caused a spike in global surface temperature in 1998 (as can be seen in Figure 4-1), as enormous amounts of heat were released from the Pacific Ocean. Since 2000, however, there have been no strong El Niño events, and neutral or La Niña conditions have prevailed. Furthermore, observations of ocean heat content support the hypothesis that the atmospheric and ocean circulation associated with cooler conditions in the Northern Pacific Ocean drives the heat deeper into the ocean, leaving less energy to warm the surface (Trenberth and Fasullo 2013). Another factor which may also have contributed to the slowdown is slightly decreased solar output during the 2005–2010 period. When the next strong El Niño event occurs, releasing stored ocean heat to the atmosphere, global surface temperatures can be expected to resume their climb (Foster and Rahmstorf 2011).

FIGURE 4-2. Observed versus modeled temperature trends for North America

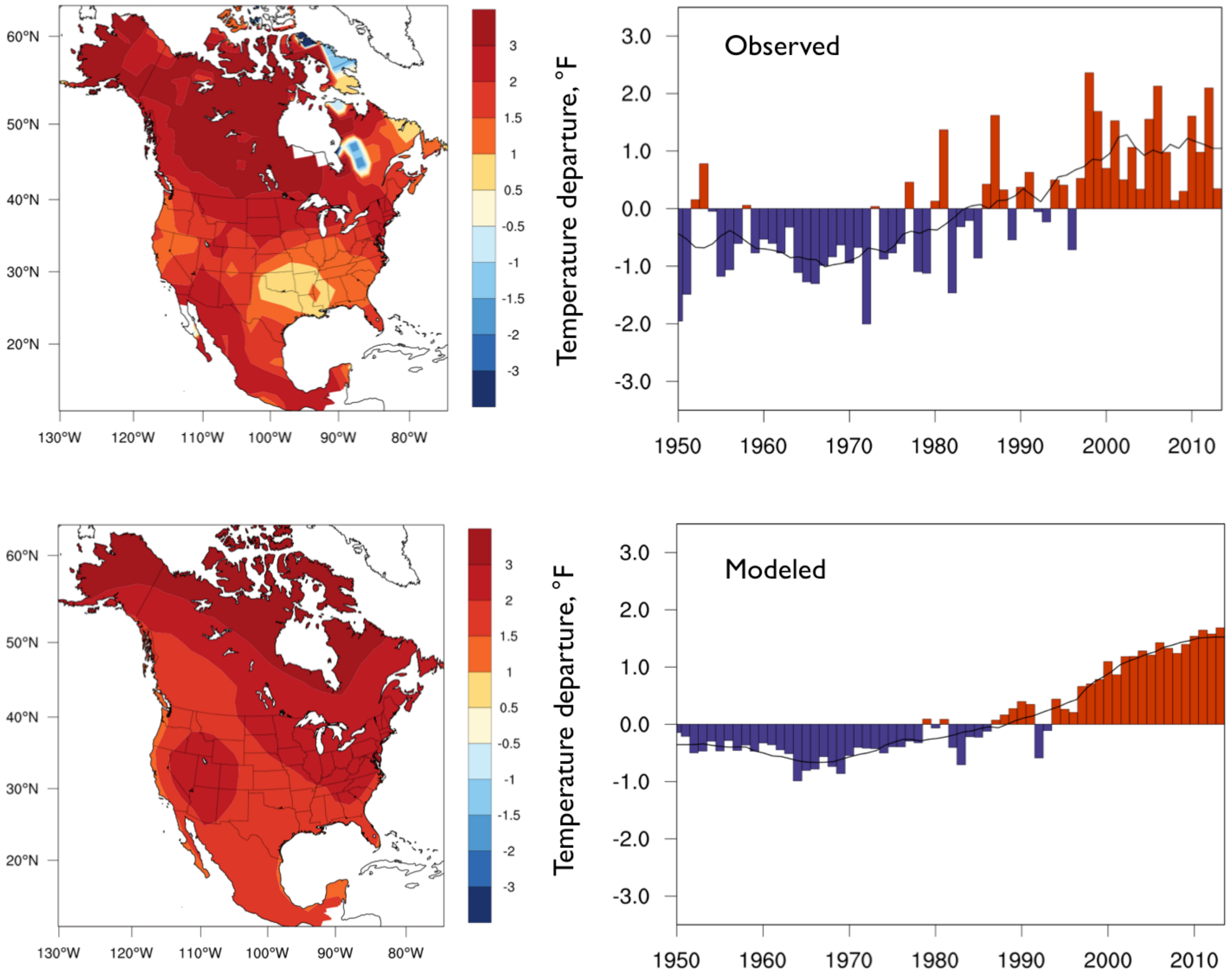


Fig. 4-2. Observed and modeled temperature trends for North America since 1950. (Upper) Observed: The local 1950–2013 trend in observed annual average surface temperature (°F; left) and the time series of the annual values of surface temperature averaged over all of North America (right). Annual departures are with respect to a 1971–2000 baseline. The black line is the 10-year running average. (Lower) Modeled: The local 1950–2013 trend in annual average surface temperature (°F; left), and the time series of the annual values of surface temperature averaged over all of North America (right), from the average of 37 CMIP5 model simulations forced with the greenhouse gas, aerosol, solar, and volcanic forcing from 1950 to 2005, and the RCP 4.5 emissions scenario from 2006 to 2013. The similarity of the observed and modeled trends suggests that anthropogenic greenhouse gas emissions have contributed most of the observed warming in the last 30 years, as is the case with the modeled warming. The simulated time-series of temperature is much smoother than the observed since it is an average of multiple simulations, and so the variability in individual simulations is averaged out. (Data source: Observed: NASA GISS global monthly gridded temperatures; Modeled: CMIP5 archive via the KNMI Data Explorer)

Because natural climate variability is greater at smaller scales, as shown in the temperature records in Figure 1-1, it is more difficult to detect an anthropogenic climate change signal at continental and smaller scales than it is at the global scale (Stott et al. 2010). Also, model simulations are less reliable on smaller scales than on the continental to global scale, in part because of the coarse model resolutions and also because of greater uncertainty in forcings at the regional scales.

Nonetheless, the similarities between the observed North American trends in temperature and the model simulations point to a substantial human influence at the continental scale. Most of the warming occurs after about 1970 in both time series, and the modeled warming of about 1.8°F since 1950 is close to the observed warming. The impression of similarity is bolstered by model experiments for North America in which the model simulations include only natural forcings, and not anthropogenic forcings, similar to the experiments at the global scale (Figure 4-1). Without the inclusion of anthropogenic forcings, the envelope of modeled North American temperatures does not encompass the observed warming since the late 1990s. Accordingly, the IPCC has concluded that anthropogenic forcing has made a substantial contribution to warming in North America, as it has for each of the other continents (IPCC 2013).

4-3. Colorado

The challenges of formally detecting and attributing anthropogenic influences in observed trends are even greater at the spatial scale of Colorado, which accounts for only 1% of the area of North America, and only 0.05% of global surface area. The strong influence of natural variability can mask even large climate forcings for several decades or longer at small spatial scales. Because of this, no formal detection study of an anthropogenic climate changes signal has been done specifically for Colorado, though several have examined sub-continental regions that include Colorado, as described below. In this section, we will discuss the potential anthropogenic influence on recent observed trends in Colorado.

Temperature

A reasonable case can be made that some component of the recent observed warming in Colorado is due to anthropogenic climate change. As shown in Figure 1-1, Colorado's temperature trajectory over the past 100 years has closely followed the trajectories of global and continental temperature. We can also compare

FIGURE 4-3. Observed versus modeled temperature trends for Colorado

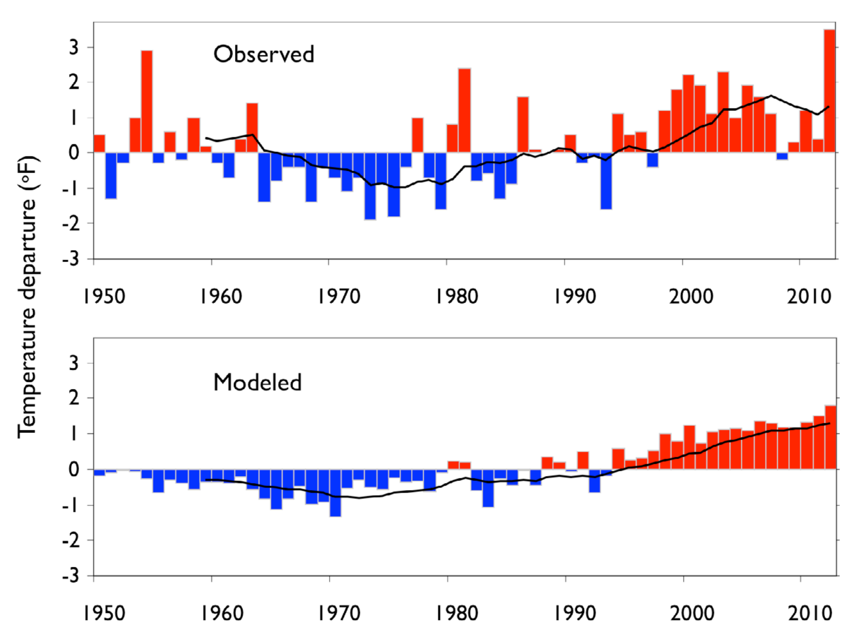


Fig. 4-3. The observed statewide annual average temperatures for Colorado, 1950–2012 (upper), compared to the ensemble average of modeled statewide annual average temperatures for Colorado from 37 CMIP5 model simulations forced with the observed anthropogenic (greenhouse gas and aerosol) and natural (solar and volcanic) climate forcing from 1950 to 2005, and the RCP 4.5 emissions scenario from 2006 to 2012 (lower). The temperatures are shown as departures from the 1971–2000 baseline. The black lines are the 10-year running means. The similarity of the observed and modeled trends suggests that anthropogenic forcing from greenhouse gas emissions may have contributed much of the observed warming in Colorado in the last 30 years. (Data sources: Observed: NOAA NCDC; http://www.ncdc.noaa.gov/cag/; Modeled: Data source: CMIP5 projections re-gridded to 1-degree grid, Reclamation 2013; http://gdo-dcp.ucllnl.org/)

the global climate model simulations of historical temperatures for Colorado (1950–2012) with the observed temperatures over that period. Figure 4-3 shows the observed temperature record for Colorado described in Section 2-3, and the median of 37 CMIP5 climate model runs for Colorado which are driven by the historical climate forcings, including greenhouse gases. The modeled temperatures vary much less from year-to-year than the observed temperatures, since the natural variability being simulated in individual model runs is averaged out in the single value shown for each year. While the clear similarities between the two time-series do not constitute a formal attribution, they suggest that Colorado is in step with larger-scale trends that have a clear anthropogenic component.

Precipitation

Historic periods of low precipitation in Colorado and the surrounding region have been attributed in part to fluctuations of ENSO, along with longer cycles such as the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO) (CCSP 2008b; Schubert et al. 2004; Seager et al. 2005). ENSO affects the tracks of moisture-bearing storms over Colorado in winter and spring. CMIP3 model simulations indicated that it is very unlikely that the anthropogenic increase in greenhouse gases played a role in the period of low precipitation in the early 2000s in western North America (IPCC 2007). Similarly, Barnett et al. (2008) were unable to show any anthropogenic cause for recent precipitation trends in the West. Hoerling et al. (2010) concluded that a downward trend in precipitation over southwestern North America from 1977–2006 was likely caused by internal (i.e., natural) variability in tropical Pacific sea surface temperatures, and was inconsistent with modeled trends driven by anthropogenic forcing. In summary, research indicates that annual precipitation—the main driver of drought in Colorado—has not exhibited changes that can be attributed to anthropogenic climate change, in contrast with annual temperature.

Snowpack, streamflow, and drought indicators

Hydrologic variables like streamflow, while highly sensitive to precipitation, are also affected by temperature and can be influenced by anthropogenic warming, even in the absence of a detectable anthropogenic effect on precipitation. This warming influence is potentially detectable in snowpack, streamflow, soil moisture, and other drought indicators. The aforementioned Barnett et al. (2008) study, along with related studies (Bonfils et al. 2008, Das et al. 2009, Pierce et al. 2008, Hidalgo et al. 2009) examined several hydroclimatic indicators, including the ratio of snow water equivalent to precipitation (SWE/P), January–March minimum temperatures, and streamflow runoff timing throughout the western U.S., including the Colorado Rockies, to detect and attribute trends over the period 1950–1999. These studies concluded that, West-wide, up to 60% of the observed trends in warming winter–spring temperatures, as well as earlier runoff and changes in snow as a fraction of total precipitation, were due to anthropogenic causes. These changes, however, were relatively smaller over Colorado compared to most areas of the West, as discussed in Section 2-4. Note that the period covered by these studies did not include the recent dry period since 2000.

In summary, research indicates that at the scale of the western United States, the observed warming trends—partly attributed to anthropogenic climate change—have led to conditions more favorable to drying of the land surface and have exacerbated the impacts of recent droughts. If we reduce the scale to only Colorado, the linkage between increased severity of recent droughts and anthropogenic climate change is plausible but less certain than at larger scales.

SIDEBAR 4-2. The 2013 Front Range floods: Did anthropogenic climate change play a role?

A severe and widespread flooding event along Colorado's Front Range from September 11–17, 2013 involved most of the rivers and creeks between Pueblo and the Wyoming border, with the highest flood stages and worst damage occurring on Lefthand Creek, St. Vrain Creek, the Big Thompson River, and the mainstem South Platte River downstream from those tributaries. A total of 20 Colorado counties were impacted. Ten people were killed by the flooding; over 1,800 homes were destroyed and almost 20,000 more were damaged. Damage to public infrastructure was also enormous: At least 200 miles of roads and over 50 bridges were damaged, along with many water conveyance and water treatment facilities. Total damage has been estimated at over $2 billion, which would make it the second most costly natural disaster (in 2013 dollars) in Colorado history, after the June 1965 floods on Cherry Creek, the South Platte River, and the Arkansas River.

The 2013 floods were caused by an unusually persistent weather pattern that consistently focused a flow of deep moisture towards the Front Range and led to rainfall totals seen in only a handful of events on the Front Range in the past century. Record or near-record precipitation was recorded during the week across the Front Range. Boulder's COOP weather station, which continues an observational record for Boulder begun in 1893, set new records for 1-day (9.08”), 2-day (11.52”) and 7-day (16.9”) totals. In the context of the entire Front Range this was a rare precipitation event, especially for September, and in some respects it was unprecedented in the observed record.

There have been previous multi-day rainfall and flood events on the Front Range with similar spatial extents and maximum total precipitation as the 2013 event: September 1938 (10” maximum), June 1965 (16”), and May 1969 (20”). The footprints of the 1938 and 1969 events are similar to that of the 2013 event, while the June 1965 event was focused further south, between Denver and Pueblo.

Because human changes have made the global atmosphere warmer and more moist, one can confidently state that all weather events are now subject to some influence of anthropogenic climate change. The potential impact of that influence on the September 2013 rain and flood event has not yet been thorougly examined. Below, we briefly discuss three dimensions of the potential anthropogenic influence.

Water Vapor

Total moisture content of the atmosphere above Denver on September 11, 2013 was observed to be at record levels for September (compared to the period 1948–2012). This mainly reflected the effectiveness of the weather pattern in funneling the moist flow to the Front Range, though a climate change contribution may have occurred. The increase in atmospheric water vapor (of 3–5% on a global basis) associated with anthropogenic warming alone may have increased the source moisture for the event and increased the intensity of heavy rainfall.

Trends in Heavy Rainfall Events

As described in Section 2-6, no increasing trend has been observed in the past century in very heavy rainfall events in Colorado, unlike other regions of the U.S. and the world. Heavy rainfall events are projected to increase in frequency in the future over many parts of the globe, and the average projection shows an increase for Colorado by the mid-21st century (Kharin et al. 2013; see Section 5-3).

The Unusual Weather Pattern

The unusually moist and persistent weather pattern in the 2013 event was very similar to the pattern in the September 1938 event. Thus the atmospheric setup for the 2013 event was rare but not unprecedented, and climate change does not need to be invoked to explain the pattern itself. It is very uncertain whether or not slow-moving weather systems like the one accompanying the 2013 rain and flood event might become more frequent with future climate change.

The historical record strongly suggests that a flood event of the extent and magnitude of September 2013 could occur even in the absence of climate change. Climate researchers at NOAA, the University of Colorado, and Colorado State University are now addressing the anthropogenic climate change contribution to this event, through analysis of observations, historical trends, and climate model experiments. In doing so, they will also assess whether the risk of similar events is likely to change in the future.

5

Projections of Colorado's Future Climate and Implications for Water Resources

Key points

- All climate model projections indicate future warming in Colorado. The statewide average annual temperatures are projected to warm by +2.5°F to +5°F by 2050 relative to a 1971–2000 baseline under a medium-low emissions scenario (RCP 4.5). Under a high emissions scenario (RCP 8.5), the projected warming is larger by 2050 (+3.5°F to +6.5°F), and much larger later in the century as the two scenarios diverge.

- Summer temperatures are projected to warm slightly more than winter temperatures. Typical summer temperatures by 2050 are projected under RCP 4.5 to be similar to the very hottest summers that have occurred in past 100 years.

- Climate model projections show less agreement regarding future precipitation change for Colorado. The individual model projections of change by 2050 in statewide annual precipitation under RCP 4.5 range from -5% to +6%. Projections under RCP 8.5 show a similar range of future change (-3% to +8%).

- Nearly all of the projections indicate increasing winter precipitation by 2050. There is weaker consensus among the projections regarding precipitation change in the other seasons.

- In the first projections of future Colorado hydrology based on the latest climate model output, most projections show decreases in annual streamflow by 2050 for the San Juan and Rio Grande basins. The projections are more evenly split between future

Barker Reservoir and Nederland. Photo: Jeff Lukas increases and decreases in streamflow by 2050 for the Colorado Headwaters, Gunnison, Arkansas, and South Platte basins. However, other hydrology projections show drier outcomes for Colorado, and the overall body of published research indicates a tendency towards future decreases in annual streamflow for all of Colorado's river basins.

- Changes in the timing of runoff are more certain than changes in the amount of runoff. The peak of the spring runoff is projected to shift 1–3 weeks earlier by the mid-21st century due to warming. Continuing impacts of dust-on-snow may increase the shift. Late-summer flows are projected to decrease as the peak shifts earlier.
- Most projections of Colorado's spring snowpack (April 1 SWE) for the mid-21st century show declines in the snowpack due to multiple effects of the projected warming. The individual model projections of change in April 1 SWE range from about -30% to +10% in most basins.
- Most climate projections indicate that heat waves, droughts and wildfires will increase in frequency and severity in Colorado by the mid-21st century due to the projected warming.
- The frequency and magnitude of extreme precipitation events are generally projected to increase globally as a warmer atmosphere is able to hold more water vapor. For Colorado, studies suggest that winter extreme precipitation events will follow this global increasing trend, but not necessarily summer extreme precipitation events.

This section describes the results from the latest temperature and precipitation projections from global climate models (GCMs) for Colorado and the western U.S. Our focus is on projections for 2050, consistent with the main time horizon being used in the State's ongoing water planning efforts. Projections for other time periods may be useful depending on the type of decision or planning horizon.

Section 5-1 begins by presenting the projected changes in temperature and precipitation on a statewide scale, derived from the GCM output, without downscaling, from the CMIP5 climate model ensemble (see Section 3-2). To illustrate how these broad-scale projections may play out at a local scale, Section 5-2 examines downscaled CMIP5 climate projections for eight subregions across Colorado, using the BCSD downscaling method (see Section 3-5). Section 5-3 describes projected changes in streamflow and other hydroclimatic variables for Colorado, which are derived from downscaled climate projections run through a separate hydrologic model. Because the development of hydrology projections using the CMIP5 climate projections is at an early stage, previous results based on the CMIP3-based projections are also shown. Section 5-4 describes the projections of climate extremes for Colorado. Section 5-5 describes the future outlook for additional aspects of water resources, while Section 5-6 summarizes the overall implications of future climate change for water in Colorado.

About the climate projections

The set, or ensemble, of CMIP5 model projections discussed in Section 5-1 and shown in Figures 5-1 through 5-7 is comprised of one projection from each of the 37 climate models run under RCP 4.5, a medium-low emissions scenario. For comparison, results from one projection from each of the 35 climate models that were run under RCP 8.5, a high emissions scenario, are shown in some figures and also summarized in the text (see Section 3.3 for descriptions of the RCPs).

Projections under RCP 2.6 (low emissions) and RCP 6.0 (medium-high emissions) are not shown in the figures or discussed in the text, but are summarized in a supplemental table available on the report website (http://wwa.colorado.edu/climate/co2014report). Both of these scenarios have lower climate forcing than RCP 4.5 at 2050, although RCP 6.0 surpasses RCP 4.5 after 2065, while RCP 2.6 takes a declining trajectory (see Figure 3-4). While the projections from the four RCPs have different multi-model averages at 2050, the ranges of the projections overlap considerably among the RCPs. We focus on RCP 4.5 and RCP 8.5 here because more projections are available for those two RCPs, and because together they span most of the range of all four RCPs.

Because individual climate projections include simulated natural variability, to more clearly discern the anthropogenic future change in each projection we need to compare two periods (historical and future) that are long enough so that the natural variability is at least partly averaged out. Here we use a 30-year averaging period. Thus, the projected changes described for 2050 are based on the projected conditions averaged over the period 2035–2064, compared to the conditions for the historical period of 1971–2000. Note that the climate continues to change throughout that future period, particularly temperature, so the changes described for 2050 are like a snapshot of a moving target.

For the same emissions scenario, the climate models produce different projected future climate changes because (1) the representation of some key climate processes differs from model to model, and (2) the multi-decadal natural variability simulated by the models is still present in the 30-year average and is not synchronized from model to model. See Sidebar 3-1 for a more in-depth discussion of these factors.

The term *projection* is deliberately used by climate scientists for long-term future simulations of future climate rather than ‘prediction’ or ‘forecast.’ The latter two terms are generally reserved for situations in which the future outcome is sensitive to the initial state of the system, but not future changes in related conditions. *Projection* indicates that the future outcome is sensitive to future changes in related conditions (emissions); the projected changes are conditional on that specific emissions scenario.

5-1. Statewide Temperature and Precipitation Projections from GCMs

Temperature

All of the climate models, under all RCPs, project that Colorado’s climate will warm substantially by 2050. Projected changes in temperature for the western US for 2050 relative to the late 20th-century observed baseline are shown on the left side of Figure 5-1. While all projections show increases in temperature by the mid-21st century, they differ in the magnitude of future warming. Under RCP 4.5 (medium-low emissions scenario), Colorado’s annual temperatures are projected to warm by +2.5°F to +5°F by mid-century relative to 1971–2000 observed baseline. Under RCP 8.5 (high emissions scenario), Colorado’s annual temperatures are projected to warm by +3.5°F to +6.5°F by mid-century. Summers are projected to warm slightly more than winters under both RCPs.

The significance of the projected warming becomes clearer when compared to the observed variability and trend in temperature for Colorado (Figure 5-2). Figure 5-2 is based on the same climate projections as in the left side of Figure 5-1, and shows how the projected temperatures for Colorado under RCP 4.5 evolve over time compared to the observed record of statewide temperatures from Figure 2-8. While the climate models are not designed to exactly simulate the historical variability in Colorado’s temperature, they still capture the general trajectory of the observed temperatures: below-average from 1950 to 1990, then above-average since 1990 with a pronounced warming trend that continues at a similar rate into the 21st century. The projected warming by 2050 is several times larger than the multi-decadal observed swings in temperature of about ±1°F over the last century. The three warmest individual years across Colorado in the observed record (1934, 1954, and 2012) were 2.5°–3.5°F warmer than the 1971–2000 baseline. Thus, the typical year by 2050 in the median projection under RCP 4.5 is warmer the very warmest years of the past century. The typical year in the median projection under RCP 8.5 is much warmer than those historical years. Overall, the anthropogenic warming signal would be clearly seen in seasonal and annual temperatures throughout Colorado by 2050, under all RCPs. Because this human-induced warming is superimposed on a naturally varying climate, the future temperature rise will not manifest as a smooth upward trend; there would continue to be relatively warmer years and cooler years as the baseline shifts upward.

Another way to place the projected warming into

Fig. 5-1 (next page). Projected annual and seasonal temperature and precipitation changes by 2050 (2035–2064) over the western US from an ensemble of 37 climate models under RCP 4.5. The large maps show the average change for all of the models (n=37) for that season, and the small maps show the average changes of the highest 20% (n=8) and lowest 20% (n=8) of the models, based on the statewide change for Colorado in temperature or precipitation. For Colorado, all models show a substantial warming (of +2.5°F to +5.5°F), but there is less agreement about the direction of precipitation change. (Data source: CMIP5 projections re-gridded to 1-degree grid, Reclamation 2013; http://gdo-dcp.ucllnl.org/)

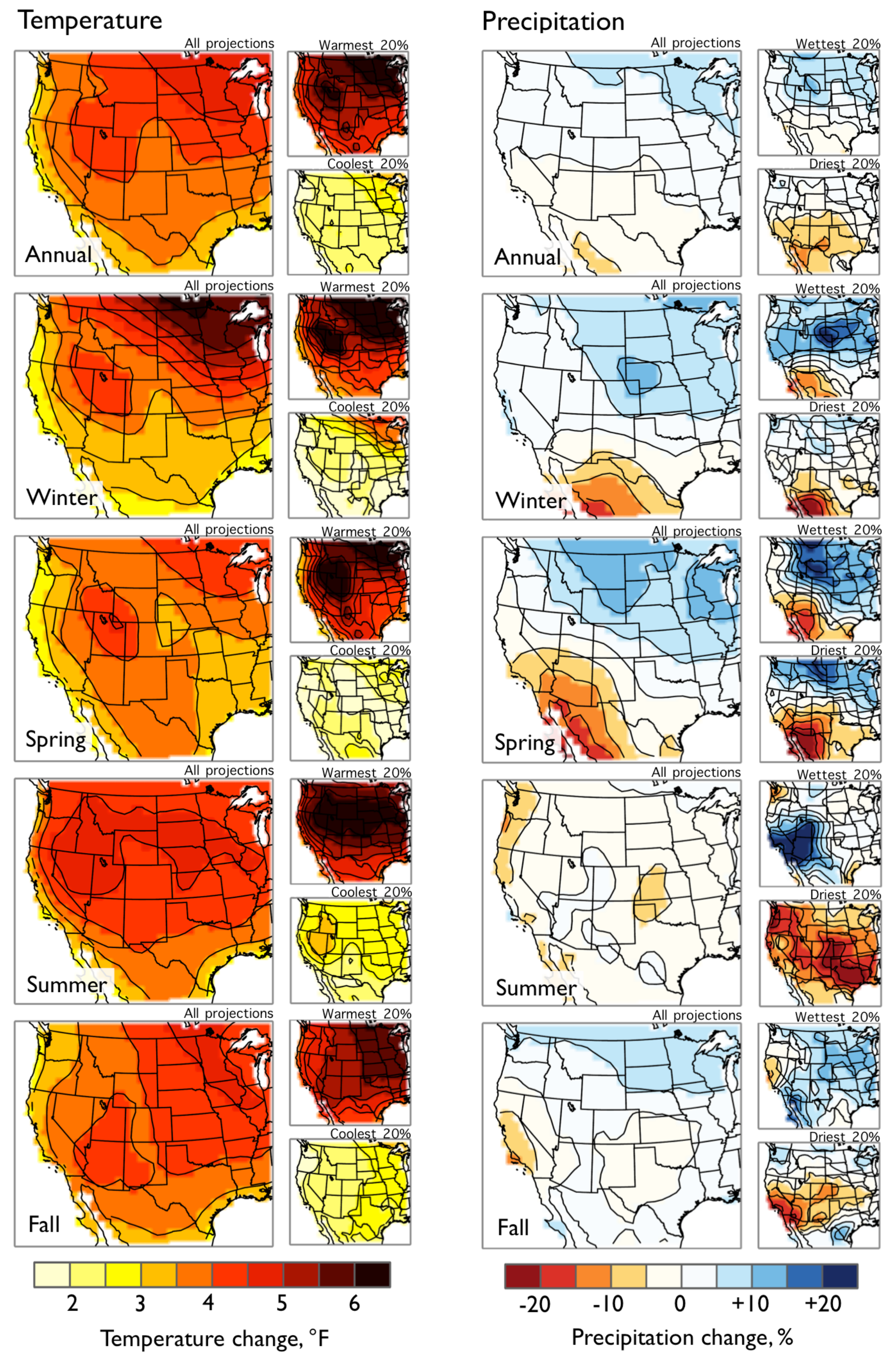


FIGURE 5-1. Projected temperature and precipitation for the western U.S. under RCP 4.5 for 2035–2064

FIGURE 5-2. Projected Colorado annual temperature under RCP 4.5 compared to observations

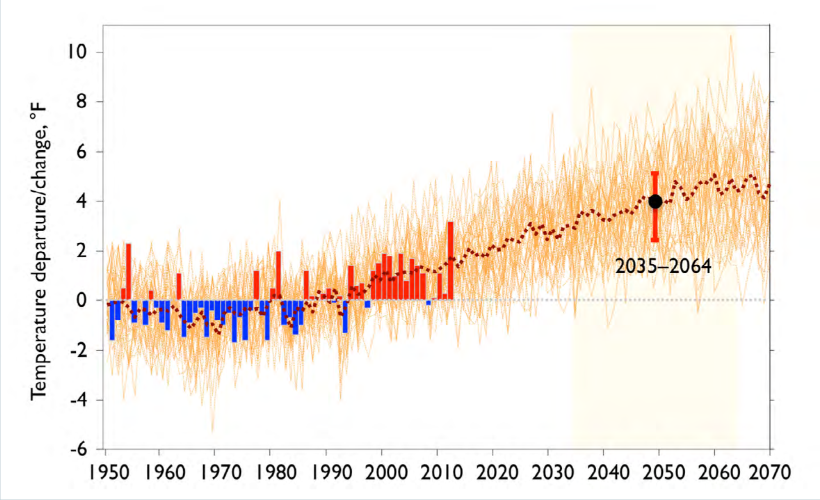


Fig. 5-2. Modeled Colorado annual temperature, 1950–2070, by 37 climate models under RCP 4.5 (yellow/orange lines) compared to the observed Colorado annual temperature anomalies, 1900–2012 (red/blue bars). All values are shown relative to the 1971–2000 baseline (gray dashed line). The thick dashed orange line is the median of the 37 projections. The median and range (10th–90th) of the projected temperatures over the mid-century period (2035–2064) is shown. The models project a continuation of the recent warming trend through the mid-21st century, with typical temperatures by then matching or exceeding the warmest years of the 20th century. (Data source: Observations: NOAA NCDC; Projections: CMIP5 projections re-gridded to 1-degree grid, Reclamation 2013; http://gdo-dcp.ucllnl.org/)

FIGURE 5-3. Projected Colorado annual and seasonal temperature change under RCP 4.5 for 2035–2064

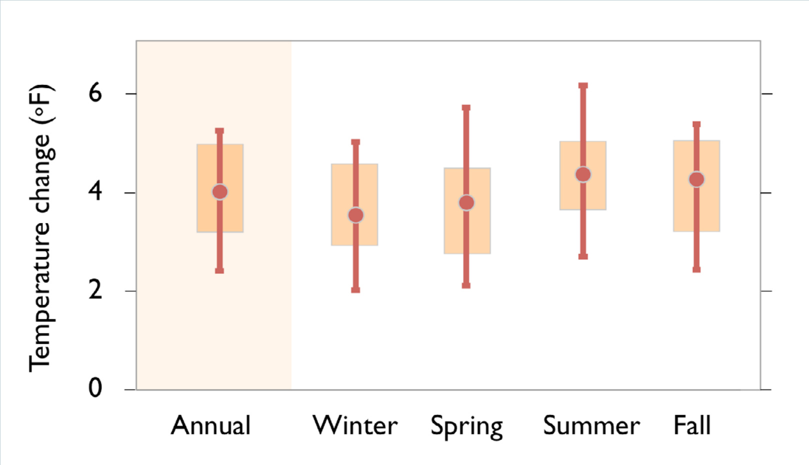


Fig. 5-3. Projected annual and seasonal temperature change for Colorado under RCP 4.5 for the 2050 (2035–2064) time period, relative to 1971–2000. The filled circles show the median (50th percentile) change across the model runs, the boxes show the range between the 25th percentile of the model runs and the 75th percentile, and the bars, between the 10th percentile and the 90th percentile. Slightly more warming is projected in summer and fall than in spring and winter. (Data source: CMIP5 projections re-gridded to 1-degree grid, Reclamation 2013; http://gdo-dcp.ucllnl.org/)

context is to equate the future shift in climate regime with the difference in today's climate between two locations in Colorado. With a 2°F warming, the seasonal temperature regime for Denver would be like the current climate of Pueblo. With a 4°F warming, Denver's temperature regime would be similar to Lamar today. With a 6°F warming, there is no analogue in Colorado; Denver's temperatures would be like Albuquerque, New Mexico, today.

Looking beyond the 2050-centered analysis period, the warming trend is projected to continue into the late-21st century under all RCPs except RCP 2.6. By the period centered on 2070 (2055–2084), the projected warming in Colorado annual temperatures under RCP 4.5 is +2.5°F to +6.5°F relative to the 1971–2000 baseline. Under RCP 8.5, the projected warming is +5.5°F to +9.5°F relative to the 1971–2000 baseline.

Because of the physical characteristics of high-elevation regions—seasonally persistent snow cover and a very dry and cold atmosphere—the future warming is expected to be enhanced at high elevations globally (Rangwala and Miller 2012). An analysis of projected 21st century temperature trends as a function of elevation in the Northern Hemisphere mid-latitudes from CMIP5 models shows more warming at higher elevations during winter, particularly in the daily minimum temperature (Rangwala et al. 2013). However, as discussed in Section 3, the global climate models do not represent the topography of Colorado very well, so it is difficult to discern whether the warming projected for the higher-elevation regions (>10,000') in the state is substantially different from that projected for lower elevations.

Precipitation

There is much less consensus among the models about the direction of projected precipitation change for Colorado than for temperature. The climate models consistently project an increase in annual precipitation for the northernmost states of the U.S., and a decrease in precipitation for the far Southwest (Figure 5-1, right). However, Colorado sits between these two regions in an area of lower model agreement. The ensemble of model projections under RCP 4.5 shows a range from -5% to +6% change in statewide annual precipitation in Colorado by the mid-21st century, with a slight majority of projections showing an increase (Figures 5-4 and 5-5). The projections also tend to show a gradient in which the southern part of the state has drier future outcomes than the northern part of the state. Projections under the RCP 8.5 emissions pathway are similar, with a range of -3% to +8% change in statewide annual precipitation by the mid-21st century (Figure 5-7).

For comparison, the range of historical variability in the 30-year running average of Colorado statewide annual precipitation from 1900 to 2012 has been about ±8%. Thus, any anthropogenic trend in precipitation in Colorado within the model range which does occur in the next several decades will be difficult to detect against the background of decadal natural variability. We can also expect year-to-year natural variability (Figure 5-4) to remain the key driver of Colorado's precipitation in any given year.

Projections of annual precipitation change for the later-century period centered on 2070 (2055–2084) are very similar to those for mid-century under both the RCP 4.5 and RCP 8.5 pathways, again with little consensus regarding the direction of change.

FIGURE 5-4. Projected Colorado annual precipitation under RCP 4.5 compared to observations

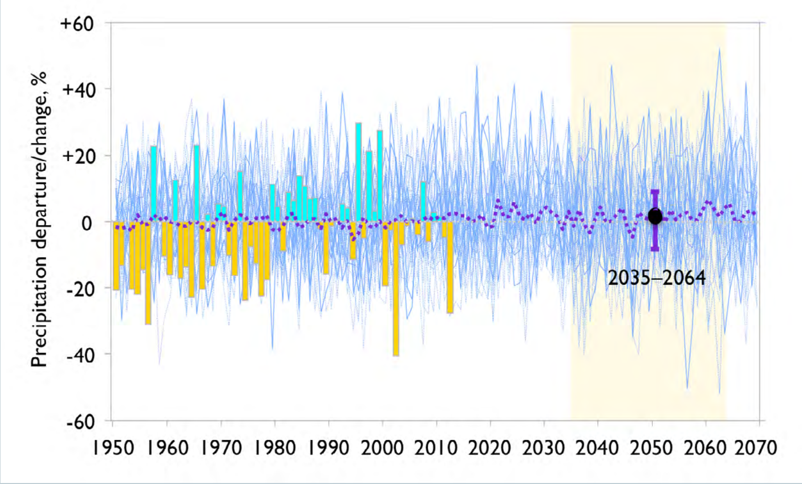


Fig. 5-4. Projected Colorado annual precipitation anomalies, 1950–2070, by 37 climate models under RCP 4.5 (blue lines) compared to the observed Colorado annual precipitation anomalies, 1900–2012 (blue/orange bars). All values are shown relative to the 1971–2000 baseline. The thick dashed purple line is the median of the 37 projections. The median (black dot) and range (red vertical line; 10th–90th percentile) of the projected precipitation changes for the mid-century period (2035–2064) are shown. The models do not agree whether statewide annual precipitation will increase or decrease in the future. (Data source: Observations: NOAA NCDC; Projections: CMIP5 projections re-gridded to 1-degree grid, Reclamation 2013; http://gdo-dcp.ucllnl.org/)

FIGURE 5-5. Projected Colorado annual and seasonal precipitation change under RCP 4.5 for 2035–2064

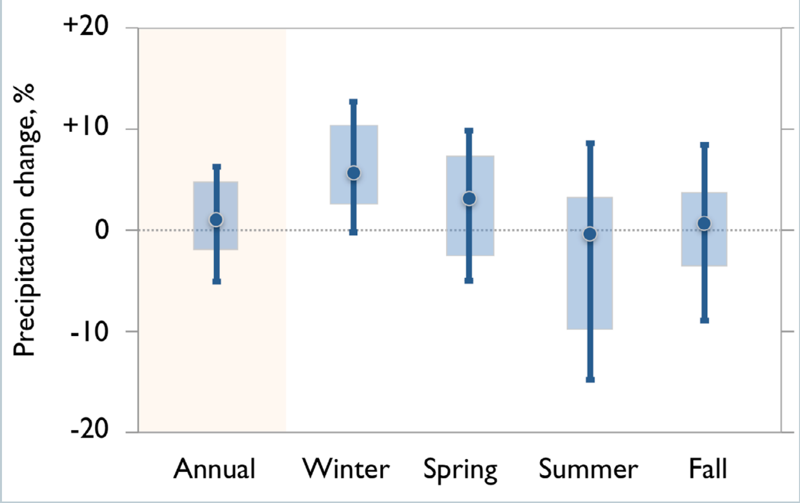


Fig. 5-5. Projected annual and seasonal precipitation change for Colorado under RCP 4.5 for the 2050 (2035–2064) time period, relative to 1971–2000. The filled circles show the median (50th percentile) change across the model runs, the boxes show the range between the 25th percentile of the model runs and the 75th percentile, and the bars, between the 10th percentile and the 90th percentile. (Data source: CMIP5 projections re-gridded to 1-degree grid, Reclamation 2013; http://gdo-dcp.ucllnl.org/)

On average, the climate models indicate a seasonal shift in precipitation for Colorado, with increasing winter precipitation (Figure 5-1, right; Figure 5-5). As with annual precipitation, the range of projections for each season encompasses both future increases and decreases. The multi-model ensemble under RCP 4.5 indicates the following changes in seasonal precipitation for Colorado by mid-21st century compared to the 1971–2000 baseline (Figure 5-5):

- Winter (Dec–Feb) precipitation: Increases in a large majority (33/37) of model runs.
- Spring (Mar–May) precipitation: Increases in a slight majority (22/37) of model runs.
- Summer (Jun–Aug) precipitation: Decreases in a slight majority (20/37) of model runs, with some runs showing the largest decreases of any season.
- Fall (Sep–Nov) precipitation: Increases in a slight majority (20/37) of model runs.

The ranges in the seasonal projections under RCP 4.5 as shown in Figure 5-5 are similar to the observed running 30-year averages for seasonal precipitation for Colorado, which have varied by roughly ±10% from the longer-term average since 1900. Thus, as with annual precipitation, any anthropogenic trends in seasonal precipitation which do occur over the next several decades will be difficult to detect.

The projected precipitation changes in the Colorado mountains, which receive the bulk of their precipitation from winter and spring storms, mainly reflect model-simulated shifts in the location of jet stream, and thus the location of the typical storm track. In many of the climate models, the storm track is projected to move slightly to the north as the climate warms (Yin 2005, Chang et al. 2012), but with somewhat wetter storms. The net effect over Colorado in most models is a seasonal shift towards more mid-winter precipitation, and in some areas a decrease in late spring precipitation. As described in Section 2-1, ENSO influences the storm tracks crossing the western U.S. and Colorado. In CMIP5, the climate models do not agree whether there will be systematic changes in ENSO in a warming climate that would shift towards more frequent or intense El Niño or La Niña conditions. The uncertainty in future ENSO behavior is a major contributor to the uncertainty in future precipitation for Colorado and the western U.S. (Dominguez et al. 2009).

Summer precipitation is projected by most models to decrease over much of the continental United States, but there is more disagreement among the models for summer than for winter (Figures 5-1 and 5-5). The extension of the North American Monsoon system into Colorado, which strongly influences our summertime precipitation, may not be simulated well by climate models. Also, the thunderstorms that dominate Colorado's summer precipitation are more difficult to simulate than winter cyclonic and frontal storms.

It is clear from Colorado's observed climate record (Figure 2-1) that precipitation amounts in the mountains—per storm event, seasonally, or annually—depend on elevation and the specific orientation of the topography relative to the flow of moisture. The spatial resolution of the global climate models is too coarse to capture these effects, and downscaling methods may not fully compensate for the deficiencies in the global models. In a very high-resolution weather model (1.2-mile gridboxes) simulation under a warmed climate with more available water vapor, precipitation over the Colorado mountains during the cold-season (November–April) increased by 12–15% versus recent observed conditions (Rasmussen et al. 2011). For comparison, only a 4% increase in precipitation was seen in the CMIP3-era GCM projection that was used to perturb the high-resolution simulation. A follow-up study with a longer simulation period found a 12% increase in winter precipitation over the same region (Rasmussen et al. 2014). These results point to the possibility that the future winters in Colorado may be wetter than projected in the global models, assuming that storm tracks don't change. However, the follow-up study (Rasmussen et al. 2014) also showed that evapotranspiration increased even more than precipitation over the Colorado mountains in a warmed climate, resulting in projection of a slight decrease in runoff from the region on an annual basis.

5-2. A closer look: Downscaled climate projections

Water resources management, planning, and use are tied to climate processes and variability at more local (i.e., basin) scales than can be captured by the

SIDEBAR 5-1. Exploring the differences between CMIP3 and CMIP5

While this report focuses on the results of the new generation of climate model projections (CMIP5), it is important to compare them to the previous generation of climate model projections (CMIP3). The CMIP3 projections have been used in many climate change assessments and studies, including some released very recently, and have been scrutinized more thoroughly than the newer CMIP5 projections. Comparing the two sets of projections is complicated because the future greenhouse gas emissions scenarios used to force the two sets of models are not the same, and because CMIP5 includes many more individual models. But by examining projections under comparable emissions trajectories, we can make a broad comparisons between the two sets of model output. The overall differences between CMIP3 and CMIP5 for Colorado are not large, and are much smaller than the spread of the individual model runs in each ensemble. This lends more credibility to the results from both sets of models than if the differences between them were larger.

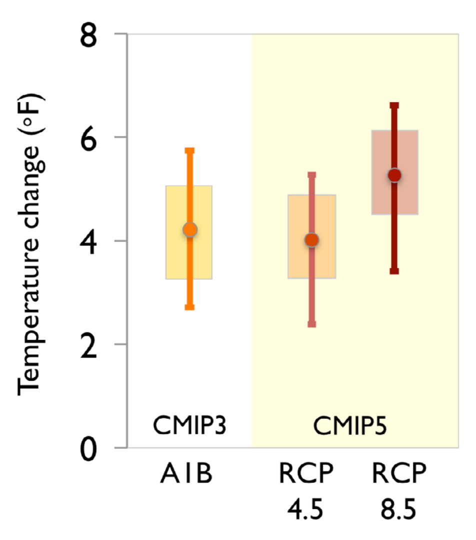
Temperature

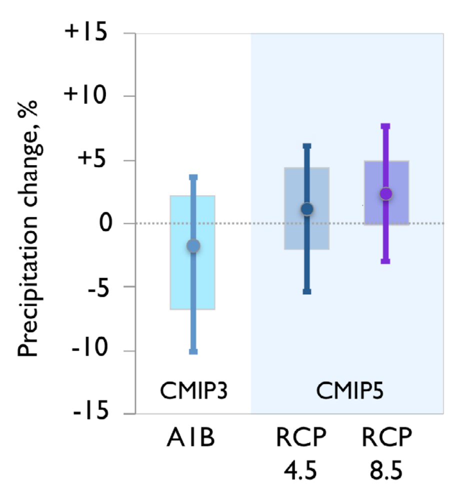
Compared to the CMIP3 ensemble of projections under the A1B emissions scenario, the CMIP5 projections under RCP 4.5 tend to have slightly less warming in summer (by 0.5°F), and slightly more warming in winter (by 0.5°F), but the median change in annual temperature is very similar, as is the spread of the projected changes (Figure 5-6). Projections under RCP 8.5, having greater radiative forcing than either A1B or RCP 4.5 at mid-century, show a larger temperature change. The warming difference in summer results from the CMIP5 projections tending to show more summer precipitation than the CMIP3 projections; summer temperature is closely tied to the amount of summer precipitation.

Precipitation

Compared to the CMIP3 ensemble of projections for A1B, the CMIP5 projections for Colorado under RCP 4.5 tend to be wetter in spring and summer, and are very similar in fall and winter. For annual precipitation, the CMIP5 projections are shifted slightly wetter than the CMIP3 projections, with the CMIP5 median projection showing a slight increase in precipitation vs. the late 20th-century baseline, while the CMIP3 median projection shows a slight decrease (Figure 5-7). Projections under RCP 8.5 show a range shifted slightly more to the wet side compared to RCP 4.5. The ranges of projections for CMIP3 and CMIP5 overlap substantially, and the overall differences between CMIP3 and CMIP5 at the annual and seasonal scale are smaller than these ranges. But because changes in precipitation are amplified during the conversion to runoff, the differences between CMIP3 and CMIP5 have relatively larger consequences for the projections of hydrologic change (see Section 5-3).

FIGURES 5-6 and 5-7. Projected Colorado annual temperature change (upper figure) and precipitation change (lower figure) change under A1B, RCP 4.5, and RCP 8.5 for 2035–2064





Figs. 5-6 and 5-7. Projected annual temperature change precipitation change for Colorado under SRES A1B (CMIP3), RCP 4.5, and RCP 8.5 for 2050 (2035–2064). The filled circles show the median (50th percentile) change across the model runs, the boxes show the range between the 25th percentile of the model runs and the 75th percentile, and the bars, between the 10th percentile and the 90th percentile. (Data source: CMIP3 and CMIP5 projections re-gridded to 1-degree grid, Reclamation 2013; http://gdo-dcp.ucllnl.org/)

projections shown in the previous section. Thus it can be informative to look at projections that have been downscaled to provide more local detail. Aside from the potential benefit of capturing smaller-scale climate features, *downscaling* is often needed to meet the input requirements of hydrologic models and other impact models that are run at spatial scales much smaller than that of the GCM output.

Compared to the "raw" GCM output, downscaling leads to a better representation of Colorado's complex topography and, in principle, the influences of that topography on climate. We again caution that while downscaled projections are more precise than the underlying GCM output (i.e., they have finer spatial resolution), they may not necessarily be more accurate in projecting future change. Like the underlying raw GCM projections, downscaled projections will still have a large spread across the model ensemble, reflecting the inherent uncertainties in projecting future climate.

To examine the implications of the model-projected changes in 2050, including the seasonal cycle, at more local scales, eight subregions across Colorado were delineated (Figure 5-8): the Northeastern Plains, the Denver Metro area, the Central Mountains, the Yampa Valley, the Grand Valley, the San Juans, the San Luis Valley, and the Arkansas Valley. Each of these subregions is about 30 miles across east-west, and 40 miles north-south. These subregions were chosen to align with the alternate climate divisions for Colorado described in Section 2-3.

For all eight subregions, the monthly average temperatures and precipitation from 1971–2000 are compared with those projected for the mid-21st century (2035–2064) using the BCSD (Bias-Correction Spatial Disaggregation) CMIP5 projections (BCSD5; Reclamation 2013); see http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/. Sidebar 3-2 describes the "wettening" effect of the BCSD approach, which tends to make these downscaled precipitation projections for 2050 slightly wetter than the original GCM output.

Table 5-1 shows the median projected monthly temperature change for mid-century under RCP 4.5 (37 models) for the eight subregions. The projected warming in all months in all eight subregions is within 1°F of the statewide median projected annual warming (4°F). The seasonal differences in the projected warming are consistent among the subregions, with the least warming in winter and early spring, and the most warming in late summer and early fall, which reflects an expected amplifying feedback on the warming due to soils drying out earlier in the summer. The differences between the subregions are greatest in winter and early spring, when the western slope is projected to warm more than the eastern slope, likely related to the precipitation increase projected for the eastern slope in most models. The range of the model projections between the 10th and 90th percentiles is 3°–4°F in all months and in all subregions, which is larger than either the seasonal differences in the median projection or the differences between subregions.

Table 5-2 shows the median projected monthly precipitation change (in %) for mid-century under RCP 4.5 (37 models) for the eight subregions. Looking first at seasonal differences across the changes, projected increases in precipitation predominate during the cold season (November–April), especially east of the Divide and in the mountains, while during the warm season (May–October) there are more projected decreases, especially east of the Divide. Given the high variability

FIGURE 5-8. Map of the eight Colorado subregions used in the analysis of downscaled climate projections

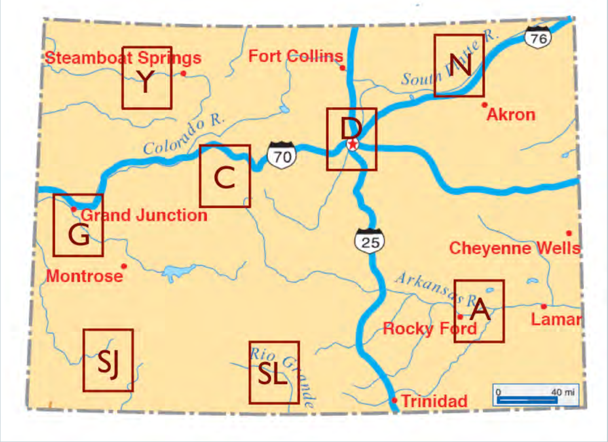


Fig. 5-8. The eight subregions used for analysis of the downscaled monthly temperature and precipitation projections. Each of the subregions is about 30 miles across east-west, and 40 miles north-south. The subregions are coded in the map as follows: N = Northeastern Plains, D = Denver Metro area, C = Central Mountains, Y = Yampa Valley, G = Grand Valley, SJ = Western San Juans, SL = San Luis Valley, A = Arkansas Valley.

in monthly precipitation over time and the large range of projected changes across the models, only median changes greater than 10% may represent an appreciable shift in the risk of wetter or drier future conditions. Considering this, the projected median increase in precipitation in most or all of the months from November–March in the east-slope subregions, the Central Mountains, and Yampa Valley is a noteworthy feature of the projections, as is the median decrease in May precipitation in southwestern Colorado (Grand Valley and the South San Juans). Note that the large percentage increases in January–March precipitation in eastern Colorado come during what is typically the driest season in those areas (see Figure 2-2), so the

TABLE 5-1. Projected monthly temperature change for eight subregions under RCP 4.5 for 2035–2064

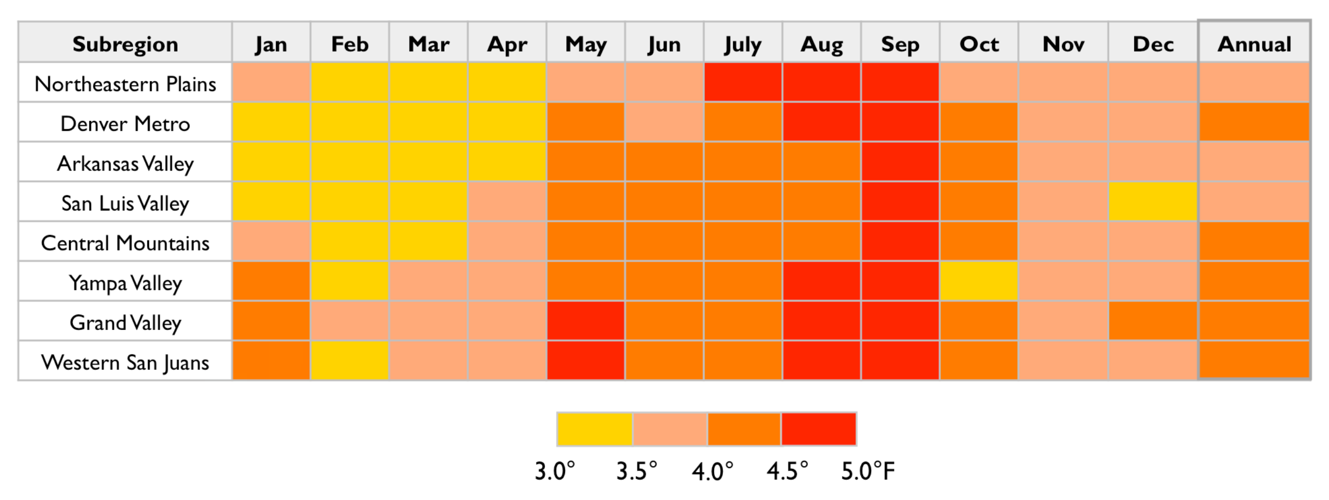


Table 5-1. Median downscaled projected increase in monthly temperature (°F) under RCP 4.5 for the eight subregions for mid-century (2035–2064) compared to 1971–2000, from 37 climate model projections. (Source: BCSD statistically downscaled CMIP5 projections, Reclamation 2013; http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/)

TABLE 5-2. Projected monthly precipitation change for eight subregions under RCP 4.5 for 2035–2064

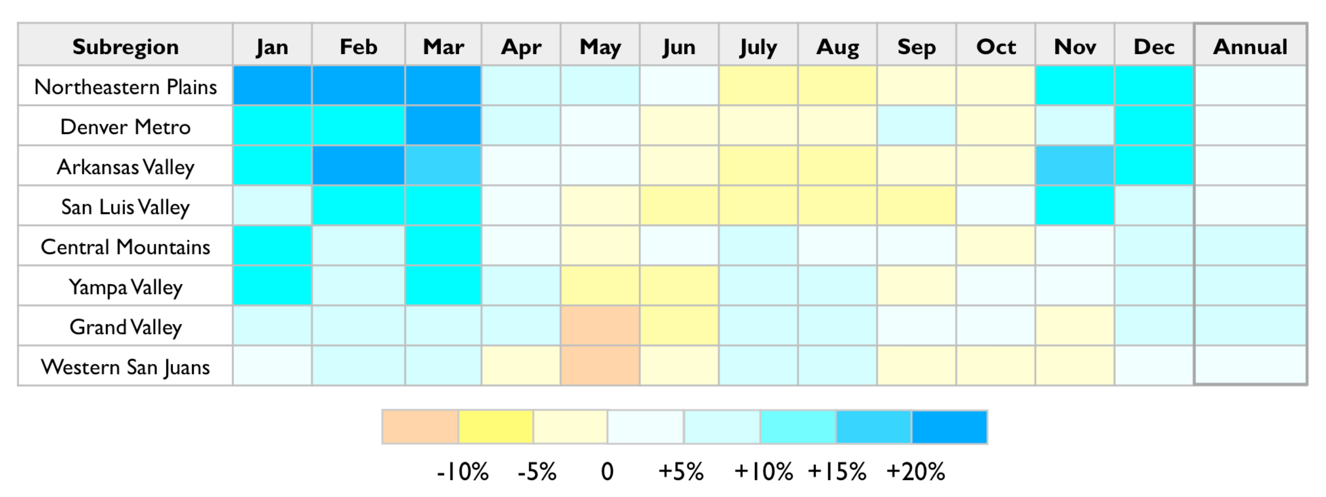


Table 5-2. Median downscaled projected monthly precipitation change (%) under RCP 4.5 for the eight subregions for mid-century (2035–2064) compared to 1971–2000, from 37 climate model projections. Median changes greater than 10% represent an appreciable projected shift towards wetter or drier conditions, relative to historical variability. Note that the range of projections for every subregion and every month includes both projected increases and decreases in precipitation. (Source: BCSD5 statistically downscaled CMIP5 projections, Reclamation 2013; http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/)

FIGURE 5-9. Projected monthly temperature change for Denver Metro subregion under RCP 4.5 for 2035–2064

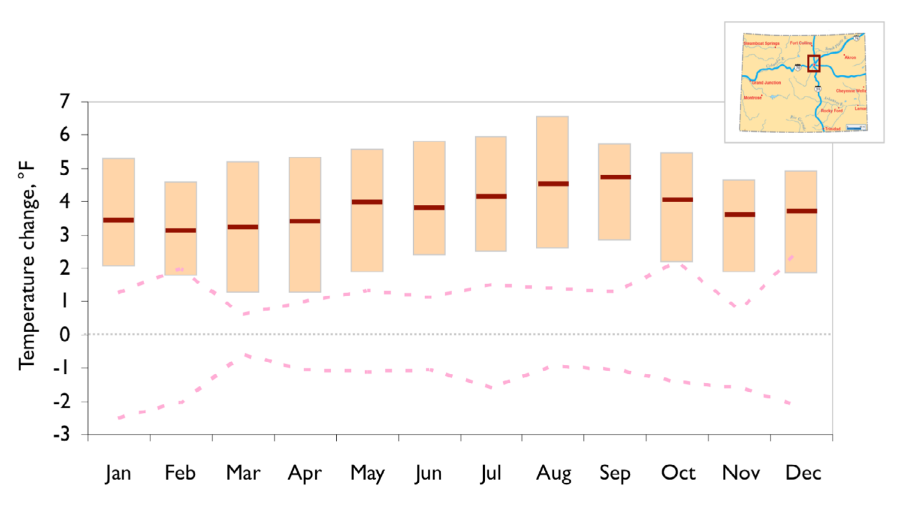


Fig. 5-9. Monthly downscaled projected temperature changes for mid-century (2035–2064) for the Denver Metro subregion under RCP 4.5. The dark red lines show the median projection for each month; the orange bars show the range from the 10th percentile to the 90th percentile of the individual model projections. The pink dashed lines show the envelope of observed multi-decadal variability in monthly temperature, derived from the running 30-year averages of a long-term (>100-year) station record within that subregion. By mid-century, projected temperatures are outside of the bounds of historical variability at local scales and monthly timescales. (Source: BCSD5 statistically downscaled CMIP5 projections, Reclamation 2013; http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/)

FIGURE 5-10. Projected monthly precipitation change for Denver Metro subregion under RCP 4.5 for 2035–2064

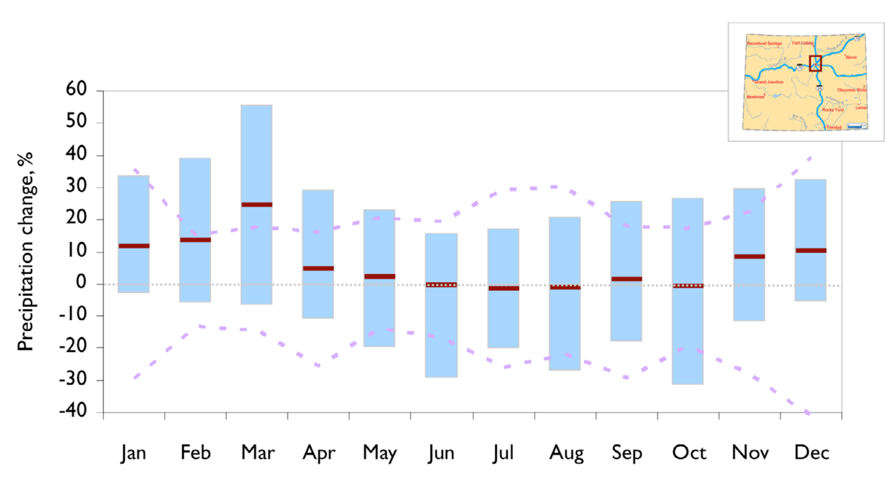


Fig. 5-10. Monthly downscaled projected precipitation changes (in %) for mid-century (2035–2064) for the Denver Metro subregion under RCP 4.5. The dark red lines show the median projection for each month; the blue bars show the range from the 10th percentile to the 90th percentile of the individual model projections. The purple dashed lines show the envelope of observed multi-decadal variability in monthly precipitation, derived from the running 30-year averages of a long-term (>100-year) station record within that subregion. By mid-century, most projections for precipitation are within the bounds of historical variability. (Source: BCSD5 statistically downscaled CMIP5 projections, Reclamation 2013; http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/)

effect on annual precipitation is not as large as it might appear.

To further illustrate the projected changes at local scales, Figures 5-9 through 5-12 show the median and range of the model-projected changes in the context of historical climate variability for two of the subregions: Denver Metro and the Western San Juans. These two subregions illustrate some of the seasonal differences in projected climate change across the state, and also the broad similarities.

Figure 5-9 shows the monthly projected temperature changes for mid-century (2035–2064) for the Denver Metro subregion. The dark red lines show the median projection for each month; these are the same values as shown in Table 5-1. The orange bars show the range from the 10th percentile to the 90th percentile of the individual model projections. The pink dashed lines show the envelope of observed variability in monthly temperature, derived from the running 30-year averages of a long-term (>100-year) station record within that subregion. The 30-year average was chosen to match the 30-year averaging period for the future projections. In all months, nearly all of the projected changes across the ensemble are outside of the envelope of observed variability, with the summer months being further outside of that envelope than the winter months.

Figure 5-10 shows the monthly

projected precipitation changes for mid-century (2035–2064) for the Denver Metro subregion, using the same scheme as the previous figure. First, there is substantial natural variability in monthly precipitation at local scales. Even when averaged over 30-year periods, precipitation varies by ±15% to ±40%, depending on the month. The ranges of the projections for each month are also large, spanning both future increases and decreases in precipitation for each month. These broad ranges result in part from the modes of natural variability being simulated by the different models not being in phase with each other over the 2035–2064 period. Examining the overlap of the observed variability with the model projections, most of the projected precipitation changes are within the envelope of past variability. Only in March are the majority of projections outside of that envelope (on the wet side), though in four other months—January, February, November and December—the range is also shifted appreciably towards wetter conditions.

Figure 5-11 shows the monthly projected temperature changes for mid-century (2035–2064) for the Western San Juans subregion. Again, in all months, nearly all of the projected changes across the ensemble are outside of the envelope of observed variability, with the warm-season months (May–October) being further outside of that envelope than the cool-season months.

Figure 5-12 shows the monthly projected precipitation changes

FIGURE 5-11. Projected monthly temperature change for Western San Juans subregion under RCP 4.5 for 2035–2064

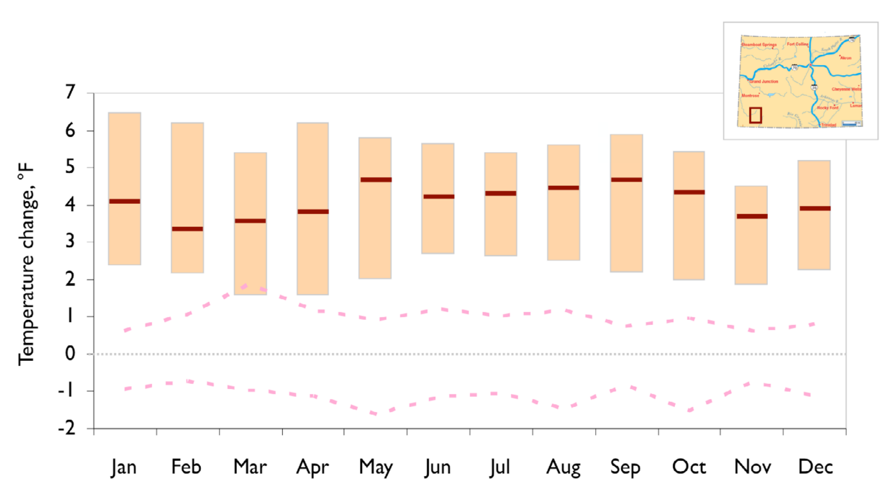


Fig. 5-11. Monthly downscaled projected temperature changes for mid-century (2035–2064) for the Western San Juans subregion under RCP 4.5. The dark red lines show the median projection for each month; the orange bars show the range from the 10th percentile to the 90th percentile of the individual model projections. The pink dashed lines show the envelope of observed multi-decadal variability in monthly temperature, derived from the running 30-year averages of a long-term (>100-year) station record within that subregion. By mid-century, temperatures will be outside of the bounds of historical variability at local scales and monthly timescales. (Source: BCSD5 statistically downscaled CMIP5 projections, Reclamation 2013; http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/)

FIGURE 5-12. Projected monthly precipitation change for Western San Juans subregion under RCP 4.5 for 2035–2064

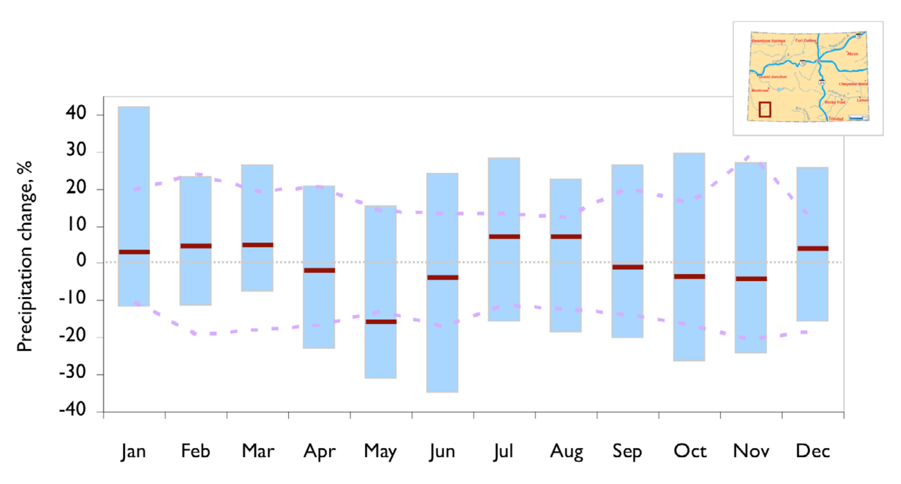


Fig. 5-12. Monthly downscaled projected precipitation changes (in %) for mid-century (2035–2064) for the Western San Juans subregion under RCP 4.5. The dark red lines show the median projection for each month; the blue bars show the range from the 10th percentile to the 90th percentile of the individual model projections. The purple dashed lines show the envelope of observed multi-decadal variability in monthly precipitation, derived from the running 30-year averages of a long-term (>100-year) station record within that subregion. By mid-century, most projections for precipitation are within the bounds of historical variability. (Source: BCSD5 statistically downscaled CMIP5 projections, Reclamation 2013; http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/)

for mid-century (2035–2064) for the Western San Juans subregion. The overall picture is similar to that for the Denver Metro region: most of the projected precipitation changes are within the envelope of past variability. Only in May are most projections outside of that envelope (on the dry side); no other month has a median projection that is more than 10% change from late-20th century conditions.

5-3. Projections of hydrologic changes

By itself, the warming projected for Colorado described in Sections 5-1 and 5-2 would have clear impacts on the hydrologic cycle; it would tend to reduce the amount of annual streamflow and to shift peak runoff earlier in the spring. However, the uncertainty in the direction and amount of future change in precipitation for Colorado greatly broadens the range of potential hydrologic outcomes.

In this section, we examine the role of temperature and precipitation in hydrology, and explore the range of future hydrologic outcomes for Colorado as presented in recent studies and assessments. Because the translation of the CMIP5 climate model projections into basin-scale hydrology output for Colorado and the western U.S. is still at an early stage, we share initial results with the caveat that subsequent hydrology results based on CMIP5 projections that use different downscaling methods or hydrologic models may show different changes. Accordingly, at this time, we encourage users to consider the CMIP5-based hydrology results alongside the CMIP3-based results, as in Figure 5-13.

Runoff and streamflow

The state of Colorado includes most or all of the headwaters of the Arkansas River, South Platte River, Colorado River, and the Rio Grande. Of these basins, the most-studied with respect to climate change impacts has been the Colorado River; it is among the most-studied basins in the country. Since the 2008 Report, many new studies of climate change impacts on hydrology for our region have been conducted, with a transition from academic studies that examine the impacts on one or several gages in a single basin (usually the Colorado River), to larger research efforts, involving water management agencies, that examine impacts on many gages across multiple basins. Three of these more recent studies are described in Sidebar 5-2.

Before examining the results of these studies, it is important to understand the concept of runoff sensitivity to climate variations. The amount of annual runoff is sensitive to changes in both temperature and precipitation; because these two factors are correlated on a seasonal and annual basis, the runoff sensitivity to each factor is difficult to discern from observations alone. Thus, controlled tests with hydrologic process models, also called land-surface models, are used to tease out the sensitivity of runoff to each factor separately.

A major goal of the recently completed NOAA-funded "Reconciling Projections of Future Colorado River Stream Flow" study (Hoerling et al. 2009, Vano et al. 2014) was to examine the runoff sensitivities for the Colorado River as estimated from different hydrologic models, as part of understanding the differences among future streamflow projections. That study found that for the widely used VIC and SAC-SMA models (see Sidebar 5-2), the runoff sensitivity to precipitation change for the Upper Colorado River Basin (at Lees Ferry) was such that a 5% decrease in annual precipitation over the basin equated to a 10%–15% decrease in annual runoff (Vano et al. 2012). Similar analyses done for the Joint Front Range Study (see Sidebar 5-2) using the SAC-SMA and WEAP models found that the runoff sensitivity to precipitation change for other river basins in Colorado was similar: a 5% decrease in precipitation led to a 8–15% decrease in annual runoff, with the South Platte and Arkansas River showing similar sensitivity (Woodbury et al. 2012). For temperature, the VIC, SAC-SMA, and WEAP models have a similar response, such that a 1°F warming is associated with a 3–4% decrease in annual runoff for river basins in Colorado (or 12–16% decrease for a 4°F warming) (Vano et al. 2012, Woodbury et al. 2012).

Changes in annual streamflow

Figure 5-13 shows hydrologic projections of changes in average annual streamflow for 2050 for seven gages representing major river basins in Colorado. The projections are from two datasets based on the CMIP3 and CMIP5 climate projections, respectively. The CMIP3-based projections (BCSD3 hydrology) were developed for the Bureau of Reclamation's West-Wide Climate Risk Assessment (WWCRA; Reclamation 2011) and also used, with a slight modification, in the Colorado River Basin Water Supply and Demand Study (Reclamation 2012). The CMIP5-based projections, the BCSD5 hydrology, were developed by researchers at NCAR with support of the U.S. Army Corps of Engineers, for a consortium that includes the Bureau of Reclamation (Reclamation 2014). Both datasets use climate model projections downscaled with the BCSD method (Reclamation 2013; see Section 5-2), then run through the VIC hydrology model to generate projections of runoff and other hydrologic variables. Figure 5-19 shows a schematic of the overall methodology. Because there are no consistent differences in the streamflow changes associated with the emissions scenario (e.g., RCP), in Figure 5-13 the results have been pooled across all of the emissions scenarios to make a more even comparison between the two ensembles of projections.

The ensemble of CMIP3-based BCSD3 hydrology projections is strongly tilted towards decreasing future annual streamflows for Colorado, with about three-quarters of the individual projections in each basin indicating less streamflow for the mid-century period. The broad ranges of projections include the possibility of increasing future streamflows in each basin. The CMIP5-based BCSD5 hydrology projections have similar ranges but are shifted away from drier outcomes in all basins. In the San Juan and Rio Grande basins, about two-thirds of the projections still show decreases in annual streamflow by 2050. In the Colorado Headwaters, Gunnison, Arkansas, and South Platte Basins, the shift is larger and the projections are more evenly split between future increases and decreases in streamflow.

The overall wetter outcomes seen in the BCSD5 hydrology projections can be at least partly attributed to two factors. First, the CMIP5 climate projections on

FIGURE 5-13. Projected annual streamflow changes for selected gages for 2035–2064, based on CMIP3 and CMIP5 climate projections

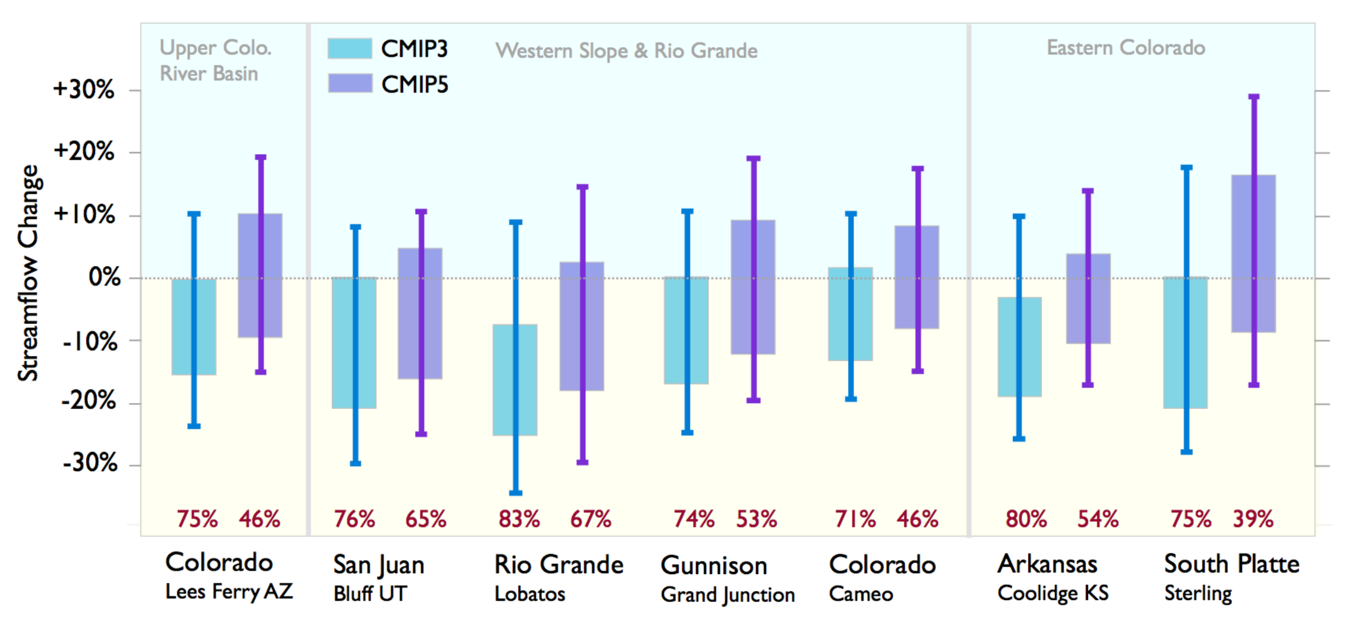


Fig. 5-13. Projected change in average annual streamflow for selected gages for 2050 (2035–2064) based on CMIP3 (BCSD3 hydrology; blue) and CMIP5 (BCSD5 hydrology; purple) climate projections under all emissions scenarios, using similar a methodology: BCSD-downscaled GCM output run through the VIC hydrologic model. The bars show the range from the 10th percentile to the 90th percentile of the individual model projections, the boxes show the interquartile range (25th to 75th percentile). The values in red show the percentage of individual projections indicating a future decrease in flow (n=112 for BCSD3; n=97 for BCSD5[hydro]). While the ranges of outcomes are broad, the projections collectively indicate a greater risk of decreasing future streamflow, especially in the southern half of the state. Note that the results for a given gage may not be representative of all gages in that basin. (Source: BCSD3 hydrology: West-Wide Climate Change Risk Assessment; Reclamation 2011; BCSD5 hydrology: Reclamation 2014; http://gdo-dcp.ucllnl.org/)

average show slightly greater future precipitation across Colorado than the CMIP3 projections (see Sidebar 5-1). Second, the BCSD downscaling procedure imparts a “wettening” effect on the precipitation changes seen in the underlying climate model projections (see Sidebar 3-2). While this effect was also seen with the CMIP3 projections, it is larger overall with the CMIP5 projections, for reasons that are not yet clear.

Both sets of streamflow projections also show a gradient across the state, more prominent in the BCSD5 hydrology projections, in which the southern half of the state has generally drier outcomes than the northern. This gradient reflects that both the CMIP3 and CMIP5 projections for annual precipitation tend to show drier outcomes for southern Colorado than for northern Colorado.

The differences between the BCSD3 and BCSD5 hydrology projections have not yet been fully explained, and further research is needed. So at this time, it is advisable to consider these hydrology projections together (Figure 5-13), recognizing that the BCSD3 and other CMIP3-based projections have undergone more scrutiny.

In all of the hydrology projections summarized in Figure 5-13, the projected warming drives increased water loss from snowpack (sublimation) and from soils and vegetation (evapotranspiration), i.e., the temperature sensitivity of runoff as described above. When an individual projection shows increased streamflow, there is a projected increase in precipitation large enough to offset the runoff-reducing effect of the warmer temperatures. When a projection shows decreased streamflow, either there is a precipitation increase insufficient to offset the warming, or a precipitation decrease that amplifies the warming. Figure 5-14 shows the balance of temperature change and precipitation change with respect to the projected runoff outcomes for the Colorado River near Cameo; there is a similar relationship in the other basins. From the climate models we have more confidence in the continued warming, which would tend to reduce runoff, than in the future precipitation change being in one direction or the other. Considering this, in light of the overall body of published research on future Colorado hydrology, while there is a broad range of future outcomes for Colorado’s river basins, and the clear possibility of increasing annual streamflow, overall there is a greater risk of decreasing annual streamflow.

FIGURE 5-14. Direction of projected annual runoff change for the Colorado River as a function of projected temperature change and precipitation change

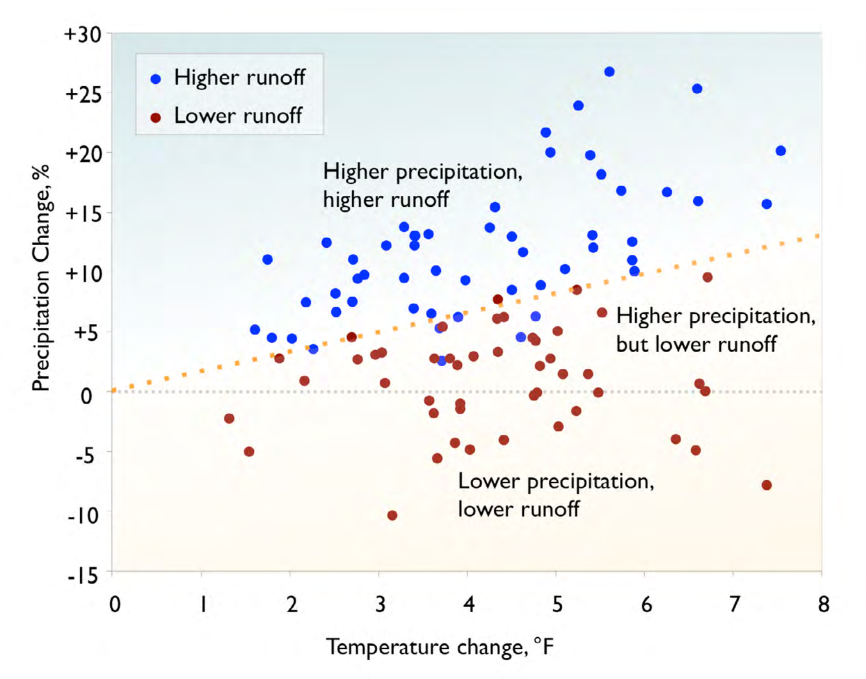


Fig. 5-14. Projected change in average annual runoff for the Colorado River near Cameo for 2050 (2035–2064) as a function of projected temperature change and precipitation change using BCSD-downscaled CMIP5 GCM output run through the VIC hydrologic model (BCSD5 hydrology). The filled circles show the 2035–2064 average temperature and precipitation change for each of 97 climate projections across all RCPs. Blue circles indicate that the projected climate was associated with a modeled increases in runoff for the same time period; red circles indicate modeled decreases in runoff. Below the sloped dashed line, increases in precipitation were offset by the effects of the projected warming, and runoff declined in nearly all cases. (Data source: Reclamation 2014; http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/)

The broad range in the projected streamflow changes for each basin in Figure 5-13 reflects that the respective uncertainties about future temperature and future precipitation change, described earlier, are compounded in the hydrologic modeling. Some of the difference between the projections is due to the underlying climate models' different simulations of natural climate variability, which is reflected even in a 30-year average (Harding et al. 2012). The presence of simulated natural variability at multi-decadal time scales is clearly seen in the ups and downs of the CMIP5-based projections for the Colorado River shown in Figure 5-15. Averaging across the model ensemble will tend to average out the natural variability in the individual projections, but will also obscure the range of potential future outcomes. The projected streamflow, for the same basin, from different studies (as in Figure 5-17) can differ due to additional factors. The selection of a particular subset of GCMs for analysis may shift the range of hydrologic outcomes relative to another subset. The downscaling and bias-correction approaches used to translate the coarser GCM grids to the finer hydrology model grids may impart different shifts to the distribution of the GCM-projected precipitation, which in turn will affect runoff (see Section 3-5 and Sidebar 3-2). The spatial resolution of the hydrologic modeling, especially in the mountainous western U.S., can have a substantial impact on results. Even when run at the same resolution, the various stand-alone hydrologic models (e.g., VIC, SAC-SMA, WEAP, CLM) have different inherent sensitivities to temperature and precipitation perturbations (Christensen and Lettenmaier 2007, Woodbury et al. 2012, Vano et al. 2012). Finally, different studies have used different future periods and different historical baseline periods, making precise comparison across studies difficult.

It is often assumed that precipitation and streamflow will become more variable from year to year under future anthropogenic climate change. Colorado's observed streamflows over the past century have shown a tendency towards increasing year-to-year variability, as measured by the coefficient of variation (CV; see Section 2-4), but it is not clear that this trend is anthropogenic in nature, nor that it should be expected to continue. Seager et al. (2012a) examined the output of 24 CMIP3 climate models; while the year-to-year variability of precipitation minus evapotranspiration (~runoff) is projected to increase over most of the globe in the 21st century, there is a projected decrease in variability for southwestern North America, including Colorado. Similar analyses of the CMIP5 climate and hydrology projections for Colorado have not yet been conducted.

Changes in runoff timing and seasonal streamflow

As noted in Section 2-4, for some water users, changes in runoff timing can be as important as changes in the amount of annual runoff. The hydrologic projections

FIGURE 5-15. Projected annual runoff for the Colorado River from 1980–2070 under RCP 4.5

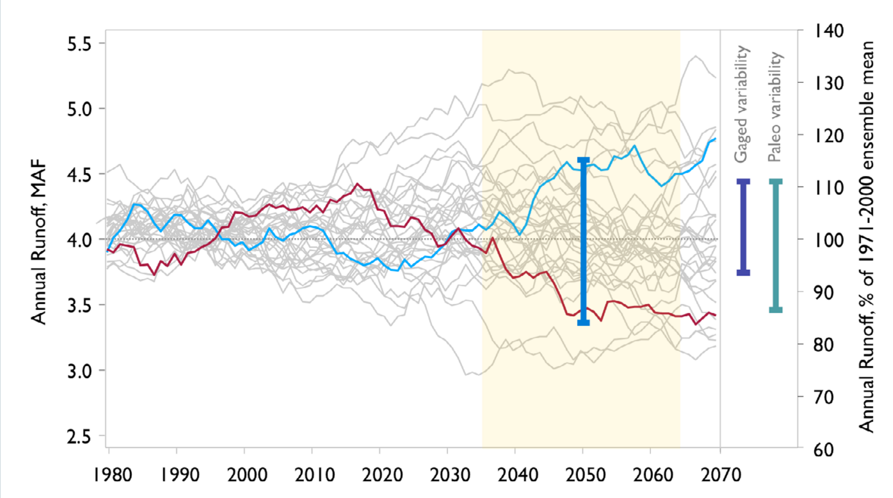


Fig. 5-15. Projected annual runoff from 1980 to 2070 for the Colorado River near Cameo, showing the 30-year averages for 31 projections under RCP 4.5, using BCSD-downscaled CMIP5 GCM output run through the VIC hydrologic model (BCSD5 hydrology). The gray traces show individual model projections, with the red and blue traces showing two selected projections that at 2050 are close to the 10th and 90th percentile changes, respectively, in runoff. The blue bar shows the actual 10th–90th percentile range of the projections. All of the projections show substantial multi-decadal natural variability. The increasing spread of projected future runoff changes over time reflects the uncertainties in the forced anthropogenic change on precipitation and temperature. By mid-century, that range of projected outcomes is broader than the past gaged variability (dark blue bar) or paleo variability (green bar) from tree-ring reconstructions. (Data source: Reclamation 2014; http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/)

have much greater agreement regarding future change in runoff timing and related changes in seasonal runoff than regarding change in annual runoff. Runoff timing is particularly sensitive to warming, and nearly all projections, even ones with increased precipitation, show the peak of runoff shifting earlier, with the extent of that shift ranging from 1–3 weeks by 2050. Figure 5-16 shows the projections of monthly runoff for the Colorado Headwaters basin for 2050 under RCP 4.5. Runoff increases in spring (March–May) in nearly all projections, while runoff decreases in summer and early fall (June–September) in nearly all projections, with the largest percentage decline in July. This overall seasonal pattern of change is also seen in the other basins in Colorado.

This shift in the seasonal timing of runoff, which was also seen in CMIP3-based hydrologic studies, would continue the recent observed trend towards earlier runoff described in Section 2-4. Some portion of the observed trend towards earlier runoff is due to the effect of dust-on-snow deposition—an effect that is not explicitly included in most of the projection-based studies. If dust-on-snow deposition in the future is similar to the high levels observed in Colorado since 2009, the shift towards earlier runoff will occur faster than indicated by the climate model output (Deems et al. 2013).

Upper Colorado River Basin and sub-basins

The Upper Colorado River Basin has been the subject of many previous climate change studies. Since the mid-1990s, these studies have consistently reported an average decrease in projected basin annual streamflow by the mid-21st century, as summarized in the 2008 Report. Those studies based on multiple climate model runs have also consistently found a broad range of projected outcomes, with some of the projected changes indicating future increases in flow (e.g., Christensen and Lettenmaier 2007).

Figure 5-17 shows the BCSD5 and BCSD3 (WWCRA) projected streamflow changes for the Colorado River near Cameo as shown in Figure 5-13, alongside the results from three other recent studies that used BCSD-downscaled CMIP3 (Reclamation 2012, Woodbury et al. 2012, CWCB 2012; see Sidebar 5-2). The BCSD5 hydrology projections, as noted earlier, depart from the previous studies by not showing a clear tendency towards decreasing annual streamflow. But

FIGURE 5-16. Projected change in monthly runoff for the Colorado River headwaters

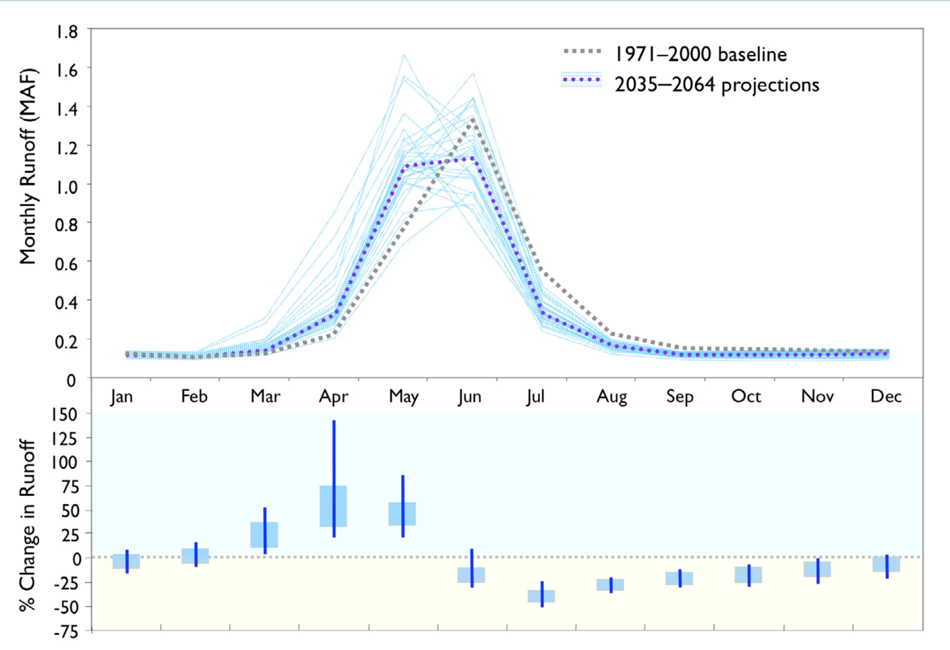


Fig. 5-16. Projected monthly runoff change for the Colorado River Headwaters for 2050 (2035-2064) under RCP 4.5, from the BCSD5 hydro dataset. The upper graph shows the projected average monthly flows for the 31 projections (light blue lines) and the ensemble median (dark blue dotted line) compared to the 1971-2000 baseline (gray dashed line). The lower graph shows the range of the monthly runoff changes from the ensemble, with the dark blue bars show the range from the 10th percentile to the 90th percentile and the light blue boxes show the interquartile range (the 25th to 75th percentile). As the hydrograph shifts earlier in the projections, March-May runoff increases while June tends to decreases, and July-September runoff sharply decreases in all projections. The other basins in Colorado show a very similar seasonal shift. (Data source: Reclamation 2014; http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/)

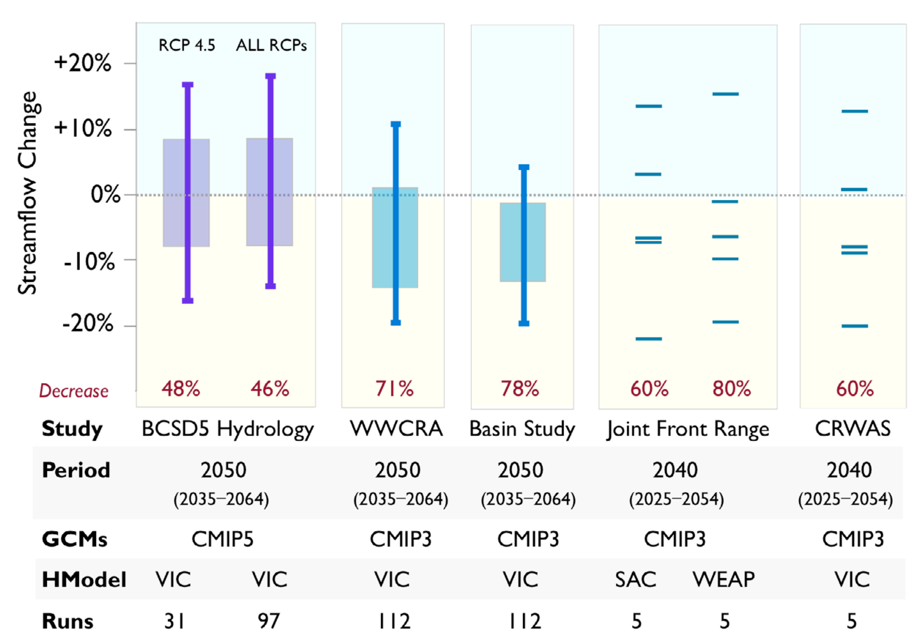
the vast majority of the BCSD5 projected changes are still within the overall envelope of the CMIP3-based projected changes, and still include the potential for large decreases in streamflow.

In both the CMIP3-based and CMIP5-based projections, there are consistent differences among the Upper Colorado sub-basins in their projected streamflow outcomes (Figure 5-13). The San Juan basin shows drier outcomes than the Gunnison or the Colorado Headwaters, which largely reflects the north-south gradient in projected precipitation for Colorado and the surrounding region.

The only recent study of future hydrology to explicitly include dust-on-snow impacts in the hydrologic modeling is Deems et al. (2013), which projected futures for the Upper Colorado River Basin under multiple climate change scenarios (from BCSD-downscaled CMIP3 projections) and dust-forcing scenarios, using the VIC hydrologic model. Both the moderate-dust and extreme-dust scenarios led to a 3% larger reduction in projected runoff at Lees Ferry by 2050 than the multi-model mean for the low-dust scenario. See Sidebar 2-3 for a description of dust-on-snow and its impacts.

Other recent climate change studies of the Upper Colorado River Basin used an approach different than those shown in Figure 5-17. Milly et al. (2005) examined the hydrologic output (i.e., runoff) directly from 12 CMIP3 GCMs. Their results showed drier runoff outcomes than the CMIP3 studies shown in Figure 5-17 in which downscaled GCM data was run through stand-alone hydrologic models. A more recent study using the hydrologic output directly from the CMIP5 GCMs likewise showed appreciably less future Upper Colorado River runoff than that projected by the BCSD5 hydrology (Seager et al. 2012b). The drier outlook seen in these two direct-from-GCM studies is likely due to the coarse representation in the GCMs of topographic effects on precipitation and hydrology in our region (see Section 3-1). Colorado's precipitation is more concentrated at the highest elevations, where evapotranspiration is lower and runoff efficiency is higher, than can be depicted in the raw GCM output. Downscaling and higher-resolution hydrologic

FIGURE 5-17. Projected changes in annual streamflow for the Colorado River for the mid-21st century from recent studies



Study	BCSD5 Hydrology		WWCRA	Basin Study	Joint Front Range		CRWAS
Period	2050 (2035–2064)		2050 (2035–2064)	2050 (2035–2064)	2040 (2025–2054)		2040 (2025–2054)
GCMs	CMIP5		CMIP3	CMIP3	CMIP3		CMIP3
HModel	VIC	VIC	VIC	VIC	SAC	WEAP	VIC
Runs	31	97	112	112	5	5	5

Fig. 5-17. Projected changes in Colorado River headwaters (Cameo gage) streamflow by the mid-21st century from five recent studies. The range of changes from the CMIP5-based projections (far left) are shifted wetter than the CMIP3 results which used similar methods. The boxplots follow the convention of previous figures. For the two studies with small ensembles of projections deliberately selected to span the range of the full ensemble, the individual projected changes are shown with horizontal bars. The values in red show the percentage of individual projections indicating a future decrease in flow. "HModel" identifies the hydrologic model used to simulate the streamflow changes, and "Runs" is the number of individual hydrologic projections. All of these studies used the BCSD method for downscaling the GCM output. (Data sources: BCSD5 Hydrology: Reclamation 2014; Colorado River Basin Study: Reclamation 2012; WWCRA: Reclamation 2011; Joint Front Range Study: Woodbury et al. 2012; CRWAS: CWCB 2012)

modeling are carried out in large part to compensate for these deficiencies in the GCMs.

South Platte River Basin

The projected changes in annual runoff for the South Platte River basin (at Sterling) for mid-century from the CMIP5-based BCSD5 dataset shown in Figure 5-13, with a range of -15% to +29%, are clearly shifted towards wetter outcomes compared to the CMIP3-based projections, reflecting that the CMIP5 climate projections call for more precipitation for northeastern Colorado than the CMIP3 projections. We need to repeat a caution offered earlier that the results for the given gage (Sterling) may not be representative of all gages in the basin. In fact, examination of sub-basin results shows that the northern tributaries of the South Platte (north of Clear Creek) have ranges of outcomes similar to the Sterling gage, while the outcomes for the southern part of the basin are shifted drier than for the Sterling gage. This north-south difference was also seen in previous hydrology projections. The CMIP3-based Joint Front Range study (Woodbury et al. 2012) projected streamflows for eight gages within the South Platte Basin: four on the mainstem between Fairplay and Henderson, and four on northern Front Range headwaters tributaries. The projected changes in annual runoff for 2040 for the northern Front Range tributaries ranged from -20% to +20% (five projections using each of two hydrologic models), with a slight majority of projections showing decreasing flows. The mainstem gages showed more sensitivity to changes in both temperature and precipitation in the separate sensitivity analysis, and so the range of projected changes for 2040 was much larger for those gages (-40% to +30%) than for the northern tributaries, and with more projections showing decreases in flow. These results for the mainstem gages are consistent with the projections for the South Platte at Sterling from the BCSD3 WWCRA results shown in Figure 5-13.

FIGURE 5-18. Projected change in April 1 snow-water equivalent (SWE) for Colorado river basins under RCP 4.5 for 2035–2064

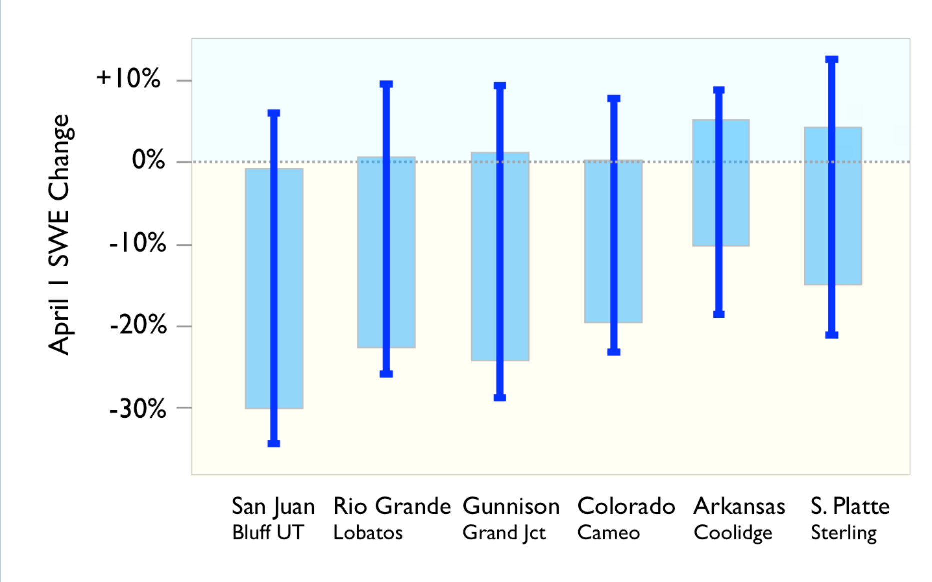


Fig. 5-18. Projected area-averaged change in April 1 snow water-equivalent (SWE) for major river basins in Colorado for 2050 (2035–2064) compared to a 1971–2000 baseline under RCP 4.5, from the BCSD5 hydrology dataset (BCSD-downscaled CMIP5 GCM output run through the VIC hydrologic model). The basins are listed in the same order as in Figure 5-13. The dark blue bars show the range from the 10th percentile to the 90th percentile of the individual model projections (n=31), while the light blue boxes show the interquartile range (the 25th to 75th percentile). By mid-century, about 75% of the projections call for decreased April 1 SWE, with basins in southwestern Colorado tending towards larger decreases. The projected SWE changes under RCP 8.5 are very similar to those under RCP 4.5 for all basins. (Source: Reclamation 2014; http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/)

As in the Colorado River basin, the projected changes in monthly runoff for the South Platte basin across all studies show a strong tendency towards earlier spring peak flows and reduced summer flows.

Arkansas River Basin

The BCSD5 projected changes in annual runoff for the Arkansas River basin for mid-century shown in Figure 5-13, with a range of -10% to +19%, are shifted wetter than previous results based on CMIP3, though not as much as in the South Platte. The Joint Front Range study (Woodbury et al. 2012) projected streamflows for the Arkansas River at Salida gage; the projected changes in annual runoff for 2040 ranged from -15% to +16% with the Sacramento model and consistently lower with the WEAP model (-23% to +16%). This illustrates the degree to which the results can vary solely due to the choice of hydrologic model. Both ranges are comparable to the BCSD3 WWCRA results for the Arkansas at Coolidge, KS, shown in Figure 5-13.

Rio Grande Basin

The BCSD5 projected changes in annual runoff for the Rio Grande basin for mid-century shown in Figure 5-13, with a range of -28% to +11%, are shifted slightly wetter than previous results based on CMIP3 but still show a strong tendency towards future flow declines. In both the CMIP5-based and CMIP3-based projections, the Rio Grande has the driest range of streamflow outcomes of all of Colorado's major river basins. The Upper Rio Grande Impact Assessment (Reclamation 2013), using the same BCSD3 hydrology runs used in WWCRA, reported the projected annual streamflows for the combined four Rio Grande "index" gages within Colorado (Rio Grande near Del Norte, Conejos River near Mogote, Los Pinos River near Ortiz, San Antonio River at Ortiz). The reported ensemble-average change is -20% by 2050, the same as the ensemble-average change reported for the Rio Grande at Lobatos in WWCRA (Figure 5-13).

Snowpack

The BCSD5 hydrology model output (Reclamation 2014) described above also includes snow-water equivalent (SWE). The projected changes in April 1 SWE by 2050 for selected major basins in Colorado are shown in Figure 5-18, with the basins listed in the same order as in Figure 5-13. As with runoff, the individual model projections span a broad range that includes both future increases and decreases in all basins. However, for all basins, decreases in April 1 SWE are seen in most of the projections, and the projected decreases in SWE are more prevalent and larger than projected decreases in annual streamflow.

These initial snowpack results using CMIP5 climate projections are very similar to the findings of previous studies based on CMIP3 climate projections, in showing a strong future tendency towards declining April 1 SWE across all major river basins in Colorado, with generally larger declines in the far western and southern basins (Christensen and Lettenmeier 2007, Battaglin et al. 2011, Reclamation 2011).

This strong tendency towards decreased April 1 SWE reflects multiple effects of the projected warming: the shift towards earlier snowmelt in the spring, the shift towards precipitation falling as rain instead of snow in the fall and spring, and greater sublimation from the snowpack throughout the season. These warming-related effects are modulated by elevation, with SWE at higher elevations seeing less overall impact from warming than lower elevations. The projections of February 1 SWE and March 1 SWE also tends towards decreases in all basins, but not as strongly as for April 1 SWE. May 1 and June 1 SWE, however, show sharp declines in nearly all projections for all basins, reflecting a broad shift towards earlier snowmelt.

An independent study projected future snowpack changes (Pierce and Cayan 2013) using the VIC hydrologic model and projections from 13 CMIP5 climate models that were downscaled using the BCCA (Bias-Corrected Constructed Analog; Hidalgo et al. 2008) method. The study examined changes for seven regions across the western US, including the "Colorado Rockies," which includes all mountain headwaters within Colorado and small portions of far southern Wyoming and eastern Utah. The reported multi-model average change in April 1 SWE for 2050 for the Colorado Rockies (-6%) is consistent with the results shown in Figure 5-18.

An important message to be taken from these snowpack projections is that in the future, springtime SWE may be a less useful predictor of April–July streamflow and annual streamflow than it is today. Regardless of the future change in precipitation, the projected warming means that less of the annual precipitation in the high country would fall as snow, and that more of the snowpack would melt and run off prior to April 1 or other benchmark dates, than in the recent past.

SIDEBAR 5-2. Recent planning-oriented studies of future hydrology for Colorado

Three recent studies of future hydrology for Colorado have produced important and consistent results, and also signaled a shift in the ownership of the research process: in all three studies, water management agencies helped design and/or conduct the analyses. Also, the three studies used as their core climate input the same dataset of downscaled GCM projections.

Those downscaled CMIP3 projections were developed by researchers from Reclamation, Lawrence Livermore National Laboratory (LLNL), and Santa Clara University to produce climate projections for the western US and beyond at a spatial resolution fine enough to drive distributed hydrology models such as the VIC (Variable Infiltration Capacity) model (Maurer et al. 2007). In 2009, a total of 112 climate projections from the CMIP3 dataset (see Section 3-2) from 1950–2099 were bias-corrected ("BC") and then spatially disaggregated ("SD") using the BCSD approach (Wood et al. 2004; see Section 3-5). The 112 BCSD3 projections included a roughly equal number of projections using the B1 (low), A1B (medium) and A2 (high) emissions scenarios (Figure 5-19).

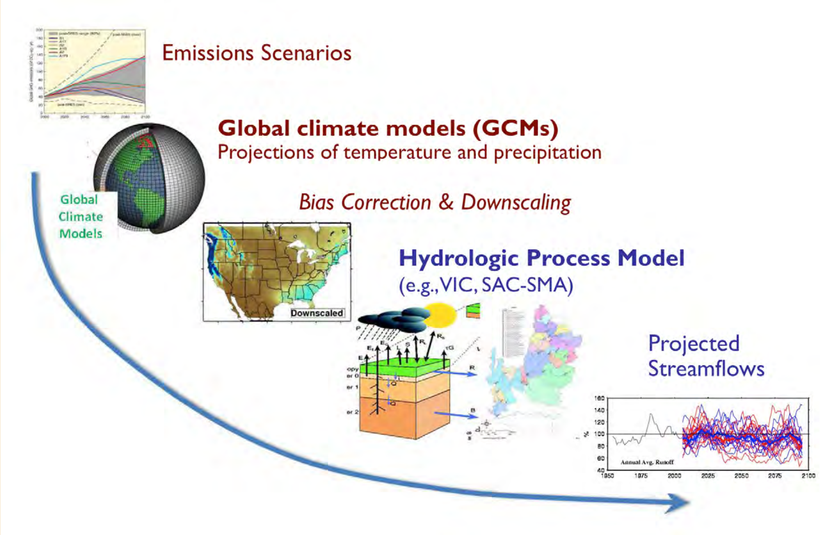


Figure 5-19. Schematic showing the flow of data and processing steps to generate projected streamflows for the three recent studies of future hydrology described in Sidebar 5-2. Emissions scenarios drive the GCMs, whose output is then bias-corrected and spatially downscaled and run through hydrologic process models, to generate the projected streamflows. (Source: Adapted from the Colorado River Basin Water Supply and Demand Study, Reclamation 2012)

The first of the three studies to be initiated, the Joint Front Range Climate Change Vulnerability Study (Woodbury et al. 2012), was carried out by a consortium of eight Front Range water providers, along with Riverside Technology, Inc. (Fort Collins), the Colorado Water Conservation Board, and the National Center for Atmospheric Research (NCAR), with additional guidance from WWA researchers and funding from the Water Research Foundation. That team selected 5 of the 112 BCSD projections to broadly capture the range of projected future temperature and precipitation. The team then used the changes in temperature and precipitation from those five climate projections to drive two hydrologic models—the National Weather Service's Sacramento Soil Moisture Accounting (SAC-SMA) model, and the WEAP (Water Evaluation And Planning system) model—and simulate streamflows for future time periods centered on 2040 and 2070. These future streamflows were generated for 18 gages in the South Platte, Arkansas, and Colorado River basins which represent the collective water supply for those eight water providers.

The second study, the Colorado River Water Availability Study (CRWAS) Phase 1, was carried out for the Colorado Water Conservation Board (CWCB 2012). In CRWAS, the same selection procedure was used to select 5 of the 112 BCSD projections for future time periods (2040 and 2070). The changes in temperature and precipitation in those projections were used to drive the VIC (Variable Infiltration Capacity) hydrology model, for 43 gages across the Colorado River basin within Colorado.

These first two studies used a delta or "period-change" approach (see Section 3-5) in simulating future hydrology. First, the changes in monthly temperature and precipitation were calculated between a historical baseline period (1950–1999) and the future period. Then those monthly changes were used to perturb the daily weather that occurred during the historical period, and that perturbed daily weather was used to simulate the daily hydrology for the future period. This approach blends the projected trends in climate with the variability of the 20th century. The CRWAS analyses also incorporated sequences of wet and dry years derived from tree-ring paleohydrology for the Colorado River (see Section 2-7), effectively expanding the range of variability in the future hydrology scenarios.

The third study, or actually a pair of nested efforts, used a different approach in which both the modeled climate changes and modeled variability from the BSCD3 projections were used to drive the VIC hydrology model. The Bureau of Reclamation, in 2011, carried out the BCSD3 hydrology projections for their West-Wide Climate Risk Assessment (WWCRA), which covered eight major river basins in the western US, including the Colorado River Basin. Then those projections were used, with a secondary bias correction, in the Colorado River Basin Water Supply and Demand Study (aka the "Basin Study"; Reclamation 2012) conducted by Reclamation with the seven Basin states. With more computer resources, Reclamation ran the VIC hydrology model with all 112 BCSD climate projections.

Considering the differences in the overall approaches, number of GCM runs, and hydrologic models used, the results of the three studies for the Upper Colorado River Basin were very consistent (see Figure 5-17). They all showed ensemble-average declines in streamflow of 3–10% for the mid-century periods compared to late-20th century observed flows, with the majority of individual runs showing declines in streamflow. In the CRWAS and the Basin Study, the modeled future hydrology was then run through system models (StateMod and CRSS, respectively) to assess the range of specific system outcomes under the future hydrology, and these results were incorporated into the final reports.

In 2013, the Reclamation-LLNL consortium developed a new set of downscaled climate model projections (BCSD5) based on CMIP5 (see Section 5-2), and in 2014 they developed corresponding BCSD5 hydrologic projections, allowing for comparison with the recent CMIP3-based studies, as shown in Figures 5-13 and 5-17. CWCB is currently conducting Phase II of CRWAS, using a period-change approach with the BCSD5 projections, similar to the approach used for Phase I.

5-4. Projections of climate extremes

As with observations of climate extremes, the projections of climate extremes need to be separated into categories, since the consensus of the models regarding the projected direction and amount of change differs according to the type of extreme.

Heat waves

With the substantial projected increase in average annual and seasonal temperatures worldwide, large increases in the 21st century in the frequency and duration of heat waves are likewise projected over most land areas across the globe (IPCC 2013). Projections of a summer Heat Wave Index similar to that shown in Figure 2-12 indicate a five-fold to ten-fold increase in heat waves by mid-century for the southwest U.S., including Colorado, based on CMIP3 projections (Gershunov et al. 2013). For Colorado, new analyses performed for this report using CMIP5 output indicate that very hottest daily maximum temperatures in summer (i.e., the hottest July day each year) will increase even more than the average summer temperatures.

Cold waves

As the overall winter climate is projected to warm, winter cold waves are expected to continue to decrease in frequency over the southwestern US, though some future cold waves may be as severe as historical cold waves (Kodra et al. 2011, Gershunov et al. 2013).

Frost-free season

With the substantial projected warming, the frost-free season across Colorado is also projected to lengthen (Walsh et al. 2014). A 4°F rise in average annual temperature by mid-century, which is consistent with the middle of the RCP 4.5 projections and towards the low end of the RCP 8.5 projections, would lead to an increase in the frost-free season length of 20–40 days. Higher elevations in Colorado, where more days in the year currently see freezing temperatures, would see the largest increases in the length of the frost-free season, with the smallest increases on the eastern Plains (Mearns et al. 2009). A longer frost-free season and growing season would not necessarily benefit agriculture, depending on the degree of future warming and associated increase in water loss from soils and crops. Likewise, any increases in forest productivity from a longer growing season could be offset by drying, leading to an earlier and longer fire season and more intense fires (see below).

Heavy precipitation

A global analysis of extreme daily precipitation (the 1-in-20-year event) using the CMIP5 projections under RCP 4.5 found that most regions globally were projected to have increases in the magnitude of the 1-in-20-year events by mid-century (~2055). In the several gridboxes that cover Colorado, the multi-model average projected increase in the size of these extreme daily precipitation events was 5–10%, similar to global average increase of 8.5% (Kharin et al 2013).

Different atmospheric processes generate warm-season convective events (i.e. thunderstorms) and winter storm events, and that future anthropogenic impacts on the respective processes may also differ. Two recent studies examined warm-season convective events for Colorado using downscaled output from CMIP3-generation climate models, run through a weather forecast model with high enough resolution to represent convective processes. While physical principles suggest thunderstorms could be more intense in a warmer climate because warmer air can potentially hold more moisture, and thus energy, and transport it into the storms (Trenberth 1999), neither study found a clear projected trend in the frequency or intensity of these warm-season convective heavy precipitation events for Colorado (Alexander et al. 2013, Mahoney et al. 2013).

Using a similar methodology, Mahoney et al. (2012) projected that the occurrence of small surface hail over high elevations of the Colorado Front Range and surrounding region in a mid-century (2041–2070) time period would dramatically decrease from historical conditions, due to a higher melting level caused by warming. In mountain regions where the heaviest summer precipitation currently tends to fall as hail, the risk of flash flooding may increase if hail falls instead as rain, which would facilitate faster runoff.

A study of future heavy winter precipitation events for the western U.S., using downscaled CMIP3 output, did find that extreme winter precipitation increased across the future climate projections, even in those runs in which the trend was for drier winter conditions, reflecting that individual mid-latitude winter storms are projected to become wetter (Dominguez at al. 2012). To summarize, it appears that winter heavy precipitation events for Colorado may follow a global tendency towards increases, but not necessarily summer heavy precipitation events.

Drought

Due to the effects of the projected warming, drought can be expected to generally become more frequent and intense compared to current conditions (Gershunov et al. 2013). A sufficiently large future increase in precipitation could counteract the effect of warming on many measures of drought; such an increase in precipitation is seen in some of the projections for Colorado. Examination of the projections of future streamflow for Colorado indicate that for those projections in which average streamflow declines (see Section 5-3), droughts as defined as sequences of consecutive below-average streamflow years also become more frequent, more intense, and longer-lasting, resulting in water deficits not experienced during the period of the observed record. Measures of agricultural drought such as soil moisture and Palmer Drought Severity Index (PDSI) are also expected to generally intensify due to warming (Gershunov et al. 2013). PDSI is more sensitive to temperature than other drought indices and may overestimate the impact of future warming on soil moisture and agriculture (Walsh et al. 2014).

Wildfire and other forest disturbances

Wildfire occurrence and the total area burned per year are projected to increase substantially into the 21st century in the Rocky Mountain West and Colorado as the climate warms (Liu et al. 2010, Moritz et al. 2012, Pechony and Shindell 2010, Spracklen et al. 2009, Yue et al. 2013). These studies' results vary due to different climate model inputs and different assumptions linking climate variables with wildfire occurrence. For the mid-21st century (~2050) compared to the late 20th century under a warming consistent with that described in Section 5-1 (2.5°F to 5°F), a 50–200% increase in annual area burned in Colorado is projected (Spracklen et al. 2009, Yue et al. 2013). The length of the fire season in Colorado is also projected to increase, by several weeks (Yue et al. 2013).

5-5. Projections of other aspects of water resources

Other aspects of water resources may see future conditions that are shifted outside of the envelope of historical experience, or at least tend towards one side of that envelope. While it is beyond the scope of this report to treat these potential impacts in detail, we summarize several of the areas of concern below. For groundwater and water quality, there may not be a sufficient scientific basis at present to support state-level assessment of climate change impacts.

Water demand

Future climate-induced changes in water demand may be as or more important than changes to water supply in determining impacts on the overall water balance of a basin. The projected warming would tend to increase the consumption of water by plants, whether crops, urban landscaping, or native vegetation. Decreased precipitation during the growing season, as is projected by a majority of the models (Figure 5-5), would exacerbate this increased water use. The Crop Irrigation Requirement (CIR) is a measure of the difference between the growing season precipitation in a given location and the calculated water use of the crop. The Colorado River Water Availability Study (CWCB 2012), found that the average annual CIR across western Colorado for the current mix and acreage of crop types was projected to increase by 7–25% by a 2040-centered period (2025–2054), based on the same five CMIP3 projections used for the streamflow projections shown in Figure 5-17. By a 2070-centered period, the CIR was projected to increase by 18–37%. The projected increase in CIR was mainly due to the projected warming, which both lengthened the growing season for perennial crops and increased crop water use for all crops. Reduced summer precipitation in many projections was also a factor.

Since the magnitude of projected future warming for a given climate forcing is very similar in the CMIP5 projections compared to CMIP3, and summer precipitation in CMIP5 also shows a tendency towards future decreases, we would expect similar projected increases in crop water use given the CMIP5 climate projections. Likewise, we would expect urban outdoor water use to increase appreciably under most CMIP5 projections, consistent with sensitivity analyses by Denver Water (see Sidebar 6-1) and others. Since the projected increases in water demand are strongly driven by increasing temperatures, there is high confidence that they will occur.

Groundwater

While surface water accounts for the large majority of the water used in Colorado, groundwater resources are the primary component of the water supply in certain portions of the state, including far eastern Colorado above the High Plains Aquifer, the San Luis Valley, the Platte River Valley, and parts of Douglas County (Georgakakos et al. 2014). For some of these groundwater resources, depletions exceed the natural recharge of the aquifer, as indicated by declining well levels over time. It is also clear from past experience in Colorado that droughts can lead to sharp declines in well levels, by increasing the pumping of groundwater for irrigation and/or reducing recharge.

The potential responses of groundwater flow and storage to projected climate change, however, are not well understood. Only recently have groundwater models included detailed representations of groundwater recharge and interactions with surface-water and land-surface processes, and there have been relatively few projections of groundwater responses to climate change for the U.S., let alone Colorado, compared to projections of surface water hydrology (Georgakakos et al. 2014). Since groundwater recharge in semi-arid regions is usually driven by precipitation, we might expect that the future trend in recharge would reflect the (uncertain) future trend in precipitation. But given that groundwater depletions exceed recharge in many basins, the most likely impact to groundwater supply from climate change will come from increased irrigation demands driven by warming (Taylor et al. 2012).

Water quality

Climate change poses multiple potential impacts to water quality, depending on how it manifests in a given basin. The most likely suite of impacts would result from the warmer water temperatures that would closely track the projected atmospheric and land-surface warming. Warmer surface waters lead to higher levels of organic matter and thus increased disinfection byproducts that are costly to remove to meet water quality standards (Vogel et al. 2012). Warming of lakes and reservoirs also reduces seasonal mixing of the water layers, potentially decreasing dissolved oxygen and leading to excess concentrations of nitrogen and phosphorous (Georgakakos et al. 2014).

If there is a decreasing trend in streamflows due to climate change (Section 5-3), concentrations of contaminants and sediment will tend to increase as streamflow volumes decrease. Climate-driven changes in watershed disturbances can also impact water quality. Wildfire, whose occurrence is projected to increase under climate change, can lead to increases in erosion and sedimentation rates in basins experiencing high-severity burns, and excess stream nitrates and turbidity (Rhoades et al. 2011).

Climate impacts on nonconsumptive uses

Climate change may also affect nonconsumptive uses of water in Colorado. A likely earlier shift in the timing of peak runoff, and lower summer streamflows, would negatively impact water-based recreation activities such as rafting and fishing. A future declining trend in annual streamflows could exacerbate the effects of timing changes on recreation use (Klein et al. 2011, Reclamation 2012).

Aquatic species and habitats may be negatively impacted by future climate change. Changes to earlier runoff timing, and lower streamflow levels, may hamper the reproduction and survival of native threatened and endangered fish species, reduce the effectiveness of fish passages at dams and diversions, and facilitate the spread of non-native species (Rieman and Isaak 2010, Klein et al. 2011). Some of these impacts have already been observed in the past few decades, and have been attributed to low flows and/or rising stream temperatures. Future changes to hydrology or water quality large enough to impact endangered species would raise the possibility of legal restrictions on water uses in the basins where those species have critical habitat.

5-6. Summary of the implications of climate projections for water and water-related resources

The global climate models consistently project a further temperature increase for Colorado by the mid-21st century. The amount of projected warming varies among the model projections depending on the trajectory of greenhouse gases and other anthropogenic forcings (RCPs), and also on each model's representation of key climate processes. The model runs under RCP 4.5 and RCP 8.5 project that by the mid-21st century, average annual and monthly temperatures in Colorado will be largely beyond the envelope of historical temperatures. Future change in average annual precipitation for Colorado is more uncertain than the change in temperature; the models do not agree regarding the direction of change.

The uncertainty in the direction of precipitation change, and to a lesser extent the uncertainty in the magnitude of warming, leads to widely diverging outcomes when the ensemble of projected climate changes is run through hydrologic models. The range of streamflow projections for the mid-21st century encompasses both potential future increases and decreases in all Colorado basins; overall, however, more of the individual projections are on the decreasing side. Water-related outcomes driven largely by temperature are more certain regarding their future direction, such as a shift to earlier snowmelt and earlier peak runoff, and increasing water use by crops and other vegetation.

Table 5-3 summarizes potential water-related impacts from climate change in different areas and sectors, and also lists selected recent studies that have assessed the corresponding vulnerabilities for portions or all of Colorado. Many of these impacts have been experienced in the past primarily during drought years; in a warmer future climate, they would tend to occur more often, even in average precipitation years. It is also important to note that many of these changes are cross-cutting and may exacerbate each other. For example, future increases in insect infestations and wildfire would tend to reduce stream shading in riparian areas, further increasing stream temperatures.

TABLE 5-3. Summary of projected changes and potential impacts to water resources for Colorado

Element	Projected changes and potential impacts	Studies that have assessed this vulnerability for Colorado
Overall surface water supply	Most projections of future hydrology for Colorado's river basins show decreasing annual runoff and less overall water supply, but some projections show increasing runoff. Warming temperatures could continue the recent trend towards earlier peak runoff and lower late-summer flows.	CWCB (2012); Reclamation (2012); Woodbury et al. (2012)
Water infrastructure operations	Changes in the snowpack and in streamflow timing could affect reservoir operations, including flood control and storage. Changes in the timing and magnitude of runoff could affect the functioning of diversion, storage, and conveyance structures.	CWCB (2012); Reclamation (2012)
Crop water demand, outdoor urban watering	Warming temperatures could increase the loss of water from plants and soil, lengthen growing seasons, and increase overall water demand.	CWCB (2012); Reclamation (2012)
Legal water systems	Earlier and/or lower runoff could complicate the administration of water rights and interstate water compacts, and could affect which rights holders receive water.	CWCB (2012)
Water quality	Warmer water temperatures could cause many indicators of water quality to decline. Lower streamflows could lead to increasing concentrations of pollutants.	EPA (2013)
Groundwater resources	Groundwater usage for agriculture could increase with warmer temperatures. Changes in precipitation could affect groundwater recharge rates.	
Energy demand and operating costs	Warmer temperatures could place higher demands on hydropower facilities for peaking power in summer. Warmer lake and stream temperatures, and earlier runoff, could affect water use for cooling power plants and in other industries.	Macknick et al. (2012)
Forest disturbances in headwaters regions	Warmer temperatures could increase the frequency and severity of wildfire, and make trees more vulnerable to insect infestation. Both have implications for water quality and watershed health.	
Riparian habitats and fisheries	Warmer stream temperatures could have direct and indirect effects on aquatic ecosystems, including the spread of non-native species and diseases to higher elevations. Changes in streamflow timing could also affect riparian ecosystems.	Rieman and Isaak (2010)
Water- and snow-based recreation	Earlier streamflow timing could affect rafting and fishing. Changes in reservoir storage could affect recreation on-site and downstream. Declining snowpacks could impact winter mountain recreation and tourism.	Reclamation (2012); Battaglin et al. (2011); Lazar and Williams (2008)

Table 5-3. Potential water-related impacts from climate change in different areas and sectors. The right-hand column lists recent studies that have qualitatively or quantitatively assessed the corresponding vulnerabilities for some or all of Colorado.

6

Incorporating Climate Change Information into Vulnerability Assessment and Planning

Key points

- Colorado water entities have been at the forefront of incorporating climate change into long-term planning, and their experience can inform future efforts by others.
- Observed records of climate and hydrology are still fundamental to assessing future climate risk, but should be supplemented with information from climate model projections and paleoclimate records.
- Planning approaches that explore multiple futures, rather than assuming a single future trajectory, are more compatible with climate projections and may improve preparedness for a changing future climate.
- The uncertainty in projections of precipitation and streamflow for Colorado should not be construed as a "no change" scenario, but rather as a broadening of the range of possible futures, some of which would present serious challenges to the state's water systems.

Great Sand Dunes National Park and the Sangre de Cristo Mountains. Photo: Wikimedia Commons, http://nl.wikipedia.org/wiki/Great_Sand_Dunes_National_Park_and_Preserve#mediaviewer/Bestand:Great_Sand_Dunes_NP_1.JPG.

Colorado's water managers and water users have over a century of experience adapting to the state's large seasonal, interannual, and decadal variability in climate and hydrology. A complex system of water storage and conveyance infrastructure has worked in tandem with institutional arrangements to store water, distribute supplies, buffer droughts, and allocate shortages when necessary.

Traditional water planning methods are based on the assumption that future climate and hydrology will have characteristics (average and variability) similar to the climate and hydrology previously observed. Paleoclimate studies, however, show there is a broader range of natural variability than was experienced in the past century (Section 2-7). Climate model projections indicate that the future may see systematic shifts in hydrologic conditions (Section 5-3). By the mid-21st century, climate change may push aspects of both water supply and water use outside of the bounds of past variability and experience.

While the traditional methods will remain useful, especially for short-term planning, many water management entities have recognized the need to look beyond the observed record. The State of Colorado, federal agencies, and local water entities have already begun to incorporate climate change into vulnerability assessment and integrated resource planning, laying the groundwork for adaptation to the future conditions. The Boulder Climate Change Study (Smith et al. 2009), the Joint Front Range Climate Change Vulnerability Study (Woodbury et al. 2012), the Colorado River Water Availability Study (CWCB 2012), and the Colorado River Basin Water Supply and Demand Study (Reclamation 2012) have quantified specific climate change impacts on water resources in Colorado, such as shortages in water deliveries.

Colorado has recently experienced "unprecedented" events that illustrate that the observed record does not fully encompass potential climate risk. The 2002 drought caused the record-lowest water-year runoff in many basins. The Front Range floods in September 2013 saw record rainfall and peak flood discharge in many locations. While these events have not been attributed to anthropogenic climate change, they are indicative of the societal challenges posed by hydrologic conditions outside the bounds of previous experience.

The uncertainty in the projections of future climate and hydrology calls for additional approaches to using hydroclimate information in planning. Section 6-1 lays out a framework for thinking about climate vulnerability and risk, the types of information needed to assess vulnerability, and the uncertainties in that information. Section 6-2 introduces approaches to using climate change information to assess future vulnerabilities and in develop integrated resource plans. Section 6-3 provides final thoughts on moving forward given the uncertainties about future climate change.

We should note that while the focus of this section is on water resources management, the main conceptual elements and methods described here are applicable to other areas of resource management and planning, including public land management, wildlife and fisheries management, urban planning, and natural hazards mitigation. Much of the key work in climate vulnerability, planning, and adaptation has occurred in these other fields.

6-1. Thinking about climate vulnerability and information uncertainty

While *vulnerability* has many definitions, here we use climate vulnerability to mean the propensity of a system to experience undesirable outcomes from a climate hazard, such as drought. Climate vulnerability is a function of the sensitivity of the system to that hazard and the adaptive capacity of the system to buffer the hazard. For example, most surface-based water-supply systems are vulnerable to drought, but the degree of vulnerability to the same drought event will vary among systems depending on the seniority of water rights, reservoir storage, ability to reduce non-essential demand, and other factors which either modify sensitivity or provide adaptive capacity. *Risk* refers to the probability or likelihood that a specific system impact will occur over a specified period of time (e.g. one year), given the expected climate and the characteristics of that system. It is closely related to vulnerability, but also takes into account the frequency and severity of the climate hazard (IPCC 2007).

Over the past century, as noted in Section 2-1, the climate vulnerability for water resources in Colorado has been driven by exposure to natural climate variability on monthly, annual, and decadal time scales. The greatest vulnerabilities for water systems tend to be found at the tail ends of the distributions of hydroclimatic variables, most often at dry extremes such as the severe drought conditions in 2002, but also at wet extremes such as the unusual rainfall and severe flooding on the Front Range in September 2013.

The projections of future climate of Colorado indicate that climate vulnerabilities and risks for water resources are likely to change, and potentially increase in many cases. Natural climate variability and its associated vulnerabilities and risks will remain important in the future. We can think of the projected future anthropogenic changes, such as a trend in annual precipitation, as being superimposed on ongoing natural variability. (Anthropogenic climate change may also alter the modes and characteristics of natural variability, though such changes are not consistently seen in the projections.)

So the climate we actually experience in the future, and our vulnerability to that climate, will reflect a combination of natural climate variability and anthropogenic climate change. Considering future climate in this way encourages the use of multiple sources of climate information to inform vulnerability assessment and planning (Table 6-1). Observed records of climate and hydrology are still critical to understanding future vulnerability and risk. Combining those records with climate model projections and

TABLE 6-1. Sources of climate information for vulnerability assessment and planning

	Paleoclimate records (Section 2-7)	Observed Records (Section 2)	Climate model projections (Sections 3 & 5)
Key information regarding climate vulnerability	Natural hydroclimate variability and extreme events at annual to century time scales	Natural hydroclimate variability and extreme events at daily to multi-decadal timescales	Future anthropogenic change in key hydroclimate variables
Time span of information	400–2,000 years ago up to present	30–120 years ago up to present	25–85 years ahead from present
Benefits	Shows broader range of natural variability than seen in the observed records (e.g., severe droughts); places observed variability in longer context; provides many sequences of wet/dry years	Provides baseline information about climate risk; relates the other sources of information to our experience of system impacts; readily available, trusted, and well-vetted	Best source of information about future anthropogenic climate changes
Limitations	Uncertainty in the proxy information; limited to annual resolution; not available for all basins and locations in Colorado	Does not capture the full range of natural variability; does not indicate future anthropogenic change; likely to underestimate future stress on systems	Large uncertainties in future changes, requiring consideration of multiple projections; complex datasets that are more difficult to obtain, analyze and interpret
Principal uses in vulnerability assessment and long-term planning	Augment the range of natural variability from observed records and/or climate models; derive additional sequences of wet/dry years	Provide a baseline of natural variability to perturb with future changes from climate models; calibrate the system responses	Extract projected future changes to perturb observed or paleo variability; examine projected variability for changes in extremes

Table 6-1. Sources of climate information for vulnerability assessment and planning and their key characteristics.

paleoclimate records creates a broader range of future climate scenarios and associated stresses that are still physically plausible. These climate scenarios can then be used to more specifically assess vulnerabilities, using methods discussed in the next section.

It is important to recognize that while these three information types can superficially appear to be comparable—all may be presented in the same unit, e.g., acre-feet—they have very different levels of uncertainty, especially the climate model projections. Observed records of climate and hydrology are not perfect representations of the "true" historical hydroclimate, though they're generally very close. Uncertainty in observed records comes first from measurement error and other influences on measurement described in Section 2-2. If the climate data are spatially interpolated, the accuracy of the interpolation becomes an additional source of uncertainty. In the case of naturalized streamflow records, the historical records or estimates of diversions and depletions used to adjust the gaged flows may be incomplete or in error.

Paleoclimate records are like observed records in that they are attempts to capture that true historical hydroclimate. Because the history sampled by paleoclimate records is much longer than for observed records, they tend to record a wider range of variability, and more occurrences of a given type of rare event. But since paleoclimate records are based on indirect proxy measurements, they have much larger uncertainties than observed records. The uncertainty can be partly quantified by examining the fit between a paleoclimate proxy and the target observed record during their period of overlap, but this does not capture other uncertainties related to choices made in modeling the relationship between the two.

For both observed climate records and paleoclimate records, there are well-established methods to generate probabilistic statements of risk that quantify the likelihood of a specified event or system outcome in the past. If one were to assume that these historic risks will not change in the future, then these same likelihoods could be used to describe future occurrences. While this assumption may still be useful for short-term planning, long-term planning (~25-year horizon and longer) under a changing climate can benefit from additional information.

We turn, then, to climate projections to provide further guidance about potential future conditions. We look especially for systematic changes that might bring us into conditions unrepresented by the other two types of records. But looking forward into the future, of course, comes with much larger uncertainties than looking back. The wide range of potential future conditions shown in an ensemble of climate projections (Section 5-1) reflects the interaction of multiple uncertainties, detailed in Sidebar 3-1. When subsequent impacts modeling is performed using the climate projections, such as hydrologic modeling to project future streamflows, additional uncertainties related to those modeling assumptions become incorporated into the results (Section 5-3).

The range of projected changes for a given hydroclimate variable (e.g., Figure 5-13) is most appropriately used as general guide to expected tendencies, not as a probability distribution that provides precise quantification of future risk. The latter would require that the individual model projections are equally likely to occur, which we don't know to be true. But neither can we clearly identify which of the projections might be more likely, which would allow us to weight the projections (see Section 3-4). The ensemble of model projections is like a roomful of individual experts who are generally knowledgeable but whose perspectives and predictions differ, and we don't know which ones to trust more than the others. So it is safest to consider the range of guidance, and whether it lies mainly to one side of the spectrum or the other. We also need to keep in mind that the range of model projections may not capture all of the uncertainty in future climate; outcomes outside of the range of the projections are also possible.

Past efforts to apply climate model projections in water resources planning have often caused frustration because of a mismatch between the inherent qualities of the information and the desired quantitative use. Some experienced practitioners have concluded that the uncertainties in climate projections are too large for the information to be directly applied in water resources planning (e.g., Stakhiv 2011). But we believe much frustration can be avoided if projections are approached with a fundamentally different mindset than other types of climate and hydrology information. Projections are best used to facilitate exploration of physically plausible climate futures and their associated vulnerabilities and risk. In the next section we describe some ways to conduct that exploration.

6-2. Approaches to vulnerability assessment and planning

In a recent white paper for the Water Utility Climate Alliance (WUCA), Means et al. (2010) laid out four major steps for water utilities seeking to adapt to climate change: (1) *Understand* - understand climate science and climate model projections; (2) *Assess* - assess water system vulnerabilities to potential climate changes; (3) *Plan* - incorporate climate change into water utility planning, and (4) *Implement* - implement adaptation strategies. This section summarizes the approaches to steps 2 and 3, focusing on those that have been carried out in Colorado, and briefly reflects on step 4.

Advances in incorporating climate change into planning and management have been led nationwide by the larger municipal water utilities—ten of which, including Denver Water, collaborate in WUCA—and the federal water management agencies. But the practices that have been developed are accessible to smaller utilities as well as other entities that manage water-related resources. These advances have also been informed by parallel developments in related natural resource fields, such as ecosystem management. New basin-scale climate change datasets for Colorado have been made available, and computing resources are becoming more affordable. The approaches described below span a range of potential complexity and cost; more sophisticated and expensive approaches are not always better. More detailed discussion of these and other approaches can be found in Means et al. (2010), Vogel and Smith (2010), Vogel et al. (2011), and Barsugli et al. (2012).

Vulnerability Assessment

Typically, a prerequisite for integrating climate change information into adaptation planning is conducting a vulnerability assessment to identify the resources and outcomes that are most sensitive to change under a range of potential future climates.

The most time-intensive type of vulnerability assessment is a scenario analysis that uses downscaled climate projections for the basin(s) of interest (Barsugli et al. 2012). This type of analysis begins with the selection of downscaled climate projections to represent the range of climate futures provided by the models, and running the selected projections in hydrology models and then management models to investigate system vulnerabilities to each scenario. The downscaled future climate projections may be input directly in the impacts models, or the future change in temperature and precipitation can be extracted from each climate model and used to perturb the observed climate, which is then used as input in the impacts models. Compared to five years ago, large ensembles of hydrology projections for Colorado basins and gages based on both downscaled CMIP3 and CMIP5 climate projections are now available.

In the Boulder Climate Change Study (Smith et al. 2009), the Colorado River Water Availability Study (CWCB 2012), and the Colorado River Basin Water Supply and Demand Study (Reclamation 2012), specific system outcomes (e.g., reservoir levels, water deliveries) were modeled for each of the selected climate projections. For the Joint Front Range Study (Woodbury et al. 2012) this last step of using the modeled hydrology in management models was left to each of the collaborating utilities to perform separately.

A simpler vulnerability assessment approach is a sensitivity analysis, in which prescribed changes consistent with the spread of climate projections (such as temperature increases of 2°F and 5°F and changes in annual precipitation of +10%, 0%, and -10%) are applied to the observed climate record, and then the perturbed observations are run through hydrology and management models. A sensitivity analysis does not require the time- and resource-intensive handling of downscaled climate model output. One limitation of this approach is that it assumes there is no future change in the characteristics of climate and hydrologic variability. Sensitivity analyses of this type have been performed by the city of Boulder (Smith et al. 2009), by Denver Water (see Sidebar 6-1), and Salt Lake City Public Utilities (Bardsley et al. 2013). The Joint Front Range study (Woodbury et al. 2012) also included sensitivity analysis as a precursor to scenario analysis using downscaled projections. If a sensitivity analysis is performed with multiple increments of temperature and precipitation change, the responses to the different scenarios can be summarized as a "response surface" for that water system. Then, when new climate projections become available, the estimated range of system impacts can be more easily updated based on the existing response surface (Brown and Wilby 2012; Vano and Lettenmaier 2014). For the multi-resource Gunnison Basin Climate Change Vulnerability Assessment, a simplified form of sensitivity analysis was employed, in which a broad ensemble of CMIP3 climate model projections was first distilled into two climate scenarios of seasonal temperature and precipitation change, called "moderate" and "more extreme." These two scenarios were then used to drive an expert-driven and qualitative vulnerability assessment for specific resources of interest, including ecosystems, species, and land uses (Neely et al. 2011).

A contrasting approach to vulnerability assessment is the bottom-up or threshold approach, in which resource managers start with their knowledge of their system and use their planning tools to identify what changes in climate would be most threatening to specific elements of their operations or long-range plans. By examining the outputs of climate models and other information, managers can then assess how often system critical vulnerabilities are triggered. The threshold approach can complement one of the other approaches. Colorado Springs Utilities is using a similar threshold approach in its ongoing Integrated Water Resource Plan (IWRP) effort. New time-series of hydrology are being generated based on perturbations of temperature and precipitation. Those found to correspond to increased system vulnerabilities will be compared with both climate model-derived hydrology and paleohydrology (see Section 2-7), in order to assess the risk associated with undesirable system outcomes.

Planning Approaches

The next step is incorporating the results from vulnerability assessment into short- and long-term planning processes. The uncertainties associated with climate change and other future conditions make multiple-outcome planning methods desirable. The methods briefly described below can be adjusted to meet the needs of different entities. See Means et al. (2010) for a more thorough discussion of multiple-outcome methods in the context of water utility planning.

A widely used approach is scenario planning, which involves identifying a set of critical uncertainties (e.g., climate, demographics, economics, regulation, technology) and developing a handful of plausible narrative scenarios that describe how each factor might evolve over time. Strategies or portfolios of strategies are developed to meet the needs of each future scenario. A near-term strategy that is appropriate for most or all of the scenarios is identified ("no regrets" or "low regrets"). The forthcoming State Water Supply Initiative (SWSI) by CWCB will use a scenario-planning approach, the results of which will inform the Colorado Water Plan. Denver Water has also used scenario planning for its most recent Integrated Resource Plan (see Sidebar 6-1).

Robust decision-making draws from scenario planning but involves dozens or even hundreds of scenarios and is more computationally intensive. Strategies are judged by how well they perform over the large ensemble of possible future conditions, and are adjusted until they perform well across the ensemble. Other approaches to multiple-outcome planning, like decision analysis, use probabilities or apply a combination of scenarios and probabilities. One drawback of this approach is that probabilities need to be assigned to the climate futures, and those probabilities are difficult to straight-forwardly derive from the climate projections.

Colorado Springs Utilities, after they complete their comprehensive risk assessment using the approach described above, plans to develop narrative storylines around those climate and hydrology scenarios for which risk was found to be greatest. In some ways, this reverses the typical scenario-planning approach. They will then use an algorithm designed to optimize for multiple objectives to identify the most robust policy and management solutions, as part of a robust decision-making process (Basdekas 2014). The solutions will then be further stress-tested against a range of futures not used in the selection process.

While the science continues to advance, the information about future climate will always have uncertainties, leading to a range of possible futures. Natural variability will still be felt across multiple time scales. Decision pathways that are robust for a range of conditions are more likely to be successful than a pathway that is optimized for a single future condition

(Lempert and Collins 2007).

Lessons learned from the Joint Front Range Study

The Joint Front Range Climate Change Vulnerability Study (Woodbury et al. 2012) involved eight water utilities and providers, along with technical experts from several organizations. The following lessons are distilled from the study report and from participants in the study:

- A simple sensitivity analysis may inform planning as much as conducting a sophisticated climate-model-intensive vulnerability assessment, depending on the capacity and needs of the organization.
- New information is always being produced, whether from climate science or other domains. This can feed a tendency to remain within the analysis step ("analysis paralysis") and not move onto planning.
- Moving forward with the planning step provides the opportunity for learning about a system's near- and long-term sensitivities to, and tradeoffs between, management and policy options under different climate conditions, in the context of other water-supply risk factors.
- Collaborative efforts involving multiple water entities enable the sharing of resources, attract technical experts to support the collaboration, and provide the same set of information so internal analyses completed by the individual entities can be compared across participants.

Implementation and Adaptive Management

Ultimately, vulnerability assessment and planning as described above should facilitate the implemetation of actions that are adaptive to the climate and other future conditions, reducing the risk of undesirable system outcomes. It is beyond the scope of this report to attempt to identify specific management actions related to water resources that may be more adaptive to the future climate. This is an emerging area of research and practice, and to date there have been few implemented on-the-ground actions, whether in water resources or other sectors, undertaken explicitly to promote adaptation to future climate (Means et al. 2010, Bierbaum et al. 2013). And the effectiveness of implemented actions may not be clear for years or decades as systems respond to the changing climate.

In part because of the lag in observing the effects of management actions, as well as the uncertain path of the future climate, an iterative or adaptive approach to management is being adopted in the water sector and natural resources management (National Research Council 2010). While there have been many different formulations of adaptive management, the general approach follows the steps 2 through 4 from Means et al. (2010) listed earlier (*assess, plan, implement*) plus two others: explicitly *monitor and evaluate* implemented actions; and periodically *revise* the management strategy based on lessons learned (Bierbaum et al. 2013). In the water sector, a particular form of adaptive management called Integrated Water Resources Management (IWRM; Kindler 2000) has been described, and several water entities in Colorado have carried out planning according to its principles.

6-3. Moving forward under climate uncertainty

As described earlier, the scientific uncertainties surrounding the trajectory of future climate in Colorado are unlikely to be reduced significantly in the near future. Moving forward with the uncertain and imperfect projections of future climate at hand will be more fruitful than waiting for "better" projections. We do have high confidence in continued warming, and the warming alone will have impacts on hydrology and water resources, especially the likely continuation of the ongoing shift to earlier timing of snowmelt and runoff. The more uncertain projections of annual precipitation and streamflow for Colorado—which in many cases show little or no average change—should not be construed as a "no change" scenario, but rather as a broadening of the range of possible water futures, some of which present serious challenges to the state's water systems. Because most systems have greater vulnerability to decreased runoff, planners may want to emphasize the dry side of the profile of future risk as revealed by the climate projections.

Managers of water supplies and water-dependent resources can work proactively to increase their knowledge of how their system may be vulnerable to

SIDEBAR 6-1. Assessment and planning for climate adaptation at Denver Water

Denver Water has conducted both simple and sophisticated climate vulnerability assessments, and has incorporated climate change in its Integrated Resource Plan (IRP). In a simple assessment in 2009, researchers used a hydrology model to explore how much annual precipitation would have to increase in the upper Colorado River (near the Cameo gage) and the upper South Platte River basins to offset 2°F and 5°F warming across both basins. For 2°F warming, annual precipitation would have to increase by 5% in both basins. To offset 5°F warming, precipitation on the upper Colorado would need to increase 8% and on the upper South Platte by 11%. So while a significant increase in annual precipitation would be needed to hydrologically break even under the two warming scenarios, such an increase does fall within the range of projected conditions for the two basins. However, a 5°F warming is a more frequent model-projected outcome than an 8% or 11% increase in precipitation (see Section 5-1).

A second simple assessment, completed in 2010, examined the impacts of 5°F warming to Denver Water's water system. The results indicated that supply could decrease by 20% and demand increase by 7% from warming alone. This shows how sensitive water utilities in Colorado are to a warmer climate. This analysis was then applied in Denver Water's most recent IRP.

Denver Water completed its first IRP in 1996 and updated it in 2002. The most recent IRP process began in 2008 and looks out to 2050. It follows a scenario planning methodology, which departed from the more traditional planning methods used in past IRPs. Scenario planning allows Denver Water to consider multiple water system challenges equally in its long-term planning, with the intention of better preparing the organization for changing and uncertain future conditions.

Climate change is one of five scenarios being examined in the IRP. Other challenges being considered are demographic and water use changes, and economic and regulatory changes. For comparison purposes, a scenario based on the traditional planning approach is also being developed. The simple 5°F sensitivity assessment described above is being used in the climate change scenario. Being new to scenario planning, Denver Water is keeping the scenarios simple to focus on process development and understanding, with the intention of adding complexity in future iterations.

In the future, Denver Water intends to test the strategy that was developed to meet the climate scenario against additional climate changes (as analyzed in the *Joint Front Range Study*; Woodbury et al. 2012) and adjust the strategy until it works across the range of climates that it is tested against. This approach would represent a simplified version of robust decision-making, described in Section 6-2.

a changing climate by performing sensitivity analyses and threshold assessments as described above. Gaining a better understanding of specific climate vulnerabilities at the local or basin level would make the climate information available now more useful, as well as prepare for incorporating forthcoming information.

Since future climate change presents significant risks to water resources, the integration of climate change into water resource planning is increasingly seen as necessary to make responsible and informed decisions. As water entities continue to explore the use of multiple-outcome planning approaches that more readily integrate the uncertain climate change information, more knowledge will be gained about their effectiveness and efficiency. Continuing dialogue and collaboration among climate scientists, water resource managers and planners, and other decision-makers will ensure that climate data is applied to planning processes in a way that is both consistent with the underlying science and produces useful outcomes.

SIDEBAR 6-2. Revisiting the unresolved issues from the 2008 Report

In the 2008 Report we noted that the then-current state of the science was unable to provide sufficient information to decision makers and stakeholders on a number of crucial scientific issues regarding Colorado's water resources. Four overlapping areas with unresolved issues were identified: climate models, research specific to Colorado, drought, and reconciling hydrologic projections. Here we annotate our remarks from 2008 (in blue) with comments about progress in these areas. Research continues in most of these areas.

[2008] **Modeling issues.** To produce model projections at the scale desired by decisionmakers, regional and local processes and their role in Colorado's climate must be better modeled. Precipitation projections and related phenomena are key uncertainties. Enhanced climate modeling efforts to include finer spatial resolution are needed that better represent Colorado's mountainous terrain and precipitation processes.

[Now] The last five years have seen improvements in the resolution of global climate models, but capturing the details of Colorado's topography and the climate processes dependent on topography is still beyond the capabilities of GCMs. Analyses of regional climate model (RCM) output (e.g., NARCCAP) have provided additional insights into how Colorado's topography interacts with the broad projected changes in temperature and precipitation (Rangwala et al. 2012). A high-resolution modeling program to better understand precipitation processes in the Colorado mountains has enhanced understanding of local topographic effects (Rasmussen et al. 2011, Rasmussen et al. 2014). However, these efforts have not reduced the large uncertainties in future projections of precipitation and related climate variables for Colorado, which result mainly from differences in the GCMs in portraying continental-scale circulation changes such as the position of the jet stream and storm tracks.

[2008] **Colorado-specific research.** Further research is needed focused on the state of Colorado and its river basins, and specifically on regions where there is little or no work, such as the basins of the Arkansas, Rio Grande, and the North and South Platte Rivers.

[Now] Since 2008 the most obvious gain in Colorado-specific research has been the increase in the availability of future hydrologic projections across Colorado's river basins, as detailed in Section 5-3. There have also been new Colorado-focused studies based on observations and/or modeling on snowpack (Clow 2010) and dust-on-snow (Painter et al. 2010, Deems et al. 2013).

[2008] **Understanding the causes of drought.** Issues include runoff efficiency, effects of increased temperatures, and uncertainty in precipitation projections. The attribution of the 2000s drought is an area of ongoing research.

[Now] The 'Reconciling Projections of Future Colorado River Stream Flow' study described in Section 5-3 led to greater understanding of the influences on runoff efficiency and the effects of increased temperatures on aspects of the hydrologic cycle.

[2008] **Hydrologic projections for the Colorado River.** There is a large range among projections of river flows (Section 5). A key uncertainty is how efficient future runoff will be in the Colorado as well as other basins. A study is underway to reconcile the differences among these projections, and to better resolve projections for future flows. These uncertainties arise both from climate models and hydrologic models.

[Now] The 'Reconciling Projections of Future Colorado River Stream Flow' study examined, diagnosed, and at least partly reconciled the differences between different hydrologic models' translation of climate inputs into runoff. It is clearer now what portion of the range of the projections of runoff is due to the hydrologic models' differences, and what is driven by differences among the climate models and other factors.

References

Adams, D. K., and A. C. Comrie. 1997. The North American monsoon. *Bulletin of the American Meteorological Society* 78: 2197–2213.

Alexander, M. A., J. D. Scott, K. Mahoney, and J. Barsugli. 2013. Greenhouse gas-induced changes in summer precipitation over Colorado in NARCCAP regional climate models. *Journal of Climate* 26: 8690–8697, doi: http://dx.doi.org/10.1175/JCLI-D-13-00088.1

Alley, W. 1984. The Palmer Drought Severity Index: Limitations and assumptions. *Journal of Climatology and Applied Meteorology* 23: 1100–1109.

Andreadis, K. M., and D. P. Lettenmaier. 2006. Trends in 20th century drought over the continental United States. *Geophysical Research Letters* 33: L10403, doi:10.1029/2006GL025711.

Arrhenius, S. 1896. On the influence of carbonic acid in the air upon the temperature of the ground. *London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 41: 237–275.

Bardsley, T., A. Wood, M. Hobbins, T. Kirkham, L. Briefer, J. Niermeyer and S. Burian. 2013. Planning for an uncertain future: Climate change sensitivity assessment toward adaptation planning for public water supply. *Earth Interactions* 17: 1–26, doi:10.1175/2012EI000501.1.

Barnett, T. P. and D. W. Pierce. 2009. Sustainable water deliveries from the Colorado River in a changing climate. *Proceedings of the National Academy of Sciences* 106(18): 7334–7338.

Barnett, T. P., D. W. Pierce, et al. 2008. Human-induced changes in the hydrology of the western United States. *Science* 319(5866): 1080–1083.

Barsugli, J., C. Anderson, J. B. Smith, and J. M. Vogel. 2009. Options for improving climate modeling to assist water utility planning for climate change. Final Report. Prepared for Water Utility Climate Alliance. September 2009.

Barsugli, J. J. 2010. What's a billion cubic meters among friends: The impacts of quantile mapping bias correction on climate projections. Abstract, 2010 Fall Meeting, American Geophysical Union, San Francisco, CA, 13–17 December 2010.

Barsugli, J. J., J. Vogel, L. Kaatz, J. Smith, M. Waage, and C. Anderson. 2012. Two faces of uncertainty: Climate science and water utility planning. *Journal of Water Resources Planning and Management* 138(5).

Basdekas, L. 2014. Is multiobjective optimization ready for water resources practitioners? Utility's drought policy investigation. *Journal of Water Resources Planning and Management* 140(3): 275–276.

Battaglin, W., L. Hay, and S. Markstrom. 2011. Simulating the potential effects of climate change in two Colorado basins and at two Colorado ski areas. *Earth Interactions* 15: 1–23, doi:http://dx.doi.org/10.1175/2011EI373.1

Bentz, B. J., J. Régnière, C. J. Fettig, E. M. Hansen, J. L. Hayes, J. A. Hicke, R. G. Kelsey, J. F. Negrón, and S. J. Seybold. 2010. Climate change and bark beetles of the western United States and Canada: Direct and indirect effects. *BioScience* 60: 602–613.

Bonfils, C., B. D. Santer, D. W. Pierce, H. G. Hidalgo, G. Bala, T. Das, T.P. Barnett, et al. 2008. Detection and attribution of temperature changes in the mountainous western United States. *Journal of Climate* 21: 6404–6424.

Brahney, J., A.P. Ballantyne, C. Sievers, and J. C. Neff. 2013. Increasing Ca_2+ deposition in the western US: the role of mineral aerosols. *Aeolian Research* 10: 77–87, http://dx.doi.org/10.1016/j.aeolia.2013.04.003

Brekke, L. D., M. D. Dettinger, E. P. Maurer, and M. Anderson. 2008. Significance of model credibility in estimating climate projection distributions for regional hydroclimatological risk assessments. *Climatic Change*, doi:10.1007/s10584-007-9388-3.

Brekke, L.D., J.E. Kiang, J.R. Olsen, R.S. Pulwarty, D.A. Raff, D.P. Turnipseed, R.S. Webb, and K.D. White. 2009. Climate Change and Water Resources Management—A Federal Perspective. U.S. Geological Survey Circular 1331. 65 pp. Available online at: http://pubs.usgs.gov/circ/1331/.

Breshears, D., et al. 2005. Regional vegetation die-off in response to global-change type drought. *Proceedings of the National Academy of Sciences* 102: 15144–15148.

Brown, C. and R. L. Wilby. 2012. An alternate approach to assessing climate risks. *Eos, Transactions of the AGU* 93(41): 401, doi:10.1029/2012EO410001.

CCSP (Climate Change Science Program). 2008a. SAP 3.1: Climate Models: An Assessment of Strengths and Limitations. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Bader D. C., C. Covey, W.J. Gutowski Jr., I. M. Held, K.E. Kunkel, R.L. Miller, R. T. Tokmakian and M.H. Zhang (Authors). Department of Energy, Office of Biological and Environmental Research, Washington, DC, 124 pp.

CCSP (Climate Change Science Program). 2008b. SAP 3.3: Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. T. R. Karl, G. A. Meehl, C. D. Miller, S. J. Hassol, A. M. Waple, and W. L. Murray (eds.) Department of Commerce, NOAA's National Climatic Data Center, Washington, DC, 164 pp.

Chang, E. K. M., Y. Guo, and X. Xia. 2012. CMIP5 multimodel ensemble projection of storm track change under global warming. *Journal of Geophysical Research* 117: D23118, doi:10.1029/2012JD018578.

Christensen, N., and D. P. Lettenmaier. 2007. A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River Basin. *Hydrology and Earth System Sciences* 11: 1417–1434.

Climate Central. 2012. The Age of Western Wildfires. August 2012, 23 pp.

Clow, D. W. 2010. Changes in the timing of snowmelt and streamflow in Colorado: A response to recent warming. *Journal of Climate* 23(9): 2293–2306.

Cook, E. R., R. Seager, R. R. Heim, R. S. Vose, C. Herweijer, and C. Woodhouse. 2009. Megadroughts in North America: Placing IPCC projections of hydroclimatic change in a long-term paleoclimate context. *Journal of Quaternary Science* 25: 48–61, doi: 10.1002/jqs.1303.

Crosbie, R. S., W. R. Dawes, S. P. Charles, F. S. Mpelasoka, S. Aryal, O. Barron, and G. K. Summerell. 2011. Differences in future recharge estimates due to GCMs, downscaling methods and hydrological models. *Geophysical Research Letters* 38(11).

CWCB (Colorado Water Conservation Board). 2012. Colorado River Water Availability Study – Phase I Report. AECOM eds., March 2012, 189 pp.

Daly, C., R. P. Neilson, and D. L. Phillips. 1994. A statistical–topographic model for mapping climatological precipitation over mountainous terrain. *Journal of Applied Meteorology and Climatology* 33: 140–158.

Daly, C., M. Halbleib, J. I. Smith, W. P. Gibson, M. K. Doggett, G. H. Taylor, J. Curtis, and P. A. Pasteris. 2008. Physiographically-sensitive mapping of temperature and precipitation across the conterminous United States. *International Journal of Climatology* 28: 2031–2064.

Das, T., H. Hidalgo, D. Cayan, M. Dettinger, D. Pierce, C. Bonfils, T.P. Barnett, G. Bala and A. Mirin. 2009. Structure and detectability of trends in hydrological measures over the western United States. *Journal of Hydrometeorology* 10: 871–892, doi:10.1175/2009JHM1095.1.

Deems, J. S., T. H. Painter, J. J. Barsugli, J. Belnap, and B. Udall. 2013. Combined impacts of current and future dust deposition and regional warming on Colorado River Basin snow dynamics and hydrology. *Hydrology and Earth System Sciences* 10: 6237–6275.

Diaz, H. F., and J. K. Eischeid. 2007. Disappearing “alpine tundra” Köppen climatic type in the western United States. *Geophysical Research Letters* 34: L18707, doi:10.1029/2007GL031253.

Doesken, N. J. 1992. The 1992 Alamosa anomaly. *Weatherwise* 45(5): 19–22.

Dominguez, F., J. Cañon, and J. Valdes. 2009. IPCC-AR4 climate simulations for the southwestern U.S.: The importance of future ENSO projections. *Climatic Change* 99: 499–514, doi:10.1007/s10584-009-9672-5.

Dominguez, F., E. Rivera, D. P. Lettenmaier, and C. L. Castro. 2012. Changes in winter precipitation extremes for the western United States under a warmer climate as simulated by regional climate models. *Geophysical Research Letters* 39: L05803, doi: 10.1029/2011GL050762.

EPA (U.S. Environmental Protection Agency). 2013. Watershed Modeling to Assess the Sensitivity of Streamflow, Nutrient, and Sediment Loads to Potential Climate Change and Urban Development in 20 U.S. Watersheds (External Review Draft). U.S. Environmental Protection Agency, Washington, D.C., 2013.

Fall, S., A. Watts, J. Nielsen-Gammon, E. Jones, D. Niyogi, J. Christy, and R. Pielke Sr. 2011. Analysis of the impacts of station exposure on the U.S. Historical Climatology Network temperatures and temperature trends. *Journal of Geophysical Research* 116: D14120.

Field, C. B., V. Barros, T. Stocker, and Q. Dahe, eds. 2011. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change.* Cambridge: Cambridge University Press. http://ipcc-wg2.gov/SREX/report/.

Foster, G., and S. Rahmstorf. 2011. Global temperature evolution 1979–2010. *Environmental Research Letters* 6: 044022.

Fowler, H. J., S. Blenkinsop, and C. Tebaldi. 2007. Linking climate change modeling to impacts studies: Recent advances in downscaling techniques for hydrological modeling. International *Journal of Climatology* 27: 1547–1578.

Freed, J. R. and F. Sussman. 2006. Converting research into action: A framework for identifying opportunities to provide practical decision support for climate change adaptation. *Water Resources Impact* 8: 11–14.

Fritze, H., I. T. Stewart, and E. Pebesma. 2011. Shifts in western North American runoff regimes for the recent warm decades. *Journal of Hydrometeorology* 12: 989–1006.

Gangopadhyay, S., T. Pruitt, L. Brekke, and D. Raff. 2011. Hydrologic projections for the western United States. *Eos, Transactions of the AGU* 92: 441, doi:10.1029/2011EO480001.

Garfin, G., A. Jardine, R. Merideth, M. Black, and S. LeRoy, eds. 2013. *Assessment of Climate Change in the Southwest United States: A Report Prepared for the National Climate Assessment.* A report by the Southwest Climate Alliance. Washington, DC: Island Press.

Georgakakos, A., P. Fleming, M. Dettinger, C. Peters-Lidard, T. C. Richmond, K. Reckhow, K. White, and D. Yates, 2014. Ch. 3: Water Resources. Climate Change Impacts in the United States: The Third

National Climate Assessment, J. M. Melillo, T. C. Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 69–112. doi:10.7930/J0G44N6T.

Gershunov, A., and T. P. Barnett. 1998. Interdecadal modulation of ENSO teleconnections. *Bulletin of the American Meteorological Society* 79: 2715–2725.

Gershunov, A., B. Rajagopalan, J. Overpeck, K. Guirguis, D. Cayan, M. Hughes, M. Dettinger, C. Castro, R. E. Schwartz, M. Anderson, A. J. Ray, J. Barsugli, T. Cavazos, and M. Alexander. 2013. "Future Climate: Projected Extremes." In *Assessment of Climate Change in the Southwest United States: A Report Prepared for the National Climate Assessment*, edited by G. Garfin, A. Jardine, R. Merideth, M. Black, and S. LeRoy, 126–147. A report by the Southwest Climate Alliance. Washington, DC: Island Press.

Goodrich, G. B. 2007. Influence of the Pacific Decadal Oscillation on winter precipitation and drought during years of neutral ENSO in the western U.S. *Weather and Forecasting* 22(1): 116–124.

Gordon, E., and D. Ojima, eds. 2014. Colorado Climate Change Vulnerability Study. Submitted to the Colorado Energy Office, State of Colorado, July 2014. Western Water Assessment.

Hamlet, A. F., P. W. Mote, M. P. Clark, and D. P. Lettenmaier. 2005. Effects of temperature and precipitation variability on snowpack trends in the western United States. *Journal of Climate* 18: 4545–4561.

Harding, B. L., A. W. Wood, and J. R. Prairie. 2012. The implications of climate change scenario selection for future streamflow projection in the Upper Colorado River Basin. *Hydrology and Earth System Sciences* 16: 3989–4007.

Hawkins, E. and R. Sutton. 2011. The potential to narrow uncertainty in projections of regional precipitation change. *Climate Dynamics* 37(1-2): 407–418.

Hawkins, E., and R. T. Sutton. 2009. The potential to narrow uncertainty in regional climate predictions. *Bulletin of the American Meteorological Society* 90: 1095–1107.

Hidalgo, H. G. 2004. Climate precursors of multidecadal drought variability in the western United States. *Water Resources Research* 40: W12504, doi:10.1029/2004WR003350.

Hidalgo, H. G., T. Das, M. D. Dettinger, D. R. Cayan, D. W. Pierce, T. P. Barnett, G. Bala, et al. 2009. Detection and attribution of stream flow timing changes to climate change in the western United States. *Journal of Climate* 22(13): 3838–3855, doi:10.1175/2009JCLI2470.1.

Hirsch, R. M., and K. R. Ryberg. 2011. Has the magnitude of floods across the USA changed with global CO_2 levels? *Hydrological Sciences Journal* 57: 1–9, doi:10.1080/02626667.2011.621895.

Hoerling, M., and J. Eischeid. 2007. Past peak water in the Southwest. *Southwest Hydrology* 6(1): 18–35.

Hoerling, M., D. Lettenmaier, D. Cayan, and B. Udall. 2009. Reconciling projections of Colorado River streamflow. *Southwest Hydrology* 8(3): 20–21.

Hoerling, M., J. Eischeid, and J. Perlwitz. 2010. Regional precipitation trends: Distinguishing natural variability from anthropogenic forcing. *Journal of Climate* 23: 2131–2145.

Hoerling, M. P., M. Dettinger, K. Wolter, J. Lukas, J. Eischeid, R. Nemani, B. Liebmann, and K. E. Kunkel. 2013. "Present Weather and Climate: Evolving Conditions." In *Assessment of Climate Change in the Southwest United States: A Report Prepared for the National Climate Assessment*, edited by G. Garfin, A. Jardine, R. Merideth, M. Black, and S. LeRoy, 74–100. A report by the Southwest Climate Alliance. Washington, DC: Island Press.

IPCC (Intergovernmental Panel on Climate Change). 2000. Nakicenovic, N., and R. Swart, eds., *Special Report on Emissions Scenarios: A special report of Working Group III of the Intergovernmental Panel on Climate Change*, Cambridge University Press, ISBN 0-521-80081-1.

IPCC (Intergovernmental Panel on Climate Change). 2007. *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H.L. Miller, eds. Cambridge: Cambridge University Press. http://www. ipcc.ch/ipccreports/ar4-wg1.htm.

IPCC (Intergovernmental Panel on Climate Change). 2013. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley, eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Julander, R. P. and Bricco, M. 2006. An examination of external influences imbedded in the historical snow data of Utah. Proceedings of the Western Snow Conference 2006, pp. 61–72.

Kenney, D. S., R. Klein, C. Goemans, C. Alvord, and J. Shapiro. 2008. The impact of earlier spring snowmelt on water rights and administration: A preliminary overview of issues and circumstances in the western states. Western Water Assessment. Available online at http://wwa.colorado.edu/publications/reports/.

Kharin, V., F. Zwiers, X. Zhang, and M. Wehner. 2013. Changes in temperature and precipitation extremes in the CMIP5 ensemble. *Climatic Change* 119(2): 345–357.

Klein, R., E. S. Gordon, W. R. Travis, J. J. Lukas, B. Udall, K. Averyt, J. Vogel, and J. Smith. 2011. Colorado Climate Preparedness Project Final Report. Prepared for the State of Colorado, Western Water Assessment. Available online at http://wwa.colorado.edu/

publications/reports/.

Knowles, N., M. D. Dettinger, and D. R. Cayan. 2006. Trends in snowfall versus rainfall in the western United States. *Journal of Climate* 19: 4545–4559.

Kodra, E., K. Steinhauser, and A. R. Ganguly. 2011. Persisting cold extremes under 21st-century warming scenarios. *Geophysical Research Letters* 38: L08705. doi:10.1029/2011GL047103.

Kunkel, K. E., T. R. Karl, H. Brooks, J, Kossin, J. H. Lawrimore, D. Arndt, L. Bosart, D. Changnon, et al. 2013a. Monitoring and understanding trends in extreme storms: State of knowledge. *Bulletin of the American Meteorological Society* 94: 499–514, doi: http://dx.doi.org/10.1175/BAMS-D-11-00262.1.

Kunkel, K. E, L. E. Stevens, S. E. Stevens, L. Sun, E. Janssen, D. Wuebbles, K. T. Redmond, and J. G. Dobson. 2013b. Climate of the Southwest U. S. NOAA Technical Report NESDIS 142-5, 79 pp.

Lareau, N., and J. D. Horel. 2012. The climatology of synoptic-scale ascent over western North America: A perspective on storm tracks. *Monthly Weather Review* 140: 1761–1778.

Lazar, B., and M. Williams. 2008. Potential impacts of climate change for western U.S. ski areas: adaptation and sustainability in the 21st century. Proceedings, International Snow Science Workshop, September 21-27, 2008, Whistler, BC.

Lempert, R. J., and M. T. Collins. 2007. Managing the risk of uncertain threshold response: Comparison of robust, optimum, and precautionary Approaches. *Risk Analysis* 27(4): 1009–1026.

Lin, J., B. E. Mapes, K. M. Weickmann, G. N. Kiladis, S. D. Schubert, M. J. Suarez, J. T. Bacmeister, and M. Lees. 2008. North American monsoon and convectively coupled equatorial waves simulated by IPCC AR4 Coupled GCMs. *Journal of Climate* 21: 2919–2937.

Littell, J. S., D. McKenzie, D. L. Peterson, and A. L. Westerling. 2009. Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003. *Ecological Applications* 19: 1003–1021.

Liu, Y.-Q., Stanturf, J., and Goodrick, S. 2010. Trends in global wildfire potential in a changing climate. *Forest Ecology and Management* 259: 685–697, http://dx.doi.org/10.1016/j.foreco.2009.09.002.

Livneh B., J. S. Deems, B. Buma, J. J. Barsugli, D. Schneider, N. P. Molotch, K. Wolter, and C.A. Wessman. In Preparation. Catchment response to bark beetle outbreak in the Upper Colorado River Basin.

Macknick, J., S. Sattler, et al. 2012. The water implications of generating electricity: water use across the United States based on different electricity pathways through 2050. *Environmental Research Letters* 7(4).

Mahoney, K., M. A. Alexander, G. Thompson, J. J. Barsugli, and J. D. Scott. 2012. Changes in hail and flood risk in high-resolution simulations over the Colorado Mountains. *Nature Climate Change* 2: 125–131, doi:10.1038/nclimate1344.

Mahoney, K., M. Alexander, J. D. Scott, and J. Barsugli. 2013. High-resolution downscaled simulations of warm-season extreme precipitation events in the Colorado Front Range under past and future climates. *Journal of Climate* 26: 8671–8689. doi: http://dx.doi.org/10.1175/JCLI-D-12-00744.1.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis. 1997. A Pacific decadal climate oscillation with impacts on salmon. *Bulletin of the American Meteorological Society* 78: 1069–1079.

Maurer E. P., A. W. Wood, J. D. Adam, D. P. Lettenmaier, and B. Nijssen. 2002. A long-term hydrologically-based data set of land surface fluxes and states for the conterminous United States. *Journal of Climate* 15(22): 3237–3251.

Maurer, E. P., and H. G. Hidalgo. 2008. Utility of daily vs. monthly large-scale climate data: An intercomparison of two statistical downscaling methods. *Hydrology and Earth System Sciences* 12: 551–563.

Maurer, E. P., H. G. Hidalgo, T. Das, M. D. Dettinger, and D. R. Cayan. 2010. The utility of daily large-scale climate data in the assessment of climate change impacts on daily streamflow in California. *Hydrology and Earth System Sciences* 14: 1125–1138.

Maurer, E. P., L. Brekke, T. Pruitt, and P. B. Duffy. 2007. Fine-resolution climate projections enhance regional climate change impact studies. *Eos, Transactions of the AGU* 88: 504.

McAfee, S.A., J.L. Russell and P.J. Goodman. 2011. Evaluating IPCC AR4 cool-season precipitation simulations and projections for impacts assessment over North America. *Climate Dynamics* 37: 2271–2287.

McCabe, G. M., J. L. Betancourt, and H. G. Hidalgo. 2007. Associations of decadal to multidecadal sea surface temperature variability with Upper Colorado River flow. *Journal of the American Water Resources Association* 43: 183–192.

Means III, E. G., Laugier, M. C., and J. A. Daw. 2010. Decision support planning methods: incorporating climate change uncertainties into water planning. Final report. Prepared for Water Utility Climate Alliance, January 2010. Available online at http://www.wucaonline.org/assets/pdf/actions_whitepaper_012110.pdf.

Mearns, L. O., W. Gutowski, R. Jones, R. Leung, S. McGinnis, A. Nunes, and Y. Qian. 2009. A regional climate change assessment program for North America. *Eos, Transactions of the AGU* 90: 311.

Meko, D. M., C. A. Woodhouse, C. A. Baisan, T. Knight, J. J. Lukas, M. K. Hughes, and M. W. Salzer. 2007. Medieval drought in the upper Colorado River Basin. *Geophysical Research Letters* 34: L10705, doi:10.1029/2007GL029988.

Melillo, J. M., T. C. Richmond, and G. W. Yohe, eds. 2014. Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program, 841 pp., doi:10.7930/J0Z31WJ2.

Miller, K., and D. Yates. 2006. Climate change and water resources: A primer for municipal water providers. Awwa Research Foundation / American Water Works Association / UCAR.

Moritz, M. A., M.-A. Parisien, E. Batllori, M. A. Krawchuk, J. Van Dorn, D. J. Ganz, and K. Hayhoe. 2012. Climate change and disruptions to global fire activity. *Ecosphere* 3. http://dx.doi.org/10.1890/ES11-00345.1

Mote, P. W., A. F. Hamlet, M. P. Clark, and D. P. Lettenmaier. 2005. Declining mountain snowpack in western North America. *Bulletin of the American Meteorological Society* 86: 39–49.

Mote, P., L. Brekke, P. B. Duffy, and E. Maurer. 2011. Guidelines for constructing climate scenarios. *Eos, Transactions of the AGU* 92(31): 257, doi:10.1029/2011EO310001.

Munson, S. M., J. Belnap, and G. S. Okin. 2011. The responses of wind erosion to climate induced vegetation changes on the Colorado Plateau. *Proceedings of the National Academy of Sciences* 108: 3854–3859, doi:10.1073/pnas.1014947108.

Murphy, K. W., and A. W. Ellis. 2014. An assessment of the stationarity of climate and stream flow in watersheds of the Colorado River Basin. *Journal of Hydrology* 509: 454–473.

Neely, B., R. Rondeau, J. Sanderson, C. Pague, B. Kuhn, J. Siemers, L. Grunau, J. Robertson, P. McCarthy, J. Barsugli, T. Schulz, and C. Knapp, eds. 2011. Gunnison Basin: Climate Change Vulnerability Assessment for the Gunnison Climate Working Group. Prepared by The Nature Conservancy, Colorado Natural Heritage Program, Western Water Assessment, and University of Alaska-Fairbanks. Project of the Southwest Climate Change Initiative. Available online at http://wwa.colorado.edu/publications/reports/.

Neff, J.C., A.P. Ballantyne, G.L. Farmer, N.M. Mahowald, J.L. Conroy, C.C. Landry, J.T. Overpeck, T.H. Painter, C.R. Lawrence, and R.L. Reynolds. 2008. Increasing eolian dust deposition in the western United States linked to human activity. *Nature Geosciences*, doi:10.1038/ngeo133.

Newman, M., G. P. Compo, and M. A. Alexander. 2003. ENSO-forced variability of the Pacific Decadal Oscillation. *Journal of Climate* 16(23): 3853–3857.

Nowak, K., M. Hoerling, B. Rajagopalan, and E. Zagona. 2012. Colorado River Basin hydroclimatic variability. *Journal of Climate* 25(2): 4389–4403.

Painter, T. H., A. P. Barrett, C. C. Landry, J. C. Neff, M. P. Cassidy, C. R. Lawrence, K. E. McBride, and G. L. Farmer. 2007. Impact of disturbed desert soils on duration of mountain snow cover. *Geophysical Research Letters* 34: L12502, doi:10.1029/2007GL030284.

Painter, T. H., J. S. Deems, J. Belnap, A. F. Hamlet, C. C. Landry, and B. Udall. 2010. Response of Colorado River runoff to dust radiative forcing in snow. *Proceedings of the National Academy of Sciences* 107: 17125–17130.

Painter, T. H., S. M. Skiles, J. S. Deems, A. C. Bryant, and C. C. Landry. 2012. Dust radiative forcing in snow of the Upper Colorado River Basin. Part I: A 6-year record of energy balance, radiation, and dust concentrations. *Water Resources Research* 48: W07521, doi:10.1029/2012WR011985.

Palmer, W. C. 1965. Meteorological drought. Research Paper No. 45. Washington, DC: U.S. Weather Bureau.

Pechony, O., and D. T. Shindell. 2010. Driving forces of global wildfires over the past millennium and the forthcoming century. *Proceedings of the National Academy of Sciences* 107 (45): 19167–19170.

Pederson, G. T., S. T. Gray, C. A. Woodhouse, J. L. Betancourt, D. B. Fagre, J. S. Littell, E. Watson, B. H. Luckman, and L. J. Graumlich. 2011. The unusual nature of recent snowpack declines in the North American Cordillera. *Science* 333: 332–335, doi: 10.1126/science.1201570.

Peterson, T. C., D. Anderson, S. J. Cohen, M. Cortez, R. Murname, C. Parmesan, D. Phillips, R. Pulwarty, and J. Stone. 2008. Why weather and climate extremes matter. In: Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands, T. R. Karl, Eds., U.S. Climate Change Science Program and the Subcommittee on Global Change Research, pp. 11–33.

Peterson, T. C., R. R. Heim, Jr., R. Hirsch, D. P. Kaiser, H. Brooks, N. S. Diffenbaugh, R. M. Dole, et al. 2013. Monitoring and understanding changes in heat waves, cold waves, floods and droughts in the United States: State of knowledge. *Bulletin of the American Meteorological Society*. doi: http://dx.doi.org/10.1175/BAMS-D-12-00066.1.

Pielke Sr., R. A., J. Nielsen-Gammon, C. Davey, J. Angel, O. Bliss, N. Doesken, M. Cai, S. Fall, D. Niyogi, K. Gallo, R. Hale, K. G. Hubbard, X. Lin, H. Li, and S. Raman. 2007. Documentation of uncertainties and biases associated with surface temperature measurement sites for climate change assessment. *Bulletin of the American Meteorological Society* 88: 913–928.

Pielke Sr., R. A., T. Stohlgren, L. Schell, W. Parton, N. Doesken, K. Redmond, J. Moeny, T. McKee, and T. G. F. Kittel. 2002. Problems in evaluating regional and local trends in temperature: An example from eastern Colorado, USA. *International Journal of Climatology* 22: 421–434.

Pielke, Sr., R. A., N. Doesken, and O. Bliss. 2003. Climate of Colorado. Climatography Report #60, National Climatic Data Center, Asheville, NC.

Pierce, D., T. Barnett, H. Hidalgo, T. Das, C. Bonfils, B. Santer,

G. Bala, et al. 2008. Attribution of declining western US snowpack to human effects. *Journal of Climate* 21: 6425–6444, doi:10.1175/2008JCLI2405.1.

Polade, S. D., Gershunov, A., Cayan, D. R., Dettinger, M. D., and Pierce, D. W. 2013. Natural climate variability and teleconnections to precipitation over the Pacific-North American region in CMIP3 and CMIP5 models. *Geophysical Research Letters* 40: 2296–2301.

Pugh E. T., and E. E. Small. 2011. The impact of pine beetle infestation on snow accumulation and melt in the headwaters of the Colorado River. *Ecohydrology*, doi: 10.1002/eco.239.

Pugh, E. and E. Gordon. 2012. A conceptual model of water yield impacts from beetle-induced tree death in snow-dominated lodgepole pine forests. *Hydrological Processes*, doi: 10.1002/hyp.9312.

Raffa, K. F., B. H. Aukema, B. J. Bentz, A. L. Carroll, J. A. Hicke, M. G. Turner, and W. H. Romme. 2008. Cross-scale drivers of natural disturbances prone to anthropogenic amplifications: The dynamics of bark beetle eruptions. *BioScience* 58: 501–517.

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

Rangwala, I. and J. R. Miller. 2012. Climate change in mountains: a review of elevation-dependent warming and its possible causes. *Climatic Change* 114: 527–547, doi:10.1007/s10584-012-0419-3.

Rangwala, I., E. Sinsky, and J. R. Miller. 2013. Amplified warming projections for high altitude regions of the northern hemisphere mid-latitudes from CMIP5 models. *Environmental Research Letters* 8, doi:10.1088/1748-9326/8/2/024040.

Rangwala, I., J. J. Barsugli, K. Cozzetto, J. Neff, and J. Prairie. 2012. Mid-21st century projections in temperature extremes in the southern Colorado Rocky Mountains from regional climate models. *Climate Dynamics*, doi 10.1007/s00382-011-1282-z.

Rasmussen, R., C. H. Liu, et al. 2011. High-resolution coupled climate runoff simulations of seasonal snowfall over Colorado: A process study of current and warmer Climate. *Journal of Climate* 24(12): 3015–3048.

Rasmussen, R., K. Ikeda, C. Liu, D. Gochis, M. Clark, A. Dai, E. Gutmann, J. Dudhia, F. Chen, M. Barlage, D. Yates, and G. Zhang. 2014. Climate Change Impacts on the Water Balance of the Colorado Headwaters: High-Resolution Regional Climate Model Simulations. *Journal of Hydrometeorology*, doi:10.1175/JHM-D-13-0118.1,

Ray, A. J., J. J. Barsugli, K. B. Averyt, K. Wolter, M. Hoerling, N. Doesken, B. Udall, and R. S. Webb. 2008. Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation. Report for the Colorado Water Conservation Board. Western Water Assessment. Available online at http://wwa.colorado.edu/publications/reports/.

Reclamation (U.S. Bureau of Reclamation). 2011. West-wide climate risk assessments: Bias-corrected and spatially downscaled surface water projections. Technical Memorandum 86-68210-2011-01. Denver: Reclamation, Technical Service Center.

Reclamation (U.S. Bureau of Reclamation). 2012. Colorado River Basin Water Supply and Demand Study. Final Report, December 2012.

Reclamation (U.S. Bureau of Reclamation). 2013. Downscaled CMIP3 and CMIP5 Climate Projections – Release of Downscaled CMIP5 Climate Projections, Comparison with Preceding Information, and Summary of User Needs. U.S. Department of the Interior, Bureau of Reclamation, 104 pp., available at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/downscaled_climate.pdf.

Reclamation (U.S. Bureau of Reclamation). 2014. Downscaled CMIP3 and CMIP5 Hydrology Projections – Release of Hydrology Projections, Comparison with Preceding Information, and Summary of User Needs. U.S. Department of the Interior, Bureau of Reclamation, 110 pp., available at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/BCSD5HydrologyMemo.pdf.

Redmond, K. T. 2003. Climate variability in the intermontane West: Complex spatial structure associated with topography, and observational issues. In *Water and climate in the western United States*, W. M. Lewis, ed, pp. 29–48. Boulder, CO: University Press of Colorado.

Regonda, S. K., B. Rajagopalan, M. Clark, and J. Pitlick. 2005. Seasonal cycle shifts in hydroclimatology over the western United States. *Journal of Climate* 18: 372–384.

Reichler, T., and J. Kim. 2008. How well do coupled models simulate climate? *Bulletin of the American Meteorological Society* 89: 303–311.

Rhoades, C. C., D. Entwistle and D. Butler. 2011. The influence of wildfire extent and severity on streamwater chemistry, sediment and temperature following the Hayman Fire, Colorado. *International Journal of Wildland Fire* 20: 430Z442

Rieman, B. E., and D. J. Isaak. 2010. Climate change, aquatic ecosystems, and fishes in the Rocky Mountain West: Implications and alternatives for management. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 46 pp.

Ritter, B. 2007. Colorado Climate Action Plan: A Strategy to Address Global Warming. 33 pp.

Routson, C. C., C. Woodhouse, and J. T. Overpeck. 2011. Second century megadrought in the Rio Grande headwaters, Colorado: How unusual was medieval drought? *Geophysical Research Letters* 38: L22703, doi:10.1029/2011GL050015.

Ruff, T. W., Y. Kushnir, and R. Seager. 2012. Comparing 20th and 21st century patterns of inter-annual precipitation variability over the western United States and northern Mexico. *Journal of Hydrometeorology* 13: 366–378.

Santer, B. D., K. E. Taylor, P. J. Gleckler, C. Bonfils, T. P. Barnett, D. W. Pierce, T. M. L. Wigley, et al. 2009. Incorporating model quality information in climate change detection and attribution studies. *Proceedings of the National Academy of Sciences* 106: 14778–14783, doi:10.1073/ pnas.0901736106.

Schlesinger, M. E., and N. Ramankutty. 1994. An oscillation in the global climate system of period 65–70 years. *Nature* 367: 723–726.

Schubert, S. D., M. J. Suarez, P. J. Region, R. D. Koster, and J. T. Bacmeister. 2004. Causes of long term drought in the U. S. Great Plains. *Journal of Climate* 17: 485–503.

Schubert, S., D. Gutzler, H. Wang, A. Dai, T. Delworth, C. Deser, K. Findell, et al. 2009. A USCLIVAR project to assess and compare the responses of global climate models to drought-related SST forcing patterns: Overview and results. *Journal of Climate*, 22: 5251–5272, doi:10.1175/2009JCLI3060.1.

Seager R., N. Naik, and L. Vogel. 2012a. Does global warming cause intensified interannual hydroclimate variability? *Journal of Climate* 25: 3355–3372.

Seager, R., Ting, M., Li, C., Naik, N., Cook, B., Nakamura, J., and Liu, H. 2012b. Projections of declining surface-water availability for the Southwestern U.S.. *Nature Climate Change*, doi:10.1038/nclimate1787

Seager, R., M. Ting, I. Held, Y. Kushnir, J. Lu, G. Vecchi, H-P. Huang, et al. 2007. Model projections of an imminent transition to a more arid climate in southwestern North America. *Science* 316: 1181–1184.

Seager, R., R. Burgman, Y. Kushnir, A. Clement, E. R. Cook, N. Naik, and J. Miller. 2008. Tropical Pacific forcing of North American medieval megadroughts: Testing the concept with an atmosphere model forced by coral reconstructed SSTs. *Journal of Climate* 21: 6175–6190.

Sheffield, J., A. P. Barrett, B. Colle, D. N. Fernando, R. Fu, K. L. Geil, Q. Hu, et al. 2013a. North American Climate in CMIP5 Experiments. Part I: Evaluation of historical simulations of continental and regional climatology. *Journal of Climate* 26(23): 9209–9245.

Sheffield, J., S. J. Camargo, R. Fu, Q. Hu, X. Jiang, N. Johnson, K. B. Karnauskas, et al. 2013b. North American Climate in CMIP5 Experiments. Part II: Evaluation of historical simulations of intraseasonal to decadal variability. *Journal of Climate* 26(23): 9247–9290.

Sillmann, J., V.V. Kharin, F.W. Zwiers, X. Zhan and D. Bronaugh. 2013. Climate extreme indices in the CMIP5 multi-model ensemble. Part 2: Future climate projections. *Journal of Geophysical Research: Atmospheres.*

Skiles, S. M., T. H. Painter, J. S. Deems, A. C. Bryant, and C. C. Landry. 2012. Dust radiative forcing in snow of the Upper Colorado River Basin. Part II: Interannual variability in radiative forcing and snowmelt rates. *Water Resources Research* 48: W07522, doi:10.1029/2012WR011986.

Smith, J. B., K. Strzepek, L. Rozaklis, C. Ellinghouse, and K. C. Hallett. 2009. The potential consequences of climate change for Boulder Colorado's water supplies. Stratus Consulting, for the NOAA Climate Program Office.

Somor, A. J., P. D. Brooks, P. A. Troch, A. A. Harpold, J. Biederman, D. D. Breshears. (In Revision). Streamflow response to beetle-caused tree mortality in subalpine catchments. *Ecohydrology.*

Spracklen, D. V., L. J. Mickley, J. A. Logan, R. C. Hudman, R. Yevich, M. D. Flanning, and A. L. Westerling. 2009. Impacts of climate change from 2000 to 2050 on wildfire activity and carbonaceous aerosol concentrations in the western United States. *Journal of Geophysical Research* 114: D20301, http://dx.doi.org/10.1029/2008JD010966

Stahle, D. W., E. R. Cook, M. K. Cleaveland, M. D. Therrell, D. M. Meko, H. D. Grissino-Mayer, E. Watson, and B. H. Luckman. 2000. Tree-ring data document 16th century megadrought over North America. *Eos, Transactions of the AGU* 81: 121, doi:10.1029/00EO00076.

Stednick, J.D., and R. Jensen. 2007. Effects of Pine Beetle Infestations on Water Yield and Water Quality at the Watershed Scale in Northern Colorado. Report as of FY2007 for 2007CO153B, Colorado Water Resources Research Institute.

Stevens, M. B., J. F. González-Rouco, and H. Beltrami. 2008. North American climate of the last millennium: Underground temperatures and model comparison. *Journal of Geophysical Research* 113: F01008, doi: 10.1029/2006JF000705.

Stevenson, S.L. 2012. Significant changes to ENSO strength and impacts in the twenty-first century: Results from CMIP5. *Geophysical Research Letters* 39: L17703, doi:10.1029/2012GL052759.

Stott, P. A., N. P. Gillett, G. C. Hegerl, D. Karoly, D. Stone, X. Zhang, and F. Zwiers. 2010. Detection and attribution of climate change: a regional perspective. *Wiley Interdisciplinary Reviews: Climate Change* 1: 192–211.

Stewart, I. T., D. R. Cayan, and M. D. Dettinger. 2005. Changes toward earlier streamflow timing across western North America. *Journal of Climate* 18: 1136–1155.

Taylor, R.G., B. Scanlon, P. Döll, M. Rodell, R. van Beek, Y. Wada, L. Longuevergne, et al. 2012. Ground water and climate change. *Nature Climate Change*, http://dx.doi.org/10.1038/nclimate1744.

Trenberth, K. E., and J. T. Fasullo. 2013. An apparent hiatus in global warming? *Earth's Future*, doi: 10.002/2013EF000165.

Vano, J. A., T. Das, and D. P. Lettenmaier. 2012. Hydrologic sensitivities of Colorado River runoff to changes in precipitation and temperature. *Journal of Hydrometeorology* 13: 932–949.

Vano, J. A. and D. P. Lettenmaier. 2014. A sensitivity-based approach to evaluating future changes in Colorado River discharge. *Climatic Change* 122(4): 621-634. doi: 10.1007/s10584-013-1023-x.

Vano, J. A., B. Udall, D. R. Cayan, J. T. Overpeck, L. D. Brekke, T. Das, H. C. Hartmann, H. G. Hidalgo, M. Hoerling, G. J. McCabe, K. Morino, R. S. Webb, K. Werner, and D. P. Lettenmaier. 2014. Understanding uncertainties in future Colorado River streamflow. *Bulletin of the American Meteorological Society* 95: 59–78. doi: http://dx.doi.org/10.1175/BAMS-D-12-00228.1

Villarini, G., F. Serinaldi, J. A. Smith, and W. F. Krajewski. 2009. On the stationarity of annual flood peaks in the continental U.S. during the 20th century. *Water Resources Research* 45: W08417, doi:10.1029/2008WR007645.

Vogel, J. M., and J. B. Smith. 2010. Climate change vulnerbaility assessments: A review of water utility practices. US EPA Report 800-R-10-001. Prepared by Stratus Consulting and Abt Associates under EPA Contract EP-C-07-023, WA 2-13, August 2010. Available online at: http://water.epa.gov/scitech/climatechange/upload/Climate-Change-Vulnerability-Assessments-Sept-2010.pdf.

Vogel, J. M., V. Zoltay, J. B. Smith, and D. Kemp. 2011. Climate change vulnerability assessments: Four case studies of water utility practices. US EPA Report 600/R-10/077A. Prepared by Stratus Consulting and Abt Associates under EPA Contract EP-C-07-023, WA 2-13, March 2011.

Vogel, J., E. Gordon, J. Brislawn, J. Barsugli, E. LeDolce, D. Mills, J. Smith, G. Aggett, and B. Harding. 2012. Boulder County Climate Change Preparedness Plan. Prepared for Boulder County Commissioners' Sustainability Office. Available online at: http://www.bouldercounty.org/doc/sustainability/ccpp.pdf

Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, et al. 2014a. Ch. 2: Our Changing Climate. Climate Change Impacts in the United States: The Third National Climate Assessment, J. M. Melillo, T. C. Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 19-67, doi:10.7930/J0KW5CXT.

Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, et al. 2014b. Appendix 4: Frequently Asked Questions. Climate Change Impacts in the United States: The Third National Climate Assessment, J. M. Melillo, T. C. Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 790–820, doi:10.7930/J0G15XS3.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam. 2006. Warming and earlier spring increases western U.S. forest wildfire activity. *Science* 313: 940–943.

Wi, S., F. Dominguez, M. Durcik, J. Valdes, H. Diaz, and C. L. Castro. 2012. Climate change projections of snowfall in the Colorado River Basin using dynamical downscaling. *Water Resources Research* 48: W05504.

Wigley, T. M. L. 2004. Input needs for downscaling of climate data. Consultant Discussion Paper, California Energy Commission, Sacramento, CA. 36 pp. Available online at http://www.energy .ca.gov/reports/2004-04-22_500-04-027.PDF.

Wilby, R.L., and I. Harris. 2006. A framework for assessing uncertainties in climate change impacts: Low-flow scenarios for the River Thames, UK. *Water Resources Research* 42: W02419, doi:10.1029/2005WR004065.

Wilby, R. L. and T. M. L. Wigley. 1997. Downscaling general circulation model output: a review of methods and limitations. *Progress in Physical Geography* 21: 530-548.

Wolter, K. E., and D. Allured. 2007. New climate divisions for monitoring and predicting climate in the U.S. *Intermountain West Climate Summary* 3(4).

Wolter, K., and J. Lukas. 2010. ENSO and Intermountain West Water Supply: A Review of WY 2010 and Outlook for WY 2011. *Intermountain West Climate Summary* 6(6).

Wood, A. W., L. R. Leung, V. Sridhar, and D. P. Lettenmaier. 2004. Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs. *Climatic Change* 62: 189–216.

Woodbury, M., M. Baldo, D. Yates, and L. Kaatz. 2012. Joint Front Range Climate Change Vulnerability Study. Denver, Water Research Foundation.

Woodhouse, C. A., and J. J. Lukas. 2006. Multi-century tree-ring reconstructions of Colorado streamflow for water resource planning. *Climatic Change* 78: 293–315.

Woodhouse, C. A., D. M. Meko, G. M. MacDonald, D. W. Stahle, and E. R. Cook. 2010. A 1,200-year perspective of 21st century drought in southwestern North America. *Proceedings of the National Academy of Sciences* 107: 21283–21288, doi:10.1073/pnas.0911197107.

Woodhouse, C.A. 2003. A 431-year reconstruction of western Colorado snowpack from tree rings. *Journal of Climate* 16: 1551–1561.

Woodhouse, C.A., and P. M. Brown. 2001. Tree-ring evidence for Great Plains drought. *Tree-Ring Research* 57: 89–103.

Yin, J. H. 2005. A consistent poleward shift of the storm tracks in simulations of 21st century climate. *Geophysical Research Letters* 32: L18701, doi:10.1029/2005GL023684.

Yue, X., L. J. Mickley, J. A. Logan, J. O. Kaplan. 2013. Ensemble projections of wildfire activity and carbonaceous aerosol concentrations over the western United States in the mid-21st century. *Atmospheric Environment* 77: 767–780, http://dx.doi.org/10.1016/j.atmosenv.2013.06.003

Glossary

Aerosols

Airborne solid or liquid particles, with a typical size between 0.01 and 10 microns (thousandth of a millimeter), that remain in the atmosphere for hours to years. Aerosols may be of either natural or anthropogenic origin. Aerosols may influence directly through scattering and absorbing radiation, or indirectly through acting as cloud condensation nuclei or modifying the properties of clouds.

Annual average temperature

The average of all daily high and low temperatures over the course of a calendar year.

Anthropogenic

Resulting from or produced by human actions.

Attribution

Climate varies continually on all time scales. Detection of climate change is the process of demonstrating that climate has changed in some defined statistical sense, without providing a reason for that change. Attribution is the process of establishing the most likely causes for the detected change with some defined level of confidence.

Climate

Climate is first defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The typical period for averaging these variables is 30 years. The most relevant variables are temperature, precipitation, humidity, atmospheric pressure and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.

Climate Divisions

Colorado has five NOAA National Climatic Data Center (NCDC) official climate divisions, which group climate data into regions by river basins, but these divisions are not necessarily representative of the complex regional climates in the state. A new set of climate divisions has been developed (Wolter and Allured 2007). These new divisions are based on groups of observing stations that vary in a similar manner for year to year, and are thought to reflect similar regional climate processes.

Climate variability

Climate variability refers to variations in the mean state and other statistics (such as standard deviations, statistics of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).

Downscaling

Downscaling is a method that derives local- to regional-scale (10 to 100 km) information from larger-scale models or data analyses. There are two general approaches: dynamical downscaling and statistical downscaling. The dynamical methods typically uses the output of regional climate models which are driven by global models at the boundary of the regional model's domain. The statistical methods are based on statistical relationships that link the large-scale atmospheric variables with local/regional climate variables. In all cases, the quality of the downscaled product depends heavily on the quality of the driving model.

El Niño-Southern Oscillation (ENSO)

The term El Niño was initially used to describe a warm-water current that periodically flows along the coast of Ecuador and Perú, disrupting the local fishery. This oceanic event is associated with a fluctuation of a global-scale tropical and subtropical surface pressure pattern called the Southern Oscillation. This atmosphere-ocean phenomenon, with characteristic time scales of two to about seven years, is collectively known as the El Niño-Southern Oscillation (ENSO). During an ENSO event, the prevailing trade winds weaken, reducing upwelling and altering ocean currents such that the sea surface temperatures warm, further weakening the trade winds. This event has a great impact on the wind, sea surface temperature and precipitation patterns in the tropical Pacific. It has climatic effects on the western U.S. by influencing the position of the jet stream and storm tracks. The cold phase of ENSO is called La Niña.

Emissions scenario

A plausible representation of the future emissions of substances that affect the radiative properties of the atmosphere (e.g., greenhouse gases, aerosols), based on a coherent set of assumptions about driving forces, such as demographic and socioeconomic development, and technological change, and their key relationships. Concentration scenarios, derived from emission scenarios, are then used as input to a climate model to drive climate projections.

Evapotranspiration

The combined process of water loss (evaporation) from the soil surface and water loss (transpiration) from vegetation. Often abbreviated as ET.

Extreme

An event that is rare at a particular place and time of year, such as a heat wave, cold wave, or heavy precipitation event. Definitions of rare vary, but an extreme weather event would normally be rarer than the 10th or 90th percentile of the observed range for that type of event. By definition, the characteristics of what is called extreme weather may vary from place to place. Single extreme events cannot be simply and directly attributed to anthropogenic climate change, as there is always a finite chance the event in question might have occurred naturally.

Forcing

The climate system can be driven, or "forced" by factors within and external to the system. Processes within the system include those related to the atmosphere, ice sheets, the oceans, the land surface, and the biosphere. Volcanic eruptions, solar variations and anthropogenic changes in the composition of the atmosphere and land use change are external forcings.

Global Climate Model

Global climate models (often abbreviated GCMs) are complex computer-based representations of the Earth's climate based on fundamental scientific principles. Two types of climate models are commonly used for long-term projections, atmosphere-ocean general circulation models (AOGCMs), and the newer and more comprehensive Earth System Models (ESMs). AOGCMs simulate the atmosphere, ocean, sea-ice, and the land-surface energy and water balance, and the interactions among these components. ESMs include additional model components that simulate the sources and sinks of carbon dioxide, methane and other atmospheric trace gases along with the detailed evolution of these chemicals in the atmosphere.

Greenhouse effect

Greenhouse gases in the lower atmosphere effectively absorb and re-emit longwave (infrared) radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. The re-emitted radiation (i.e., heat) is emitted to all sides, including downward to the Earth's surface. Thus, greenhouse gases trap heat within the surface-atmosphere system, causing the earth's surface and lower atmosphere to be about 57°F warmer than without the action of the greenhouse gases. This is called the (natural) greenhouse effect. An increase in the concentration of greenhouse gases leads to the greater absorption and re-emission of infrared radiation, and so more heat is trapped. This radiative forcing leads to an enhancement of the greenhouse effect and even warmer temperatures at the earth's surface and in the lower atmosphere.

Greenhouse gases

Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of longwave (infrared) radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere. Moreover, there are a number of entirely human-made greenhouse gases in the atmosphere, such as the halocarbons (HFCs and PFCs) and other chlorine- and bromine-containing substances.

Hydrologic drought

Hydrologic drought refers to the condition of below-normal streamflow, lake and reservoir, and groundwater levels.

IPCC

The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 by World Meteorological Organization (WMO) and United Nations Environmental Programme (UNEP) to provide assessments of the state of knowledge on climate change based on peer-reviewed and published scientific/technical literature on regular time intervals. The IPCC Fifth Assessment Report (AR5) was released in 2013 and 2014.

Mean

The arithmetic average of a series of values. The mean of the series (5, 6, 8, 12, 19) would be 50 divided by 5, or 10.

Median

The middle value of a series of values. The median of the series (5, 6, 8, 12, 19) would be 8. Like the mean, the median captures the "central tendency" of the range, but is less influenced than the mean by outlying values, such as 19 in the example above. The median is also the same as the 50th percentile of a series of values.

Megadrought

A megadrought is a sustained and widespread drought that lasts at least decade or more.

Model bias

The systematic error of a climate model assessed by comparing the temperature and precipitation (and other variables) at the model grid with a gridded observational dataset over a given period.

Model grid

The spatial scale represented in a climate model.

North American Monsoon

The North American Monsoon (NAM), is experienced as a pronounced increase in rainfall from July to mid-September over large areas of the southwestern United States and northwestern Mexico. Geographically, the NAM precipitation region is centered over northern Mexico, and the regime extends northward into Arizona, New Mexico, and Colorado.

Pacific Decadal Oscillation

The Pacific Decadal Oscillation (PDO) is a pattern of ocean variability in the North Pacific that is similar to ENSO in some respects, but has a much longer cycle (20–50 year). Specifically, it is defined as the standardized difference between sea surface temperatures (SSTs) in the north-central Pacific and Gulf of Alaska.

Paleoclimate

Climate during periods prior to the development of measuring instruments, for which only proxy climate records such as tree rings, ice cores, and lake sediments are available. In Colorado, paleoclimate refers to the period ending in the mid- or late 1800s.

Palmer Drought Severity Index

An index formulated by Palmer (1965) that compares the soil moisture balance in an area during a specified period with the normal amount expected during that same period. The PDSI is based on a procedure of hydrologic or water balance account by which excesses or deficiencies in moisture are determined in relation to average climatic values. The calculation of the index is based on monthly temperature and precipitation to represent potential and actual evapotranspiration, infiltration of water into a given soil zone, and runoff.

Percentile

A measure indicating the value below which a given percentage of findings occur, out of a group of findings. For example, the 10th percentile is the value below which only 10% of a group of findings occur (and so 90% of the findings are greater than that value).

PRISM

Parameter-elevation Regressions on Independent Slopes Model.

Projection

A simulation of the response of the climate system to emission or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios; usually refers to simulations by climate models. Climate projections are distinguished from climate predictions in order to emphasize that climate projections depend upon the emissions (or radiative forcing) scenario used, which are based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized and are therefore subject to substantial uncertainty.

Regional climate models (RCMs)

These models are similar to global climate models but run at finer scales over smaller spatial domains. They use the coarser global climate model output to drive the conditions at the boundaries of their domain and then simulate wind, temperature, clouds, evapotranspiration, and other variables on the finer grid with their domain.

Representative Concentration Pathways (RCPs)

See Emissions scenarios.

SNOTEL

SNOwpack TELemetry. A West-wide system for obtaining snow water equivalent, precipitation, air temperature, and other hydrologic measurements from remote data sites via radio transmission.

Snow-water equivalent (SWE)

The amount of water contained within the snowpack. It can be thought of as the depth of water that would theoretically result if you melted the entire snowpack instantaneously.

Streamflow

Water flow within a river channel, typically expressed in cubic feet per second for instantaneous streamflow, or in acre-feet for annual streamflow. Synonymous with discharge.

Water Year

The 12-month period from October 1 through September 30. The water year is designated by the calendar year in which it ends and which includes 9 of the 12 months. Thus, the 12-month period ending September 30, 2014, is the 2014 water year.

Acronym List

AOGCM
Atmospheric-Oceanic General Circulation Model

AR4
Fourth Assessment Report of the IPCC (2007)

AR5
Fifth Assessment Report of the IPCC (2013-14)

BCSD
Bias-Correction Spatial Disaggregation [downscaling method]

CMIP3
Coupled Model Intercomparison Program – Phase 3

CMIP5
Coupled Model Intercomparison Program – Phase 5

COOP
National Weather Service Cooperative Observer Network

ENSO
El Niño-Southern Oscillation

GCM
Global Climate Model (also: General Circulation Model)

GHG
Greenhouse Gas

IPCC
Intergovernmental Panel on Climate Change

NARCCAP
North American Regional Climate Change Assessment Project

NCA
National Climate Assessment

NCAR
National Center for Atmospheric Research

NCDC
National Climatic Data Center

NOAA
National Oceanic and Atmospheric Administration

NRCS
Natural Resource Conservation Service

NWS
National Weather Service

PDSI
Palmer Drought Severity Index

PRISM
Parameter-elevation Regressions on Independent Slopes Model

RCM
Regional Climate Model

RCP
Representative Concentration Pathway

SAP
Synthesis and Assessment Product (from USGCRP)

SNOTEL
Snowpack Telemetry

SRES
Special Report on Emissions Scenarios

SWE
Snow Water Equivalent

USGCRP
U.S. Global Change Research Program

VIC
Variable Infiltration Capacity [hydrology model]

WEAP
Water Evaluation And Planning system [hydrology model]

WGI
Working Group I of the IPCC

WWA
Western Water Assessment

Western Water Assessment

CIRES

University of Colorado
Boulder

CO DNR
COLORADO
Colorado Water
Conservation Board
Department of Natural Resources