Climate Change in Colorado

A report for the Colorado Water Conservation Board

Third Edition | 2023

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Reference map

The eleven alternate climate divisions, with names assigned by the authors based on how they are often referred to in relation to climatology or local convention.

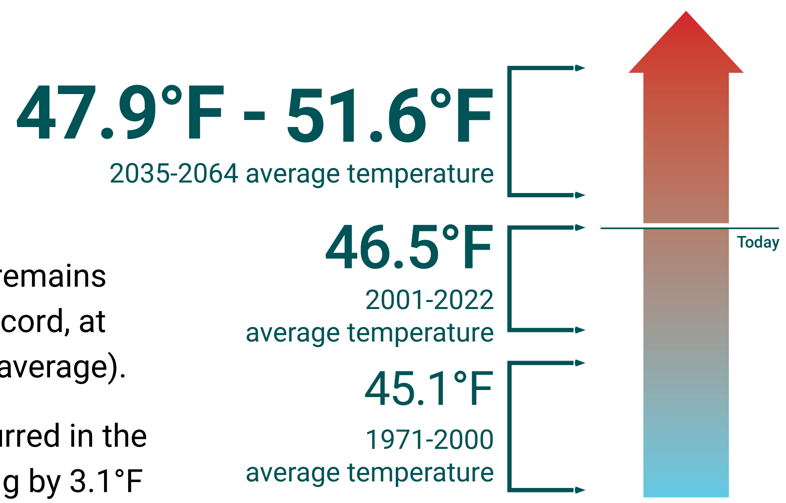
For further information, visit the Colorado climate divisions sidebar in Chapter 2.

Visit our website for interactive charts and data

Executive Summary

Key Messages for Chapter 2

Temperature



- Statewide annual average temperatures warmed by 2.3°F from 1980 to 2022.
- Only one year in the 21st century has been cooler than the 1971-2000 average. 2012 remains the state's warmest year in the 128-year record, at 48.3°F (3.2°F warmer than the 1971-2000 average).
- The greatest amount of warming has occurred in the fall, with statewide temperatures increasing by 3.1°F from 1980-2022.
- Southwestern and South-central Colorado have experienced the largest magnitude of warming.
- The observed warming trend in Colorado is strongly linked to the overall human influence on climate and recent global warming. The observed warming over the last 20 years is comparable to what was projected by earlier climate models run in the 2000s.
- Further and significant warming is expected in all parts of Colorado, in all seasons, over the next several decades.
- By 2050 (the 2035-2064 period average), Colorado statewide annual temperatures are projected to warm by +2.5°F to +5.5°F compared to a 1971-2000 baseline, and +1.0°F to +4.0°F compared to today, under a medium-low emissions scenario (RCP4.5).
- By 2070 (the 2055-2084 period average), Colorado statewide annual temperatures are projected to warm by +3.0°F to +6.5°F compared to the late 20th century, and +1.5°F to +5.0°F compared to today, under RCP4.5.
- By 2050, the average year is likely to be as warm as the very warmest years on record through 2022. By 2070, the average year is likely to be warmer than the very warmest years through 2022.
- Summer and fall are projected to warm slightly more than winter and spring.

Climate variable/event	Recent trend	Projected future change	Confidence in change
Average Temperature	Warmer	Warmer	Very High
Annual Precipitation	Lower	Uncertain	Low

Table 2.1 Summary of the observed and projected changes in annual average temperature and annual precipitation for Colorado, as detailed in the following sections. "Confidence in change" reflects the judgment of the authors, based on both the assessments in higher-level climate reports (NCA, IPCC) as well as relevant literature and model output for Colorado.

Precipitation

- Colorado has observed persistent dry conditions in the 21st century. According to water year precipitation accumulations, October 1 – September 30, four of the five driest years have occurred since 2000.
- Drying trends have been observed over the majority of the state during the spring, summer, and fall seasons.
- Northwest Colorado summer precipitation has decreased 20% since the 1951-2000 period.
- Southwest Colorado spring precipitation has decreased 22% since the 1951-2000 period.
- Precipitation is slightly more favorable over the northern mountains during a La Niña winter. For most regions and the remaining seasons, wetter conditions are slightly enhanced during an El Niño.
- The direction of future change in annual statewide precipitation for Colorado is much less clear than for temperature. The climate model projections for 2050 range from -7% to +7% compared to the late 20th century average, under a medium-low (RCP4.5) emissions scenario.
- The model projections for precipitation change by 2070 are very similar to those for 2050.
- Most climate models project an increase in winter (Dec-Feb) statewide precipitation; the model consensus is weaker for the other seasons. The models do suggest enhanced potential for large decreases (-10% to –25%) in summer precipitation.

Executive Summary

Key Messages for Chapter 3

Climate variable/event	Recent trend	Projected future change	Confidence in change
Spring Snowpack	**Lower**	Lower	Medium ◒
Runoff timing	**Earlier**	**Earlier**	**High** ●
Annual Streamflow	**Lower**	Lower	Medium ◒
Evaporative demand	**Higher**	**Higher**	**High** ●
Summer soil moisture	**Lower**	**Lower**	**High** ●

Table 3.1 Summary of the observed and projected changes in hydrology and water resources for Colorado, as detailed in the following sections. "Confidence in change" reflects the judgment of the authors, based on both the assessments in higher-level climate reports (NCA, IPCC), as well as relevant literature and model output for Colorado. In general, there is higher confidence in the changes in variables that are driven mainly by warming and less by the more uncertain change in annual precipitation.

Snowpack

- April 1 SWE (snow-water equivalent) during the 21st century has been 3% to 23% lower than the 1951-2000 average across Colorado's major river basins.
- Future warming will lead to further reductions in Colorado's spring snowpack. Most climate model projections of April 1 SWE in the state's major river basins show reductions of -5% to -30% for 2050 compared to 1971-2000; the individual projections that show increasing snowpack assume large increases in fall-winter-spring precipitation.
- The seasonal peak of the snowpack is projected to shift earlier by a few days to several weeks by 2050, depending on the amount of warming and the precipitation change. This warming-driven shift could be accelerated by increases in dust-on-snow events.

5-30%
Reduction of
April 1 SWE by 2050

Streamflow

- Since 2000, annual streamflow in all of Colorado major river basins has been 3% to 19% lower than the 1951-2000 average.
- Modeling studies have attributed up to half of the observed decrease in streamflow since 1980 in Colorado river basins to warming temperatures.
- Future warming will act to reduce annual streamflows. Most climate model projections of annual streamflows in the state's major river basins for 2050 show reductions of 5% to 30% compared to 1971-2000.
- Higher future streamflow would require large overall increases in precipitation to offset the effects of warming, an outcome that appears unlikely.
- Summer and fall streamflows are projected to decline significantly by 2050 as the seasonal runoff peak shifts earlier, by 1-4 weeks, due to warming.

Soil Moisture

- Modeled soil moisture based on meteorological observations suggests overall declines in high-elevation soil moisture from 1980-2022.
- Future warming will lead to declines in summer (June-August) soil moisture throughout the state. Spring (March-May) soil moisture will likely increase at higher elevations as snowmelt shifts earlier.
- Rapid depletion of soil moisture under warm conditions exacerbates warming. When summer sunshine hits a landscape with dry soil a greater fraction of solar energy directly heats the surface, leading to even warmer conditions.

Evapotranspiration

- The evaporative demand ("thirst") of the atmosphere—as measured by potential evapotranspiration (PET) and Reference ET—has increased across Colorado since 1980, mainly due to the warming trend. Statewide, growing-season PET increased by 5% from 1980-2022.
- Additional future warming will drive greater evaporative demand; all climate model projections show statewide annual PET increasing by 8-17% by 2050, compared to 1971-2000.

Executive Summary

Key Messages for Chapter 4

Climate variable/event	Recent trend	Projected future change	Confidence in change
Heat waves	**More frequent/intense**	**More frequent/intense**	**Very High**
Cold waves	**Fewer**	**Fewer**	Medium
Droughts	**More frequent/intense**	**More frequent/intense**	**High**
Wildfires	**More and larger**	**More and larger**	**High**
Extreme precipitation	**More intense**	**More frequent/intense**	Medium
Flooding	Mixed	**Higher**	Medium
Windstorms	Uncertain	Uncertain	Low
Severe thunderstorms	Uncertain	More frequent?	Low
Hail	Uncertain	More large hail?	Low
Tornadoes	Uncertain	Uncertain	Low
Winter storms	Uncertain	Larger storms?	Low
Dust on snow events	**Greater dust levels**	**Greater dust levels**	Medium

Table 4.1: Summary of the observed and projected changes in climate extremes and hazards for Colorado, as detailed in the following sections.

Heat waves and cold waves

- Hot days and heat waves have become more common, and the number cold nights and cold waves has decreased across Colorado in recent decades, but the changes have not been equal. There have been significant increases in extreme heat across most of the state, whereas the decrease in extreme cold has been more modest.
- Projected future changes are similarly asymmetric: Heat waves are projected to increase in frequency by as much as ten-fold by the middle of the 21st century, whereas the frequency of cold waves is projected to decrease by less than half.

Wildfire

- Since 2000, Colorado has experienced a large increase in the number of large wildfires and in the annual area burned by all wildfires; on average, fires have burned at higher elevations and with higher intensity than in the late 20th century . While several factors have contributed to these trends, warming temperatures are a major driver.
- Future warming is expected to lead to further increases in the occurrence of large wildfires and in annual area burned by all fires, especially in forest ecosystems, according to multiple studies. A greater percentage of fires will occur in the fall, winter, and spring than at present.

Heavy and extreme rainfall

- There are some indications of recent increasing trends in heavy and extreme rainfall in Colorado, but these are not consistent across all indicators and time periods, unlike in other regions of the U.S.
- Atmospheric moisture (precipitable water; PW) has generally increased over Colorado, but not by as much as one would predict from the warming atmosphere alone.
- Future warming, by increasing the moisture-holding capacity of the atmosphere, will make heavy and extreme rainfall more likely unless counterbalanced by declining trends in other storm "ingredients". Climate-model projections for Colorado show overall increases in the magnitudes of heavy and extreme rainfall events.

Drought

- Warming temperatures have increased the severity of 21st century droughts in Colorado.
- Regardless of changes in precipitation, it is likely that warmer temperatures will contribute to more frequent and severe droughts. Warmer temperatures will also decrease the benefit of wetter years.

Floods

- Gaged streamflow records show no widespread, consistent trends in the magnitude of flood events in Colorado of different frequencies (e.g., 1-year, 20-year, 50-year, 100-year).
- The expectation that heavy and extreme rainfall events will increase in Colorado implies increases in future flood risk as well, but there are many factors influencing how rainfall is translated into runoff. Increased exposure to flooding through floodplain development may be more important than climate-driven changes in risk.

Thunderstorm hazards

- Because of the relatively short data record for thunderstorm hazards and the influences of changing observation systems, the sign and magnitude of any long-term changes is unclear.
- Some studies have suggested increases in the average size of hail in a warmer climate, with smaller hail becoming less frequent but larger hail more frequent. Overall, however, there remain large uncertainties regarding future changes, as data limitations and the infrequent and localized nature of these storms makes them challenging to study in the context of a changing climate.

Executive Summary: Key Messages for Chapter 4

Non-convective windstorms

- Colorado is prone to intense winds in the mountains and from downslope windstorms along the Front Range. These windstorms can cause considerable damage, and can exacerbate wildfires, such as in the 2021 Marshall Fire. Long-term changes in extreme winds have not been extensively studied, and potential future changes are highly uncertain.

Winter storms

- Despite warming temperatures in the winter, there are no detectable trends in winter severity across the Colorado Front Range and Eastern Plains. There are also minimal trends in large snowfall events.
- Several notable and high impact winter storm events have occurred over eastern Colorado in the last decade, including extreme cold, high winds, strong cold fronts, and large accumulations of snow.
- Future trends in winter storms remain highly uncertain, but the risk of high-impact winter events is likely to remain.

Dust-on-snow

- Dust-on-snow events have emerged as a concern since 2000 due to better understanding of its hydrologic effects, as well as an overall increase in the occurrence of dust-on-snow. Dust-on-snow causes earlier melt and runoff and may reduce annual runoff.
- It is likely that in a future warmer climate, drier conditions in the dust-source regions will allow for greater dust emission and thus deposition on snowpacks. Dust-on-snow and warming will both drive earlier snowmelt and runoff.

Chapter 1 | Introduction

About this report

This is the third edition of Climate Change in Colorado. In 2008, the Western Water Assessment program at the University of Colorado Boulder, in collaboration with the Colorado Water Conservation Board (CWCB), produced the first edition, Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation ((*Ray et al. 2008*)). 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 2008 Report was notable for being one of the first state-level climate change assessments; today, similar assessments have been conducted in at least 25 states.

Several years later, the CWCB partnered with the Western Water Assessment to undertake a thorough update and revision of the 2008 Report, the result of which was also called Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation ((*Lukas et al. 2014)*). This update again covered the observed trends and future projections of hydroclimate variables—including temperature, precipitation, snowmelt, and runoff—that determine both water supply and demand for the state. The 2014 report also had a broader scope and more detail in many areas than the 2008 report, doubling its length compared to its predecessor.

The main findings about recent climate trends and projected future climate change for Colorado were consistent between the two reports: Colorado's climate has become much warmer and further warming is expected; precipitation has been highly variable, and its future direction was uncertain; significant future changes to the water cycle are likely due to the effects of warming alone, including decreases in snowpack and runoff.

The information in the 2008 and 2014 reports has been used as guidance for many statewide and local water planning and climate planning documents and processes, including the Colorado River Water Availability Study (*CRWAS;* (*CWCB 2012*) and (*CWCB 2019a*)), Colorado Water Plan (*CWCB 2023*), Colorado Climate Plan (*State of Colorado 2018*), and the Colorado Drought Mitigation and Response Plan (*CWCB 2018*). The 2008 and 2014 reports have each been cited in about 100 peer-reviewed studies, indicating that they have been highly regarded and relied upon in the scientific community as well.

For this third edition of Climate Change in Colorado, we cover a similar scope, though with overall less detail compared to the 2014 report. The core function of the report is still to describe recent trends in Colorado's climate and hydrology and interpret the model-based projections of future climate and hydrology. Compared to its predecessors, this report has greater coverage of climate extremes and hazards, including heat waves, droughts, wildfires, and extreme precipitation and floods. The overall societal impacts of climate change will be driven by both changes in these extreme events and by pervasive changes in the average climate.

While this report provides a scientific basis to prompt further studies of water resources impacts and support planning and adaptation efforts, the assessment of specific local sensitivities and vulnerabilities is beyond the scope of this report. Several other resources, including the Colorado Water Plan (*CWCB 2023*), the Analysis and Technical Update to the Colorado Water Plan (*CWCB 2019b*) and the Colorado River Water Availability Study (*CRWAS*), Phase II (*CWCB 2019*) provide more detailed assessments of climate change impacts on water resources at the basin scale and smaller. The Colorado Climate Change Vulnerability Study (*Gordon and Ojima 2015*) focused on vulnerabilities due to climate change across multiple sectors, including water. A forthcoming compendium study to this report will further describe climate impacts and vulnerabilities based on hazards identified here.

Organization of the report

The key findings of this report are summarized at the beginning of each chapter and in the Executive Summary that precedes Chapter 1.

Chapter 2 provides analysis of the observed and projected changes in temperature and precipitation. Chapter 3 provides analysis of the observed and projected changes in Colorado's water, including snowpack, streamflow volume and timing, soil moisture, and evapotranspiration. Chapter 4 assesses the observed and projected changes in different climate hazards and extremes. Appendix A provides supplemental information on the observational climate dataset and the climate model projections used in the report.

The Global Context for Colorado's Climate

While Colorado's climate has characteristics specific to our state's particular geography, it plays out within a much broader arena: the global climate system. Since the 2014 report, the evidence that human influences have impacted the global climate system has only strengthened. The latest report from the Intergovernmental Panel on Climate Change (*IPCC 2021*) states that

> *It is unequivocal that human influence has warmed the atmosphere, ocean, and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere [snow and ice] and biosphere have occurred. (Summary for Policymakers, p. 4)*

The observed globally averaged warming of the earth's surface (land and ocean) as of early 2023 has reached 1.4°F (0.8°C) since 1980, and a total of 2.0°F (1.1°C) relative to the 1850-1900 period. It is estimated that the total warming influence of human drivers is responsible for all the globally averaged warming relative to 1850-1900, while solar and volcanic drivers and natural climate variability have had little net effect over this period (*IPCC 2021*). The most important human drivers of warming are the increases in greenhouse gases, principally carbon dioxide (CO2) and methane (CH4), which have acted to trap additional heat in the lower atmosphere and at the earth's surface compared to pre-industrial (<1750) conditions. As of 2022, the annually averaged level of CO2 in the atmosphere was at 420 parts per million (ppm), higher than at any time in at least 2 million years (*IPCC 2021*). The anthropogenic (human-caused) increases in CO2 (+50%) and methane (+150%) since 1750 greatly exceed the natural changes in those two gases that occurred over thousands of years between past glacial and interglacial periods (*IPCC 2021*).

The rapid global warming of the past several decades, a rate unprecedented in at least 2000 years, is associated with pervasive changes to the earth system (*IPCC 2021*), including:

- Global retreat of glaciers, decreases in Arctic sea ice area and volume, mass loss from the Greenland and Antarctic ice sheets, and decline in Northern Hemisphere snow cover.
- An acceleration in the rate of global sea level rise since the 1970s due to both thermal expansion of ocean water and increasing melt from glaciers and ice sheets.

- Increases in global water vapor levels and global annual precipitation as evaporation has increased and the water cycle has intensified.
- Widespread increases in the frequency and/or severity of extremes and natural hazards such as heat waves, heavy precipitation, droughts, and tropical cyclones.
- Overall poleward and upslope shifts in the distributions of many plant and animal species as their habitable climate zones shift due to warming.

These global climate trends and changes have shaped the recent evolution of Colorado's climate and will continue to do so. Like nearly every other part of the globe, Colorado has warmed substantially over the past century, particularly since the 1980s, as described in Chapter 2. Figure 1.1 shows that the overall trajectory of Colorado's observed temperatures since 1900 has closely followed those of U.S. and global temperatures. Like other land areas, Colorado has warmed more than the global average--which mainly reflects the slower-warming oceans that cover 71% of the Earth's surface. This relative difference between Colorado's warming and the globally averaged warming is expected in future warming as well.

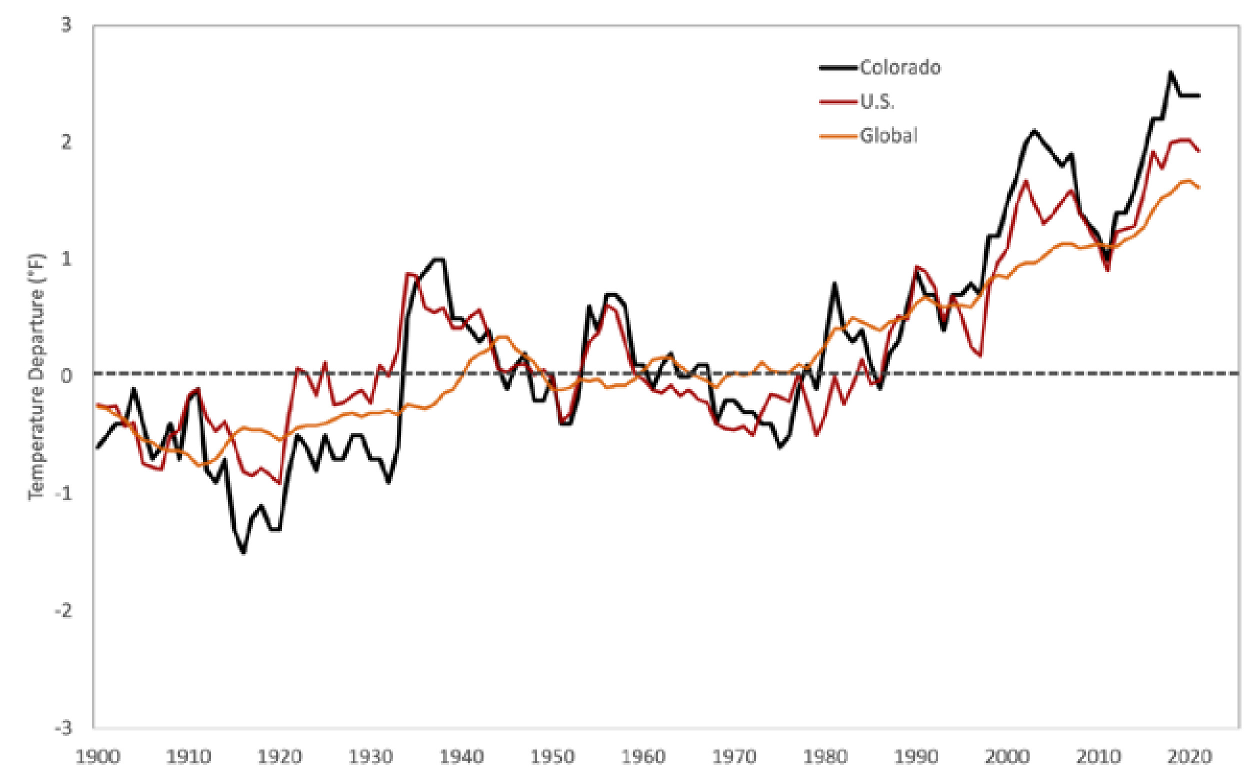


Figure 1.1: Observed 5-year running mean surface temperature departure from a 20th century baseline for Colorado (red), the U.S. (orange), and the globe (yellow). Data from NOAA National Centers for Environmental Information.

Chapter 2 | Changes in Colorado's Climate

KEY MESSAGES

Temperature

- Statewide annual average temperatures warmed by 2.3°F from 1980 to 2022.
- Only one year in the 21st century has been cooler than the 1971-2000 average. 2012 remains the state's warmest year in the 128-year record, at 48.3°F (3.2°F warmer than the 1971-2000 average).
- The greatest amount of warming has occurred in the fall, with statewide temperatures increasing by 3.1°F from 1980-2022.
- Southwestern and South-central Colorado have experienced the largest magnitude of warming.
- The observed warming trend in Colorado is strongly linked to the overall human influence on climate and recent global warming. The observed warming over the last 20 years is comparable to what was projected by earlier climate models run in the 2000s.
- Further and significant warming is expected in all parts of Colorado, in all seasons, over the next several decades.
- By 2050 (the 2035-2064 period average), Colorado statewide annual temperatures are projected to warm by +2.5°F to +5.5°F compared to a 1971-2000 baseline, and +1.0°F to +4.0°F compared to today, under a medium-low emissions scenario (RCP4.5).
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- Summer and fall are projected to warm slightly more than winter and spring.

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- Drying trends have been observed over the majority of the state during the spring, summer, and fall seasons.
- Northwest Colorado summer precipitation has decreased 20% since the 1951-2000 period.
- Southwest Colorado spring precipitation has decreased 22% since the 1951-2000 period.
- Precipitation is slightly more favorable over the northern mountains during a La Niña winter. For most regions and the remaining seasons, wetter conditions are slightly enhanced during an El Niño.
- The direction of future change in annual statewide precipitation for Colorado is much less clear than for temperature. The climate model projections for 2050 range from -7% to +7% compared to the late 20th century average, under a medium-low (RCP4.5) emissions scenario.
- The model projections for precipitation change by 2070 are very similar to those for 2050.
- Most climate models project an increase in winter (Dec-Feb) statewide precipitation; the model consensus is weaker for the other seasons. The models do suggest enhanced potential for large decreases (-10% to –25%) in summer precipitation.

2.1 Overview

This chapter assesses recent trends and likely future changes in the basic indicators of Colorado's climate—average temperature (monthly, seasonal, annual), and precipitation (monthly, seasonal, annual)—based on the best available scientific guidance.

Colorado's Average Climate

Colorado's climate reflects its mid-continental location, high elevations, and the complex topography of the mountains, plains, and plateaus. Topographic influences on weather and climate processes result in large variations in climate over short distances. Wind, humidity, temperature, and precipitation patterns are all modulated by sharp changes in elevation and the orientation of mountain ranges and valleys (*Doesken et al. 2003*).

The state's interior location results in frequent sunshine, low humidity, and large variations in daily temperature ranges and annual temperature variability. The distance from large sources of moisture (i.e., Pacific Ocean and Gulf of Mexico) results in lighter precipitation for the lower elevations. High mountain ranges benefit from Pacific moisture moving eastward during the winter months.

Average Temperature

For most parts of the state, on average, January tends to be the coldest month of the year, and July is the warmest (Figure 2.1). Topography plays a role in temperatures – in general, temperatures decrease with elevation. Average high elevation temperatures (over 10,000 feet above sea level [asl]) range from single digits in the winter months to 60s and 70s (°F) in the summer. For lower elevation areas and the plains (elevations around 5,000 ft asl or less), average temperatures dip to the teens in the winter and frequently top the 90s (°F) in the summer. Middle elevations offer warm temperatures in the summer, but rarely into the 90s, with frequent single digit temperatures in the winter. Extremes across the state range from negative temperatures (with winter temperatures observed below -40°F in the high mountain valleys) to triple digits (over 110°F occurring in the lower river valleys of the eastern plains of Colorado).

Average Precipitation

Topography also plays an important role in influencing precipitation processes and patterns. Precipitation typically increases with elevation in all seasons, but especially in winter when nearly all moisture falls as snow. The seasonal cycle of precipitation is highly dependent on location (Figure 2.1). The Eastern Plains are generally wetter during the spring and summer months, with a May peak in northeast Colorado and a July peak in southeast Colorado. The higher mountain areas tend to be wetter during the winter and early spring months, and southwest Colorado's wettest months coincide with the occurrence of the North American Monsoon in August and September. Annual precipitation totals are less than 10 inches in the San Luis Valley, while the high mountain ranges typically receive over 40 inches of liquid precipitation in one year (with amounts observed between 60 and 80 inches in wet years).

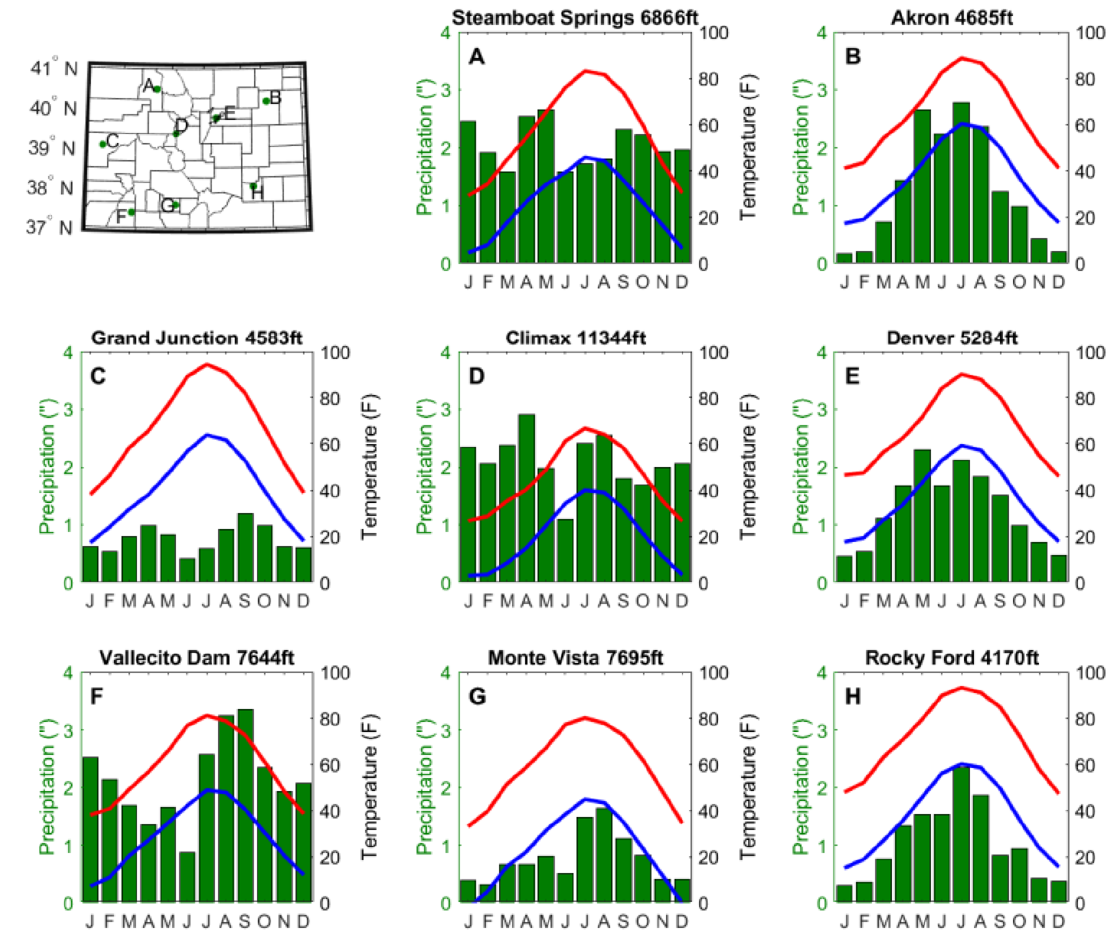

Figure 2.1: 1991-2020 normal monthly precipitation (green bars), daily average maximum (red line) and daily average minimum (blue line) temperatures for eight National Weather Service Cooperative Observer Program (COOP) stations around the state. Precipitation in inches and temperature in degrees Fahrenheit. Locations of the eight stations are labeled on the top left map.

Data

For recent trends and variability in temperature and precipitation, we have relied on NOAA nClimGrid, a gridded dataset based on weather observations from hundreds of sites across Colorado, and corrected for biases from changes in instrumentation, changes in the daily time of observation, moves in station location and other inhomogeneities. An earlier version of nClimGrid was used in the 2014 report. See Appendix A for more information on this dataset and a comparison with a similar dataset.

For likely future changes in temperature and precipitation, as with the previous two reports, we relied on the simulations (projections) from global climate models (GCMs). The 2014 report featured results from the then-latest global archive of GCM projections, known as CMIP5 (Coupled Model Intercomparison Project, Phase 5; see Appendix A for more information about the CMIPs). The 2014 report also compared those results from the previous archive (CMIP3).

In this report, we show results from CMIP5 as well as the most recent archive of GCM projections (CMIP6) that was released in 2020-21. The projections from CMIP6 have not yet been used to generate basin-scale projections of hydrology and water resources (such as in Chapter 3); thus, we have chosen to emphasize CMIP5 projections throughout Chapters 2, 3, and 4 to maintain consistency among the analyses. We also examine the differences between the CMIP5 and CMIP6 projections for Colorado.

Sidebar: Colorado climate divisions

NOAA's official set of climate divisions for the U.S. (*Guttman and Quayle 1996*) splits Colorado into five divisions that correspond to the large river basins in the state (the Arkansas, Platte, Rio Grande, Colorado, and Republican). However, there are limitations of these divisions for climate analysis and monitoring. For example, all of western Colorado is included in a single climate division, even though the climates (and climate variability) of northwest and southwest Colorado have major differences. *Wolter and Allured (2007)* developed a method for alternate divisions based on seasonal variability at long-term stations, and an adaptation of these divisions was used in the 2014 Climate Change in Colorado report. For this report update, we applied the Wolter and Allured method of hierarchical cluster analysis to monthly gridded data from 1950-2021 to establish a set of 11 alternate climate divisions that are used throughout this report (Figure 2.2). These divisions have the advantage of providing information that is more granular than the existing climate divisions, and more representative of available data than county-level calculations. A manuscript fully describing the method for developing these divisions has been submitted to the Journal of Applied and Service Climatology.

Figure 2.2: The eleven alternate climate divisions, with names assigned by the authors based on how they are often referred to in relation to climatology or local convention.

2.2 Temperature

The most fundamental and pervasive effect of anthropogenic (human-caused) climate change is an overall warming of the climate system. This global warming has manifested in nearly all regions of the world in the past several decades.

Observed temperature changes

Colorado statewide temperatures have warmed since systematic instrumental observation records began in the late 19th century (Fig. 2.3). When compared to the 1971-2000 average, only one year in the 21st century had below-average annual temperature. Seven of the top 10 hottest years on record have occurred since 2010. Recent mean temperatures (2001-2022) have averaged 1.4°F warmer than the 1971-2000 average (45.1°F).

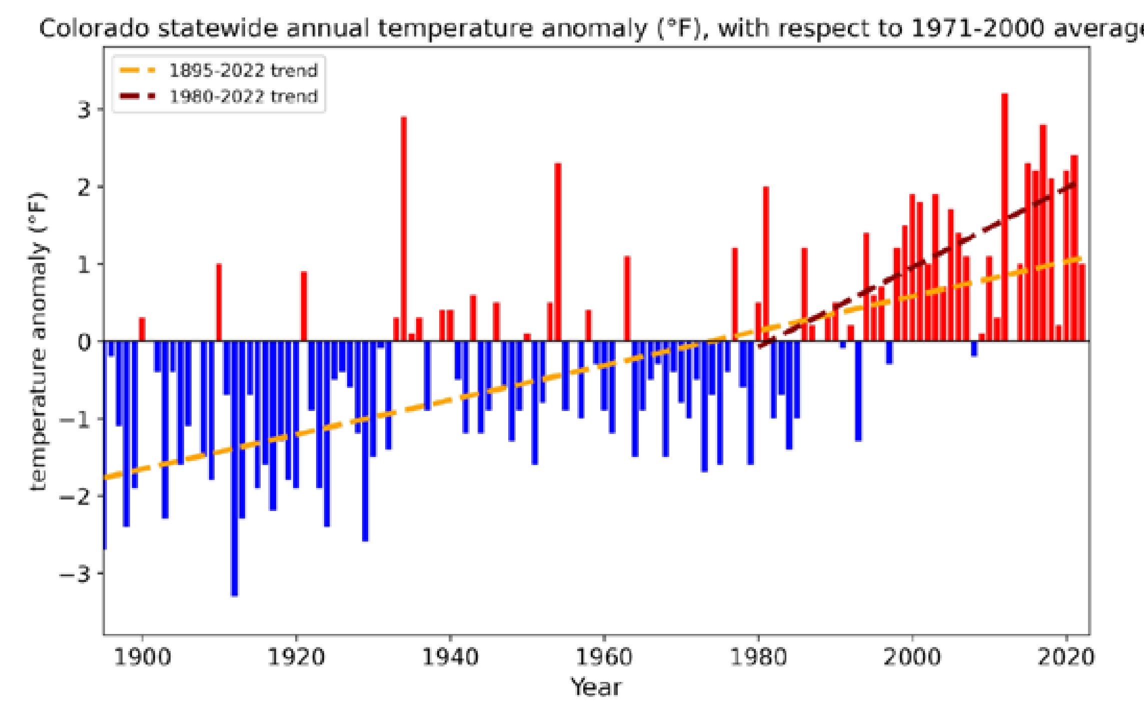

Figure 2.3: Colorado statewide temperature anomaly (°F) with respect to the 1971-2000 average of 45.1°F. The 1895-2022 trend (yellow dashed), and 1980-2022 (red dashed) lines are included.

We analyzed temperature changes by season, both long-term (from 1895-2022) and more recent trends (1980-2022). From 1895-2022, the winter season (Dec-Jan-Feb) shows the greatest warming (Table 2.2). However, since 1980, winter warming has diminished, largely due to recent cooling observed in February. Fall season (Sep-Oct-Nov) temperatures have warmed more than any other season for 1980-2022 (Table 2.2). While all seasons have exhibited increasing trends in both short- and long-term periods, with seasonal changes ranging between +1°F to +3°F for the 1980-2022 period.

Statewide	1895-2022 change	1980-2022 change
Winter	+3.3°F	+1.0°F
Spring	+2.6°F	+1.7°F
Summer	+2.7°F	+2.5°F
Fall	+2.1°F	+3.1°F
Annual	+2.9°F	+2.3°F

Table 2.2: Changes in statewide average annual and seasonal temperature as calculated by the linear trend, 1895-2022 (middle column) and 1980-2022 (right column).

We also analyzed seasonal and annual temperature changes for each of the 11 alternate climate divisions (see sidebar for description of climate divisions). Figure 2.4 shows the seasonal changes in temperature for each division for the recent period of 1980 to 2022. Most notably, the greatest warming has occurred in the fall (Fig. 2.4d) for each climate division. Summer warming has also been significant (Fig. 2.4c), with larger changes in the western climate divisions. The south and the west have observed more warming in the spring (Fig. 2.4b). The Northern Front Range (including the majority of the state's population) has experienced little to no warming in spring, while the Central Mountains and South Park area experienced little to no warming during the winter (Fig. 2.4a). Annually, the greatest warming has been observed over the Southwest and San Luis Valley climate regions.

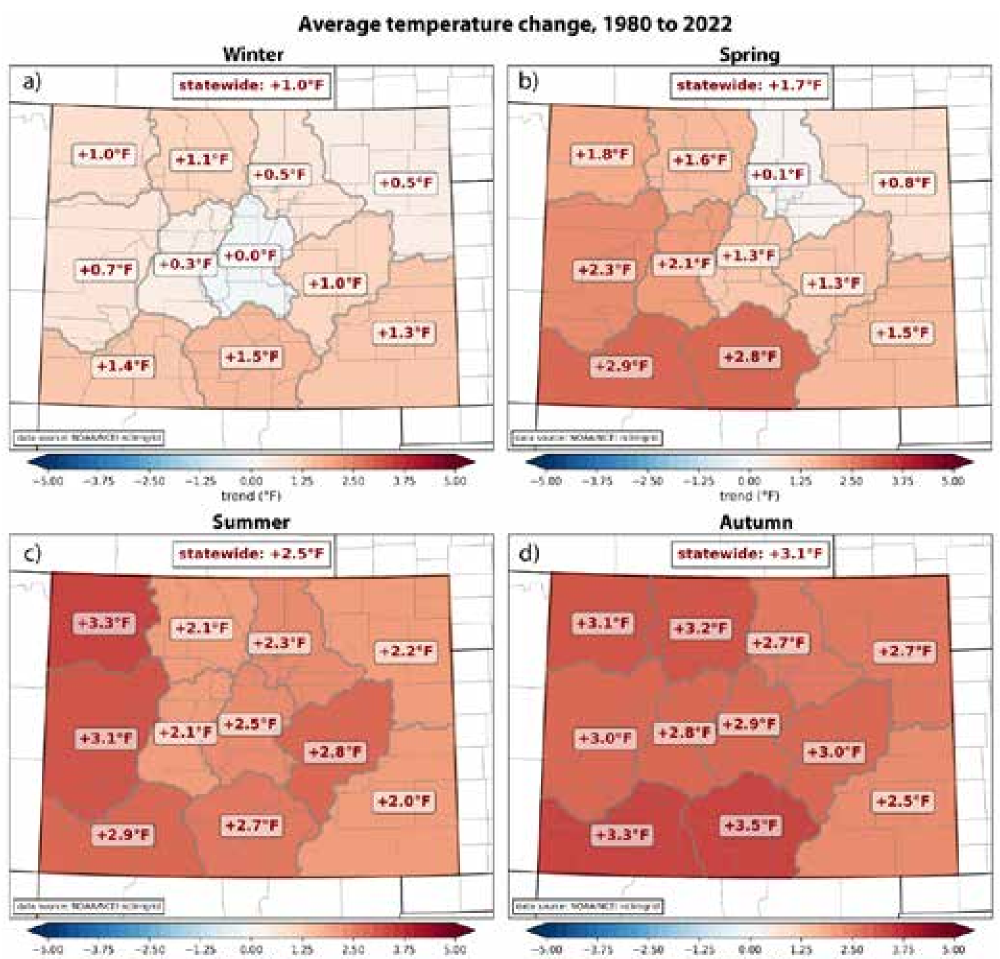

Figure 2.4: Changes in observed climate division temperatures, 1980-2022, for (a) winter, December-January-February, (b) spring, March-April-May, (c) summer, June-July-August, and (d) fall, September-October-November.

Attribution of the observed trends

The pervasive observed warming trends across Colorado are comparable, in terms of timing and magnitude, to warming trends that have been observed regionally, nationally, and globally. At the global scale, human influence has been the main driver of observed warming in the past several decades (*USGCRP 2017*, *IPCC 2021*). The warming trend in the southwest U.S., including Colorado, has likewise been primarily attributed to human influence (***Lehner et al. 2018***). Figure 2.5 shows that the trajectory of observed annual average temperature for Colorado (gray) since 1950 is comparable to the trajectories of median modeled temperatures from the CMIP3 (yellow) and CMIP5 (orange) climate model ensembles. These model runs assume greenhouse gas emissions and atmospheric concentrations similar to what has actually occurred through 2022. The similarity between the observed and modeled statewide warming trends is consistent with the evidence at broader spatial scales that indicates human influence has played a substantial role in Colorado's recent warming trend.

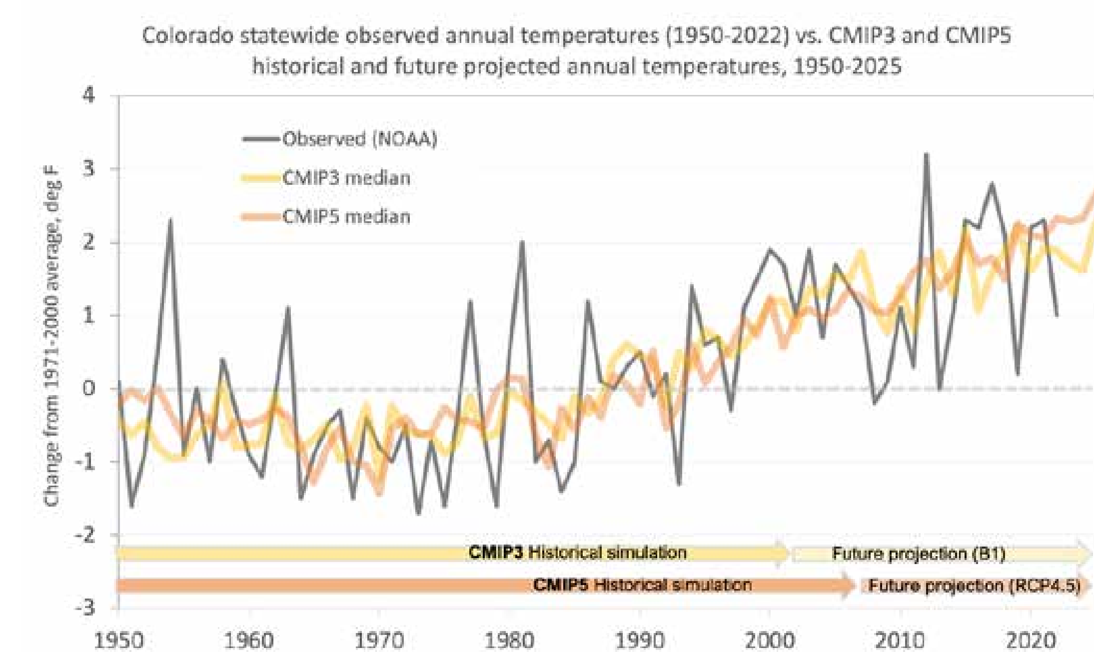

Figure 2.5: Observed statewide annual average temperatures 1950-2022 (same data as in Figure 2.3), compared with the median historical simulation plus the median future projection from the CMIP3 and CMIP5 climate model ensembles, respectively. (Data: Observations: NOAA NCEI nClimGrid, https://www.ncei.noaa.gov/cag/; CMIP3 and CMIP5 projections: GDO-DCP, https://gdo-dcp.ucllnl.org/)

Future temperature projections

There is very high confidence that the climate of Colorado will continue to warm in all seasons through the mid-21st century, given our understanding of the physical mechanisms for warming, the observed warming trend, and climate model projections. While the magnitude of warming is uncertain, by 2050, Colorado's average annual temperatures will likely match or exceed the very warmest years of the past, bringing large changes in the frequency and severity of heat waves, as we will discuss in Section 4.1. Note that in the analyses below, we focus on the medium-low emissions scenario RCP4.5, used for the CMIP5 climate model runs, and its counterpart SSP2-4.5, used for the CMIP6 model runs. The section "Emissions Scenarios" in Appendix A explains why we focused on these scenarios and provides more information about these and other emissions scenarios.

Under RCP4.5, Colorado statewide annual temperatures are projected by the CMIP5 climate models to warm by +2.5°F to +5°F compared to the late 20th century (1971-2000) average (Figure 2.6). We continue to use this 1971-2000 baseline to maintain consistency with the analysis of climate projections in the 2008 and 2014 reports, and in other state reports such as the Colorado Water Plan. Colorado has already warmed by about 1.5°F beyond this baseline, as detailed below.

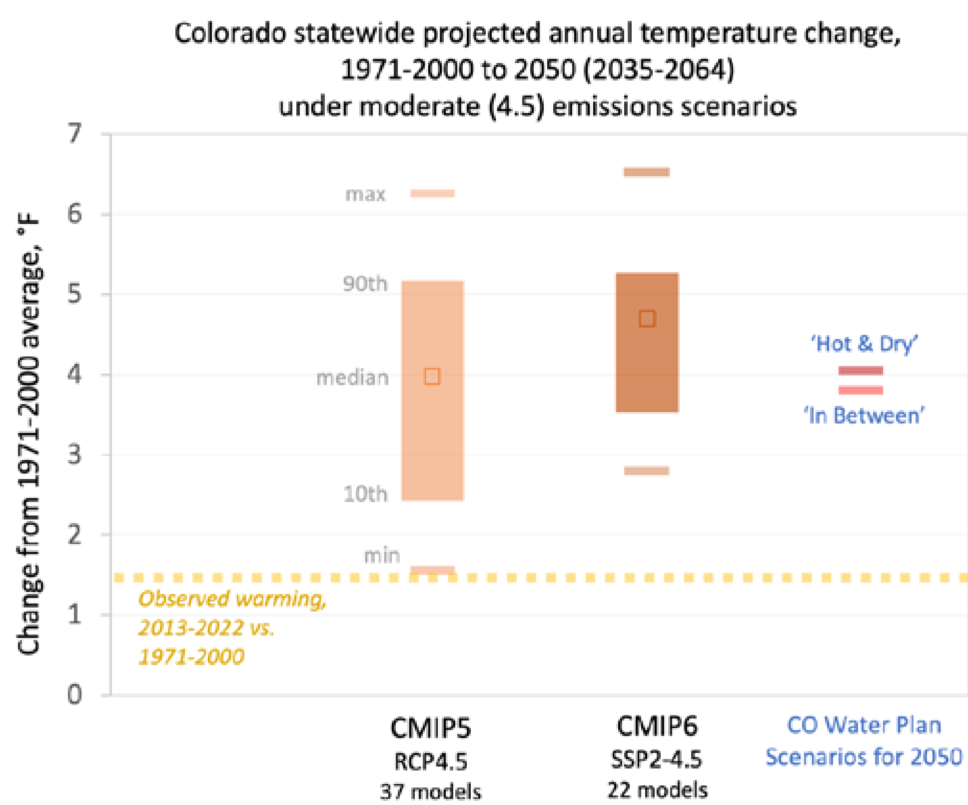

Figure 2.6: Projected future temperature change for Colorado statewide for a 2050-centered period (2035-2064) relative to 1971-2000, from the CMIP5 and CMIP6 climate models under medium-low emissions scenarios. The solid orange bars show the middle 80% of the model projections (10th-90th percentiles); the two orange dashes show the minimum and maximum projections; the open squares show the median projections. (Data: Observations: NOAA NCEI nClimGrid, https://www.ncei.noaa.gov/cag/; CMIP5 data: GDO-DCP, https://gdo-dcp.ucllnl.org/; CMIP6 data: KNMI Climate Explorer, https://climexp.knmi.nl; CO Water Plan Scenarios: CWCB (2019); https://cwcb.colorado.gov/colorado-water-plan/technical-update-to-the-plan)

Under a comparable emissions scenario (SSP2-4.5), the CMIP6 models show a range of warming that is shifted upward, especially at the low end, compared to CMIP5, showing +3.5°F to +5°F warming for Colorado, as taken from the 10th to 90th percentiles of the projected values. The two red bars on the right side of Figure 2.6 show that the climate change scenarios for 2050 used in the Colorado Water Plan (*CWCB 2015*, *CWCB 2023*) are within the range of both CMIP5 and CMIP6 under 4.5 emissions scenarios. It is not surprising that the CMIP6 models show overall warmer futures for Colorado than CMIP5, since the global temperature response of the CMIP6 models given additional increments of greenhouse gases (i.e., climate sensitivity) is overall higher than for the CMIP5 models (see Appendix A for more detail on the CMIP6 "hot" model issue.)

It is important to remember that Colorado has already observed, through 2022, a substantial fraction of the projected warming relative to the 1971-2000 baseline: about +1.5°F, depending on the calculation method (Fig. 2.6). Thus, the projected statewide warming for 2050 shown by the CMIP5 models is +1.0°F to +3.5°F relative to "today", and in the CMIP6 models, +2.0°F to +3.5°F relative to today. The fact that Colorado has already experienced +1.5°F of warming relative to 1971-2000 suggests that the lowest-warming projections in the CMIP5 ensemble, below the 10th percentile, are now very unlikely outcomes.

Most of the projections under a medium-low (4.5) emissions scenario, whether from CMIP5 or CMIP6, show a mid-century climate that is, on average, at least 3°F warmer than the 1971–2000 baseline. If this does occur, an "average" year in 2050 will be warmer than the very warmest individual years observed through 2022 (Figure 2.7).

For a later future period centered on 2070 (2055-2084), the CMIP5 models under medium-low (RCP4.5) emissions scenario projects Colorado statewide temperatures to have warmed +3.0°F to +6.5°F of warming relative to 1971-2000, and +1.5°F to +5.0°F of warming relative to today. For the same 2070-centered period, the CMIP6 models under a comparable emissions scenario (SSP2-4.5) show warming of +4.0°F to +7.0°F relative to 1971-2000, and so +2.5°F to +5.5°F of warming relative to today. As seen in Figure 2.7, the difference between the CMIP5 and CMIP6 median warming under the 4.5 scenarios increases to about 1.0°F by 2070.

With continued warming over the next few decades, the future temperatures at every location in Colorado will become more like those currently experienced in places that are to the south, or lower in elevation. With 2°F of further warming, the seasonal temperature regime for Denver would become more like the current temperatures in Pueblo. With 4°F of further warming, Denver's temperature regime would be similar to Lamar today. With 6°F of further warming, Denver's temperatures would be slightly warmer than the current temperatures in the warmest parts of the lower Arkansas Valley (Las Animas and La Junta), and similar to Albuquerque, New Mexico. Note that this comparison only speaks to temperatures, not precipitation; Denver is very unlikely to experience a large decline in precipitation that would make the overall climate like Albuquerque's, even with 6°F of warming.

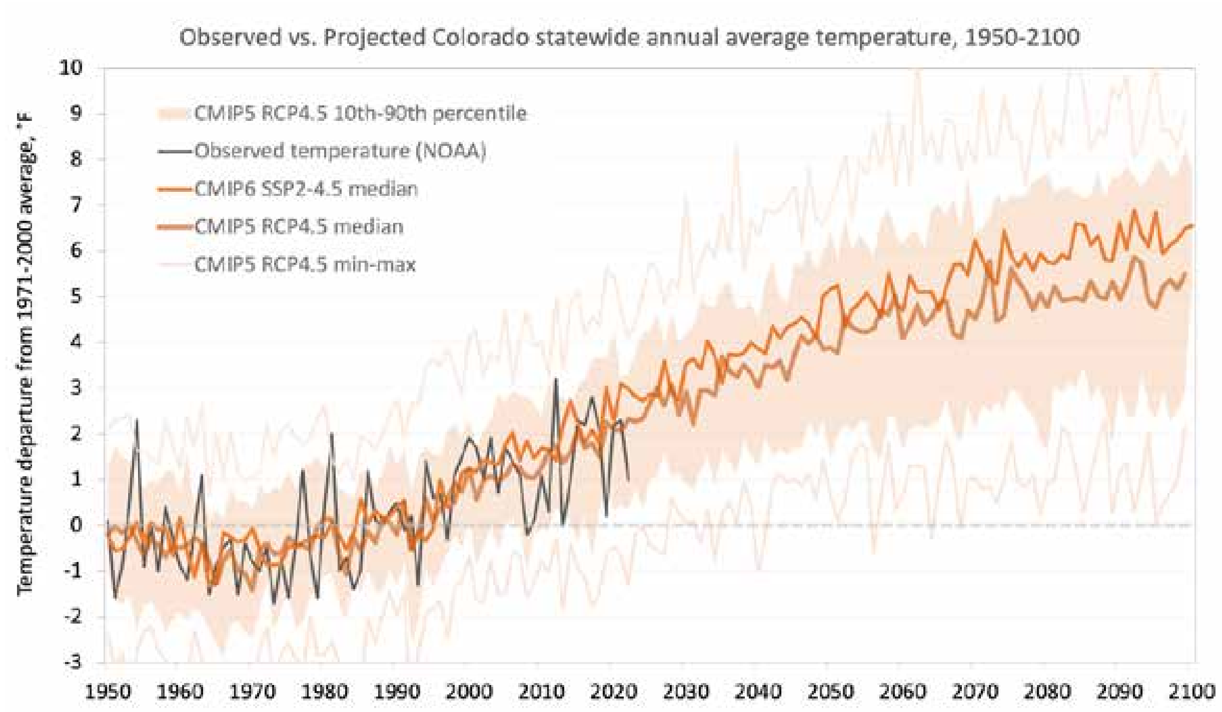

Figure 2.7: Projected change in Colorado statewide average annual temperatures to 2100, relative to a 1971-2000 baseline, from CMIP5 models (median and range) and CMIP6 models (median only) under medium-low emissions scenarios (RCP4.5, SSP2-4.5), compared to observed temperatures through 2022. (Data: Observations: NOAA NCEI nClimGrid, https://www.ncei.noaa.gov/cag/; CMIP5 data: GDO-DCP, https://gdo-dcp.ucllnl.org/; CMIP6 data: KNMI Climate Explorer, https://climexp.knmi.nl)

Under a given emissions scenario (e.g., RCP4.5), the differences in warming across the various projections have two sources. The primary one is that the various climate models have different inherent sensitivity to each increment of greenhouse gases, because of how physical feedbacks are represented in each model. The second and lesser source is the "noise" of model-simulated natural (internal) variability. The 30-year averaging period (e.g., 2035-2064) used here is designed to reduce this noise, but some projections will happen to simulate a relatively warmer, or cooler, few decades in the middle of the longer-term warming trend, and we cannot easily distinguish the noise from the background signal (the warming trend). The effect of this noise is more problematic for the precipitation projections than for temperature projections, as will be discussed in section 2.3.

Figure 2.8 shows the statewide seasonal temperature changes projected by CMIP5 models under RCP4.5, using the same data as shown in Figures 2.6 and 2.7. Overall, summer and fall show slightly greater future warming than winter and spring, though the differences between the seasons are relatively small compared to the magnitude of the overall projected warming. The CMIP6 models show the same pattern: summer and fall are expected to warm slightly more than winter and spring.

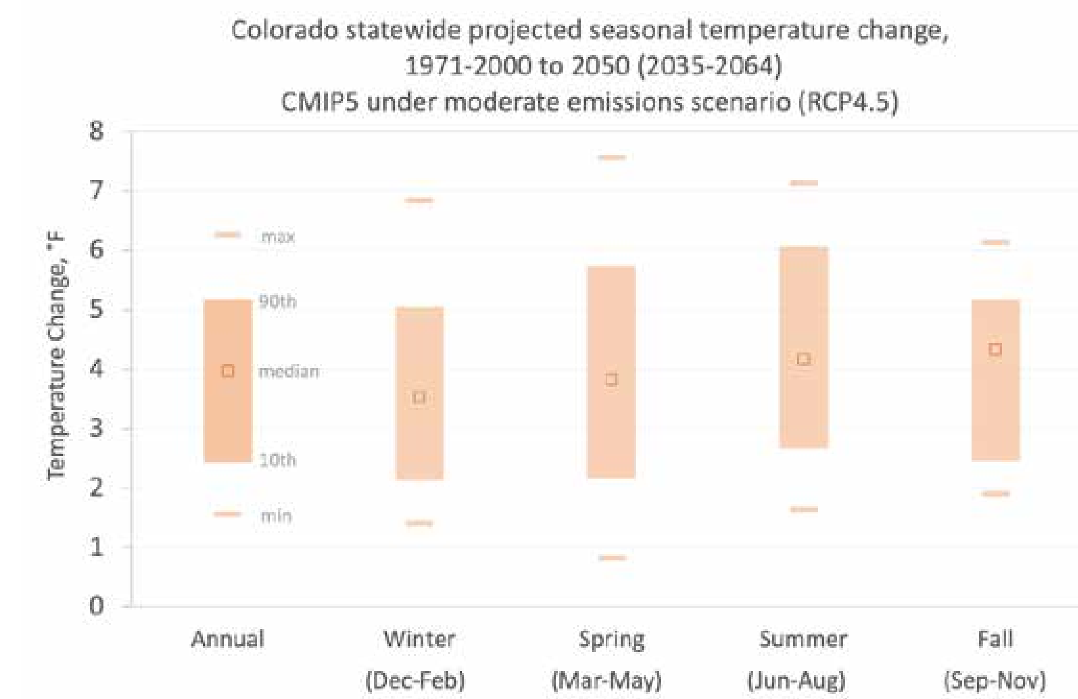

Figure 2.8: Projected future change in seasonal temperatures for Colorado statewide for a 2050-centered period (2035-2064) relative to 1971-2000, from CMIP5 (36 models/projections) under a medium-low emissions scenario (RCP4.5). The solid orange bars show the middle 80% of the model projections (10th-90th percentiles); the two orange dashes show the minimum and maximum projections; the open squares show the median projections. (Data: CMIP5: GDO-DCP, https://gdo-dcp.ucllnl.org/).

Downscaled (regional) projections of temperature

The "raw" output from climate models provides useful estimates of future climate changes at the global scale down to statewide scales. But the spatial resolution of the data, generally 100-km (60-mi) to 300-km (180-mi) grid boxes in the midlatitudes, is too coarse to adequately represent the complex terrain of Colorado and its effects on climate, or for the data to be used as inputs for watershed hydrology modeling or other impact modeling. Thus, global climate model output is typically downscaled through statistical methods, or via higher-resolution regional climate models (RCMs), in order to better represent localized changes to weather and climate, and to facilitate further modeling. The process of downscaling also includes a bias-correction step which adjusts for systematic biases or offsets between the model-projected climate at regional scales and the observed historical climate, over the period of overlap between the two (e.g., 1950-2005).

For a closer look at how the projected future climate change may vary in different areas in Colorado, we analyzed the CMIP5-LOCA (LOcalized Constructed Analogs) statistically downscaled climate projection dataset developed by Pierce et al. (2014). These projections were not available at the time of the 2014 Report, but they have since been used in many climate assessments and studies, including ***USGCRP (2017, 2018)***, ***Lukas et al. (2020)***, and ***Reclamation (2021)***. Taking the 11 alternative climate divisions described earlier in this chapter, we obtained CMIP5-LOCA data for a 0.75° x 0.75° (40 mi./64 km x 52 mi./83 km) quadrangle within each division.

Figure 2.9 shows the projected change in annual average temperature under RCP4.5 between the historical baseline (1971-2000) and the 2050-centered future period (2035-2064) for the 11 alternative climate divisions. All of them are expected to see substantial future warming into this mid-century period. Slightly greater future warming is generally seen in the divisions in Western Colorado and the northern Front Range, with slightly less warming seen in South Park and the San Luis Valley divisions. Keep in mind that these differences in the projected changes in average temperature between the divisions, which are at most 0.7°F, are much smaller than the overall warming across all divisions (median: 4.1°F), or the uncertainty in the warming across the ensemble of 32 projections (generally ± 2°F). The key point is that all parts of the state are expected to warm at rates that are similar to the statewide average.

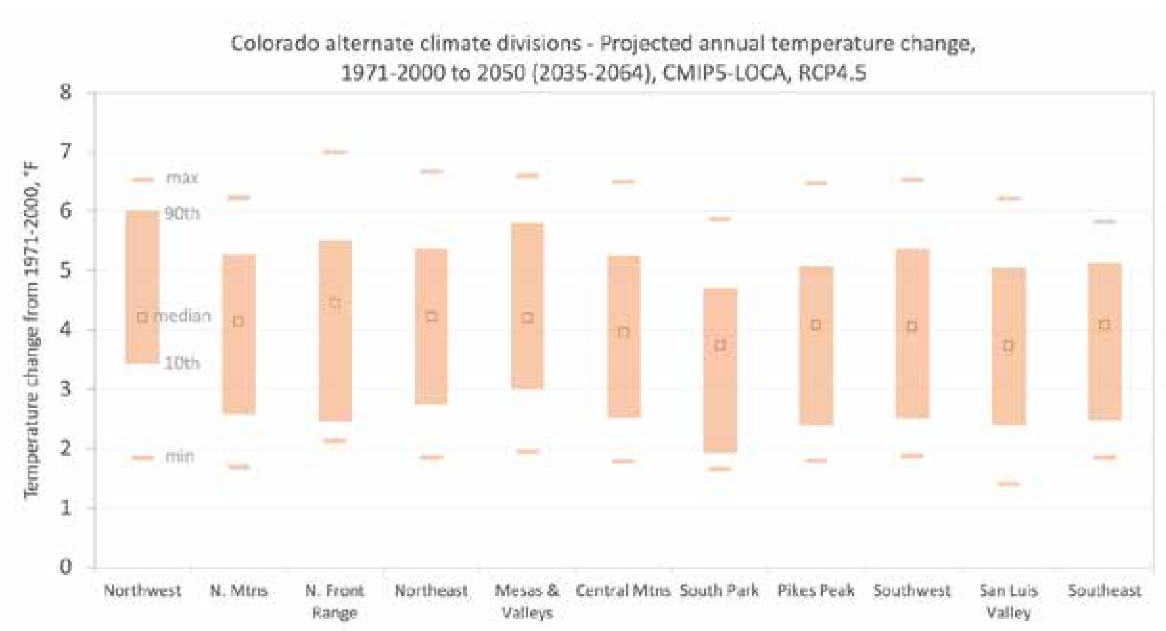

Figure 2.9: Projected future change in annual average temperature in 11 alternative Colorado climate divisions for a 2050-centered period (2035-2064) relative to 1971-2000, from an ensemble of 32 CMIP5-LOCA climate projections under a medium-low emissions scenario (RCP4.5). The solid orange bars show the middle 80% of the model projections (10th to 90th percentiles); the two orange dashes show the minimum and maximum projections; the open squares show the median projections. (Data: CMIP5-LOCA: GDO-DCP, https://gdo-dcp.ucllnl.org/)

2.3 Precipitation

In Colorado, statewide precipitation exhibits high variability at both year-to-year and longer-term decadal timescales (Figure 2.10). With respect to the 1971-2000 average, annual precipitation has varied from 6 inches below average to 6 inches above average. The smoothed time series (Fig. 2.10, gray line) shows frequent extended dry periods with wet periods in between.

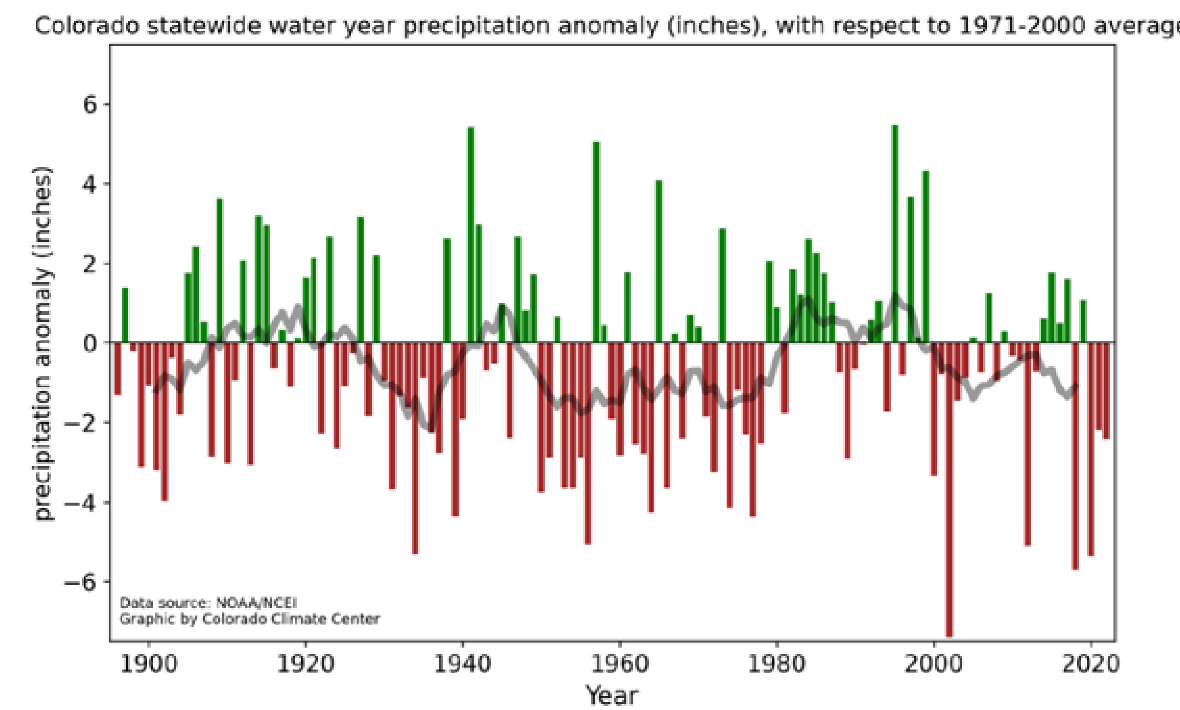

Figure 2.10: Colorado statewide water year precipitation anomaly (inches) with respect to the 1971-2000 average of 18.51 inches. Smoothed 10-year running mean (gray line) included.

Observed precipitation changes

Since the relatively wetter periods of the 1980s and 1990s, Colorado has experienced more persistent dry conditions since 2000. The differences in precipitation and temperature variability necessitate different approaches in analyzing their changes. Rather than calculating a linear trend, we calculate the difference in precipitation between the period 2001-2022 and the period 1951-2000. Statewide, precipitation was 4% lower in 2001-2022 compared to the 1951-2000 average (Table 2.3). These decreases have largely been concentrated in spring, summer, and autumn.

Statewide	Change from 1950-2000 to 2001-2022
Winter	+3%
Spring	-7%
Summer	-6%
Autumn	-5%
Annual	-4%

Table 2.3: Recent changes in statewide annual and seasonal precipitation, as calculated by the difference between the 1950-2000 average and the 2001-2022 average.

Dry conditions since 2000 have been particularly notable in western Colorado, with the Southwest division having precipitation decreases of 22%, 11%, and 12% in spring, summer, and fall, respectively (Fig. 2.11b, 2.11c, 2.11d). In contrast, winter precipitation increased over this period, but the increase was largely observed in lower-elevation regions of Colorado, where winter is typically the driest part of the year, thus the seasonal change had less impact on annual precipitation (Fig. 2.11a). The higher elevations saw relatively small changes in winter precipitation over this period.

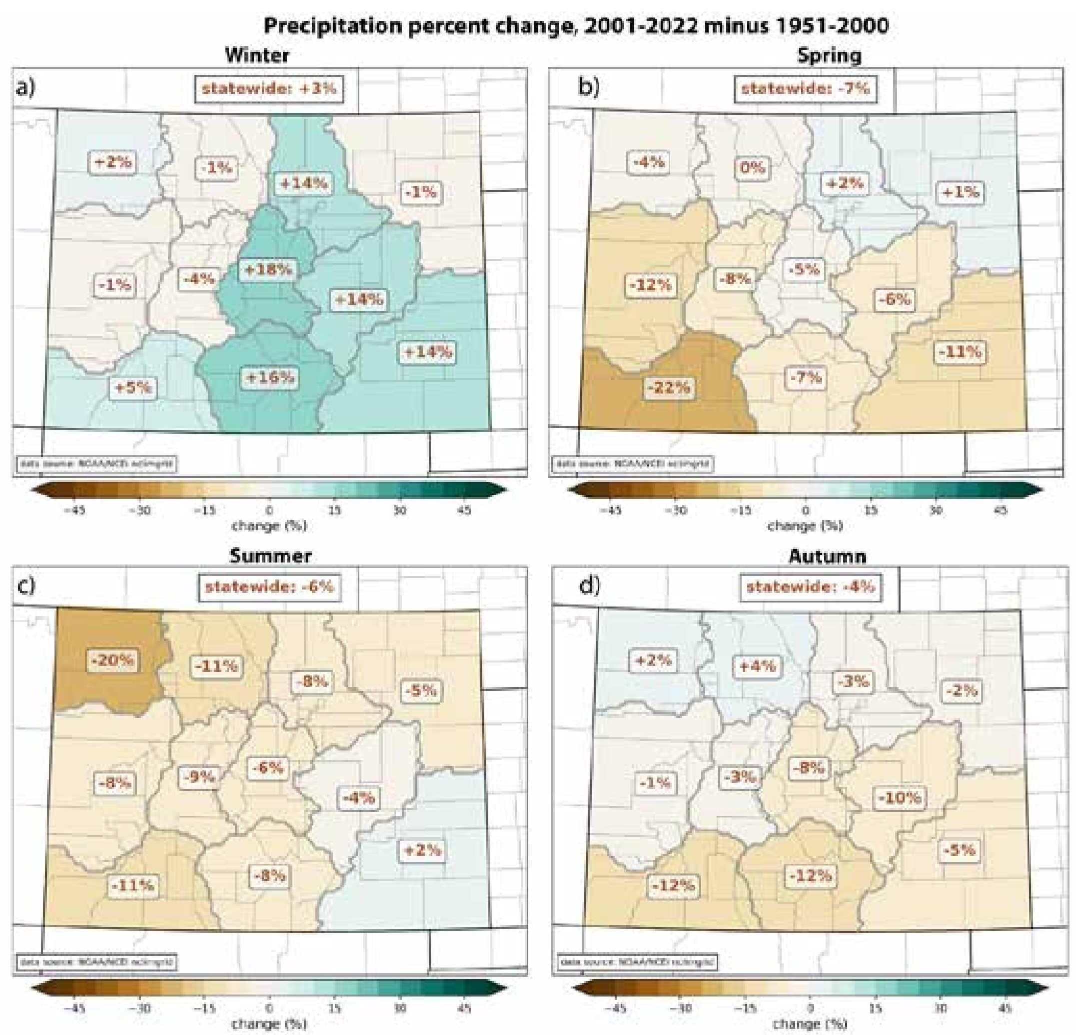

Figure 2.11: Percent change in precipitation between the periods 1951-2000 and 2001-2022, for (a) winter, December-January-February, (b) spring, March-April-May, (c) summer, June-July-August, and (d) fall, September-October-November (d).

Colorado's precipitation variability is partially modulated by the El Niño-Southern Oscillation (ENSO). ENSO is an episodic interaction that occurs between the tropical Pacific Ocean and the atmosphere, which results in the occurrence of three different phases (recurring every 2 to 7 years): El Niño (warmer ocean temperatures in the tropical Pacific), La Niña (cooler ocean temperatures), and neutral (when there is neither an El Niño or La Niña). Variability in ENSO strongly influences global weather patterns. Coastal areas of the U.S. tend to have the strong correlations with ENSO variability. The general pattern in the western U.S. is that wetter conditions are favored

in the Southwest during an El Niño and wetter conditions are favored in the Northwest during a La Niña. With Colorado on the eastern edge of these areas (far from the ocean), and bisecting the two regions latitudinally, the state's relationship with ENSO is more complex.

La Niña winters tend to be wetter for our northern and central mountains (Fig. 2.12, DJF panel). Aside from that signal, La Niña is generally associated with drier conditions around the state. El Niño favors wetter conditions along the Front Range and west slope in the spring, in northeast Colorado in the summer, and over large portions of the state in the fall (Fig. 2.12). While the relationship between Colorado precipitation and ENSO does exist, ENSO only accounts for a small percentage of precipitation variability. While ENSO forecasts can be used as a guide for more or less favorable precipitation patterns around the state, its year-to-year predictive potential is limited.

El Niño conditions occurred more frequently in the 1980s and 1990s, while La Niña conditions have been much more common since the turn of the century. Colorado's climate connection with ENSO, and its relative frequencies over the last 40-50 years, may have partially contributed to the persistent dry conditions observed over most of the state since 1980.

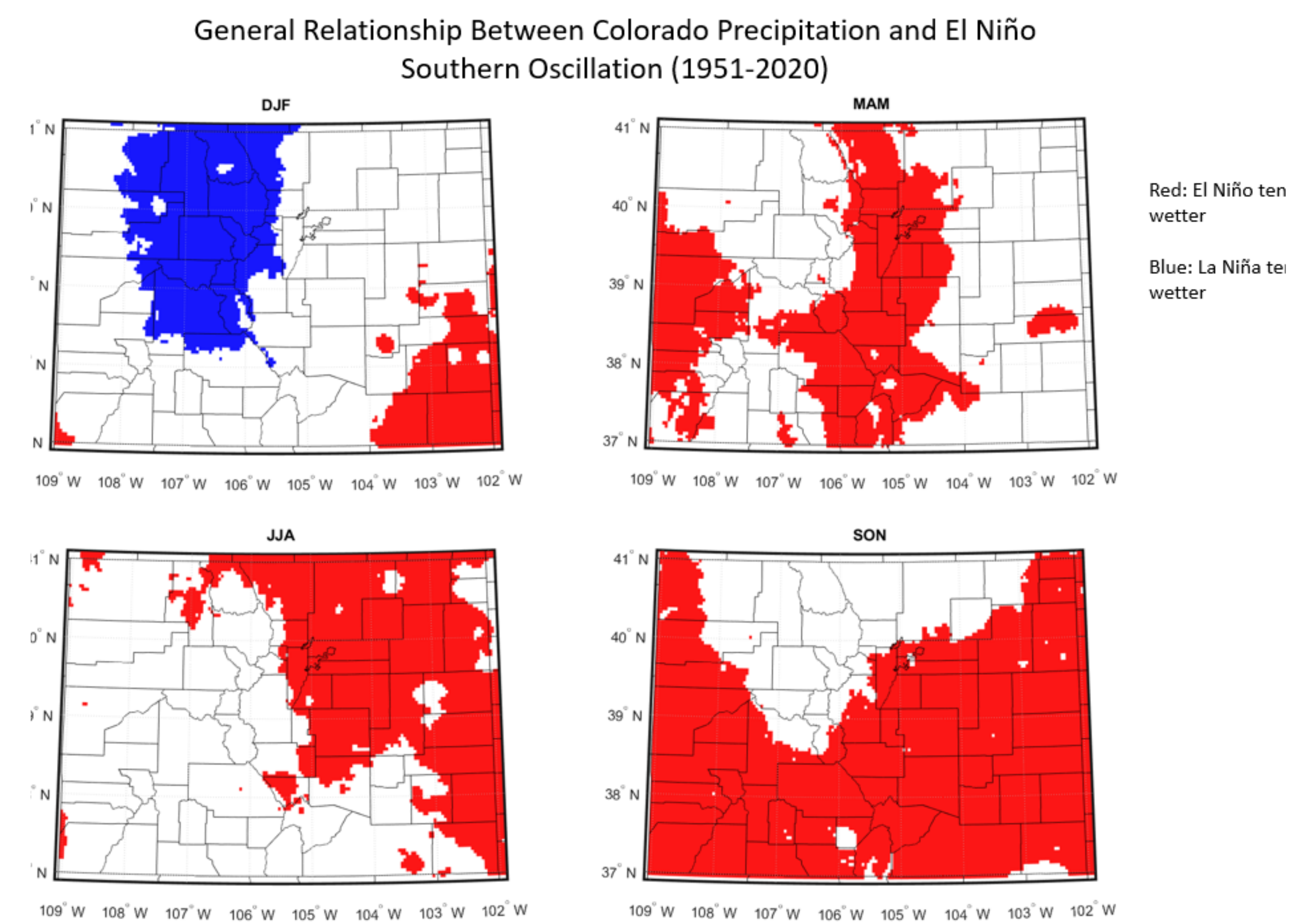

Figure 2.12: General relationship between El Niño Southern Oscillation and Colorado seasonal precipitation. Areas of correlation are shaded red when El Niño tends to be wetter and blue if La Niña tends to be wetter.

Future precipitation projections

The future direction of precipitation change in Colorado is much less certain than for temperature change. The climate models lack consensus about whether Colorado will on average see less, more, or about the same annual precipitation in the future, reflecting potentially offsetting physical mechanisms, as well as the greater complexity of the physical processes controlling precipitation compared to temperature. The climate models—CMIP3, CMIP5, and CMIP6—consistently project is the northernmost U.S. states and Canada will see overall higher annual precipitation in the future, and that the far Southwest and Mexico will see lower annual precipitation in the future. Colorado is in a transition zone between these regions of greater model consensus; this has opposing implications for the northern (more likely wetter) and southern (more likely drier) portions of Colorado, as will be explored in the next section, on downscaled projections of future precipitation.

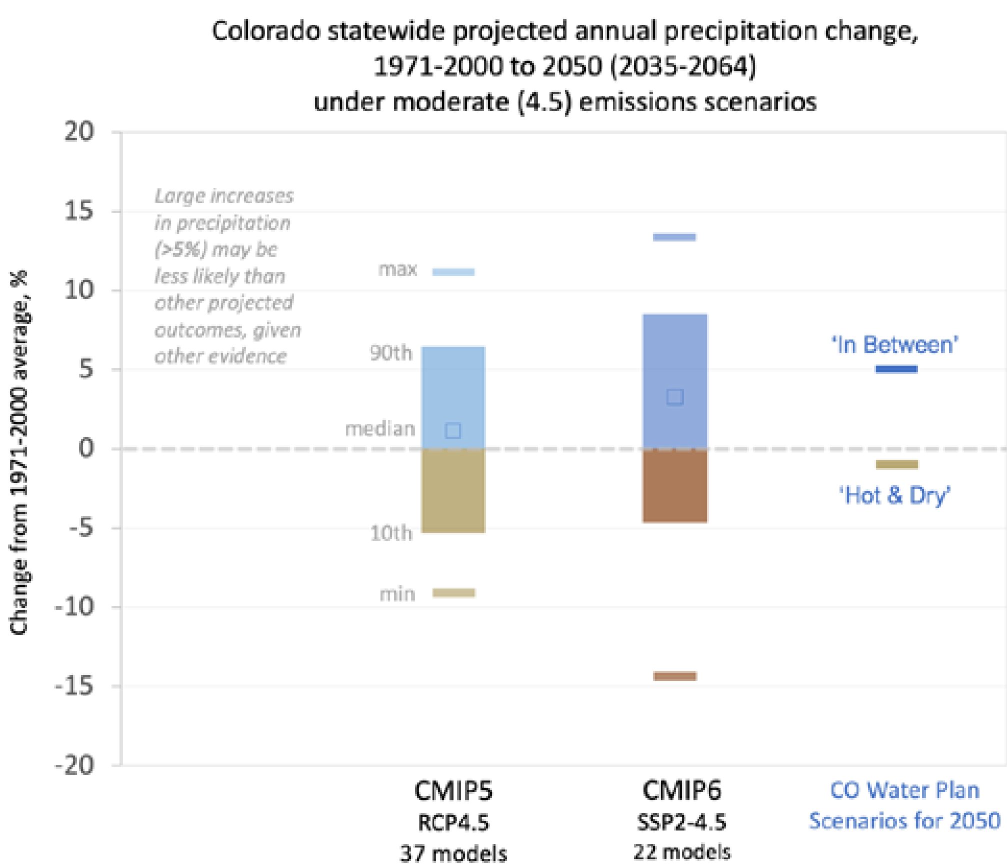

Figure 2.13: Projected future change in average annual precipitation for Colorado statewide for a 2050-centered period (2035-2064) relative to 1971-2000, from the CMIP5 and CMIP6 climate models under medium-low emissions scenarios. The solid blue and brown bars show the middle 80% of the model projections (10th-90th percentiles); the two dashes show the minimum and maximum projections; the open squares show the median projections. (Data: Observations: NOAA NCEI nClimGrid, https://www.ncei.noaa.gov/cag/; CMIP5 data: GDO-DCP, https://gdo-dcp.ucllnl.org/; CMIP6 data: KNMI Climate Explorer, https://climexp.knmi.nl; CO Water Plan Scenarios: CWCB (2019); https://cwcb.colorado.gov/colorado-water-plan/technical-update-to-the-plan)

Figure 2.13 illustrates the projected changes in statewide annual precipitation for Colorado from CMIP5 and CMIP6 models straddle the no-change line under a medium-low emissions scenario, with some projections showing wetter conditions for 2050 (2035-2064) and some showing drier conditions for 2050. The two blue bars

on the right side of Figure 2.13 show that the climate change scenarios for precipitation in 2050 used in the Colorado Water Plan (*CWCB 2015*, *CWCB 2023*) are within the range of both CMIP5 and CMIP6 under 4.5 emissions scenarios, although the "Hot & Dry" scenario is not as dry as many of the projected precipitation outcomes. Note that even the 90th percentile (+6%) and 10th percentile (-5%) changes shown by the models are much smaller than the observed year-to-year variability in statewide precipitation (+30% to −40%), although these changes are similar to the largest observed deviations in running 30-year averages in precipitation.

Most CMIP5 projections also show increases in year-to-year and decadal variability in annual precipitation for Colorado and the interior West over the next several decades (*Lukas et al. 2014*, (*Pendergrass et al. 2017*)). This suggests more frequent occurrences of both very dry and very wet years, and multi-year periods, than seen in the historical record. It also suggests more frequent oscillations from one extreme to the other, such as from 2018 to 2019.

With each model generation since CMIP3, there has been a slight shift towards wetter outcomes. However, the range of projected changes (i.e., model uncertainty) has not shrunk from CMIP5 to CMIP6. For a 2070-centered period, the CMIP5 models show the range of precipitation outcomes shifted slightly wetter than for 2050.

Figure 2.14 shows the seasonal precipitation changes projected by CMIP5 models under RCP4.5 for a 2050-centered period, using the same dataset shown in Figures 2.13. The slight overall model signal towards increased annual precipitation (far left) is strongly accentuated for winter (Dec-Feb) precipitation and to a lesser degree for spring (Mar-May) precipitation. Summer (Jun-Aug) precipitation shows the largest range and uncertainty across the models, with the greatest tendency towards large decreases among the seasons. The projections for fall (Sep-Nov) precipitation are very similar to annual, with a slight tendency towards increased precipitation. The CMIP6 models show outcomes for seasonal precipitation that are very similar to CMIP5.

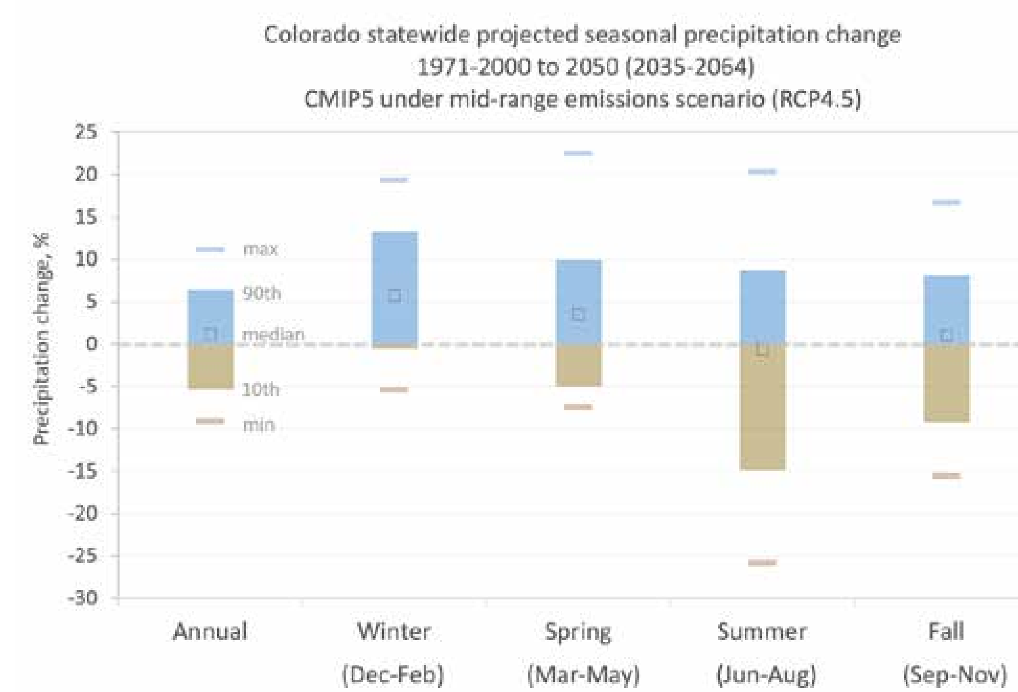

Figure 2.14: Projected future change in seasonal precipitation for Colorado statewide for a 2050-centered period (2035-2064) relative to 1971-2000, from CMIP5 (36 models/projections) under a medium-low emissions scenario (RCP4.5). The solid blue and brown bars show the middle 80% of the model projections (10th-90th percentiles); the two dashes show the minimum and maximum projections; the open squares show the median projections. (Data: CMIP5: GDO-DCP, https://gdo-dcp.ucllnl.org/)

The climate models disagree about the direction of change in future precipitation for Colorado in part because they disagree about how much the average storm track in the fall, winter, and spring over the western U.S. will shift northward. This northward shift has been observed already and is expected to continue, as a consequence of warming-induced expansion of the dry subtropical high-pressure zone that dominates the climate in the region south of Colorado (*Harvey et al. 2020*; *McAfee et al. 2011*). At the same time, individual storms that affect Colorado will tend to be wetter, as a warmer atmosphere holds more moisture (*Seager et al. 2010*); the implications of this relationship for extreme precipitation will be explored in Chapter 4.

A second key factor leading to model disagreement regarding precipitation change is how ENSO will change in a much warmer climate. Some CMIP5 and CMIP6 models show more frequent and intense El Niño events (on average associated with wetter conditions for Colorado), while others show more frequent and intense La Niña events (associated with drier conditions). None of the CMIP5 and CMIP6 model simulations capture the recent observed sea-surface temperature (SST) trends in the tropical Pacific, which show a systematic shift towards a more La Niña-like SST gradient from east to west. It is not clear if this shift is associated with anthropogenic influences on the climate system ((*Seager et al. 2019*),(*Heede et al. 2020*)), (*Lee et al. 2022*) or natural (internal) variability (*Zhang et al. 2021*) If this observed trend towards a more La Niña-like tropical Pacific is in fact anthropogenically forced, then drier precipitation outcomes for Colorado would be more likely to occur over the next several decades.

As described earlier in Chapter 2, observed annual precipitation for Colorado from 2000 through 2022 was about 4% lower than the second half of the 20th century (1951-2000). While several studies suggest that this recent period of reduced precipitation across the southwest U.S. is likely due to natural variability ((*Barnett et al. 2008*), (*Hoerling et al. 2010*), (*Lehner et al. 2018*)), other analyses suggest that there is a long-term anthropogenic trend towards lower precipitation in the southwest U.S., including Colorado—though this effect is small enough to be overwhelmed by natural variability on decadal timescales ((*Gao et al. 2011*), (*Hoerling et al. 2019*)).

If any anthropogenic decrease in Colorado's average annual precipitation does occur over the rest of the 21st century, as a large minority of the projections indicate, that would substantially worsen the impacts of warming temperatures on future hydrology. Conversely, only a relatively large increase in statewide annual precipitation (>5%) would ameliorate the impacts of future warming. That outcome, while not off the table, cannot be counted on.

Again, note that the climate models simulate the natural (internal) variability in precipitation as well as the anthropogenic (forced) change signal. Each projection from one climate model simulates a unique sequence of variability (e.g., ENSO events), not synchronized with other models. Even when using a 30-year averaging period (e.g., 2035-2064) for calculation of future change, some long-term variability is picked up in the future "change" for a given model projection. This is consistent with how the real future climate will evolve: there will still be variability in precipitation (whose characteristics may change), which will potentially be superimposed on a forced trend in precipitation.

Downscaled (regional) projections of precipitation

For a closer look at how the projected future precipitation changes may vary in different regions of Colorado, we analyzed the CMIP5-LOCA downscaled climate projection dataset, as described under Temperature (section 2.2, above).

Figure 2.15 shows the projected change in annual precipitation, under RCP4.5, between the historical baseline (1971-2000) and the 2050-centered future period (2035-2064) for the 11 alternative Colorado climate divisions. In each division, the downscaled model projections do not agree on the direction of future precipitation change, with the range of projections extending from large increases to large decreases, as with the statewide projections (Figure 2.15). But in general, the ranges of projections for the northern divisions (Northwest, N. Mtns, N. Front Range, Northeast) are shifted towards wetter outcomes than for the southern divisions (Southwest, San Luis Valley, Southeast). Whatever the overall future change in annual precipitation for Colorado as a whole--more, less, or about the same--the southern divisions are likely to have a drier outcome than the rest of the state, especially the northern divisions.

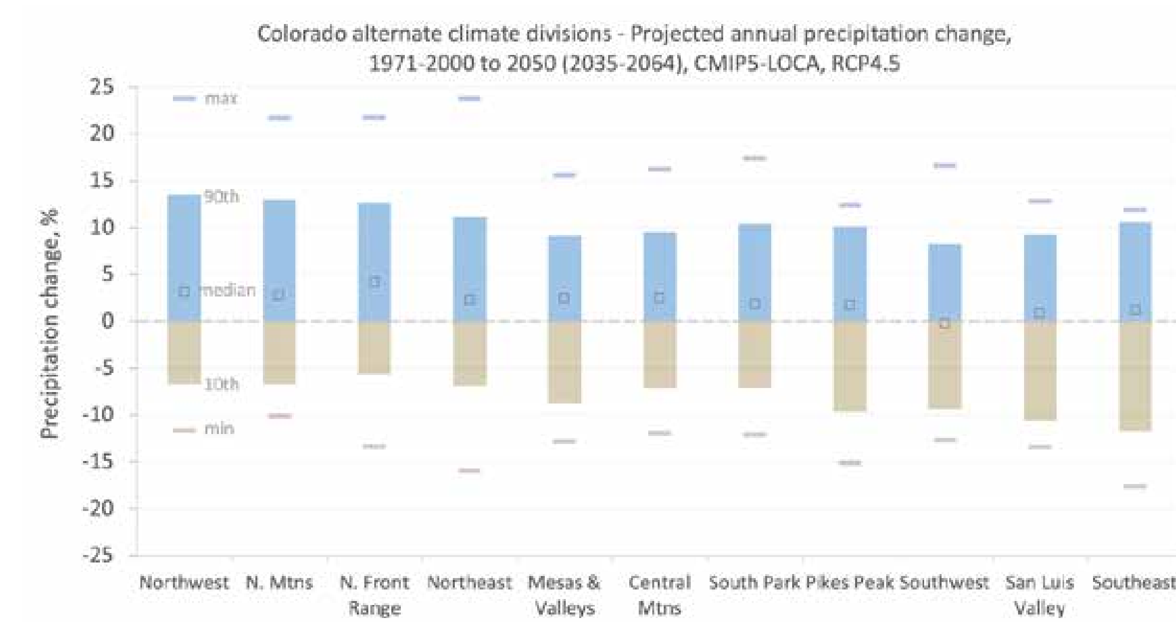

Figure 2.15: Projected future change in annual precipitation in 11 alternative Colorado climate divisions for a 2050-centered period (2035-2064) relative to 1971-2000, from an ensemble of 32 CMIP5-LOCA climate projections under a medium-low emissions scenario (RCP4.5). The solid blue and brown bars show the middle 80% of the model projections (10th-90th percentiles); the two dashes show the minimum and maximum projections; the open squares show the median projections. (Data: GDO-DCP, https://gdo-dcp.ucllnl.org/)

Chapter 3 | Changes in Colorado's Water

KEY MESSAGES

Climate variable/event	Recent trend	Projected future change	Confidence in change
Spring Snowpack	**Lower**	Lower	Medium
Runoff timing	**Earlier**	**Earlier**	**High**
Annual Streamflow	**Lower**	Lower	Medium
Evaporative demand	**Higher**	**Higher**	**High**
Summer soil moisture	**Lower**	**Lower**	**High**

Table 3.1 Summary of the observed and projected changes in hydrology and water resources for Colorado, as detailed in the following sections. "Confidence in change" reflects the judgment of the authors, based on both the assessments in higher-level climate reports (NCA, IPCC), as well as relevant literature and model output for Colorado. In general, there is higher confidence in the changes in variables that are driven mainly by warming and less by the more uncertain change in annual precipitation.

Snowpack

- April 1 SWE (snow-water equivalent) during the 21st century has been 3% to 23% lower than the 1951-2000 average across Colorado's major river basins.
- Future warming will lead to further reductions in Colorado's spring snowpack. Most climate model projections of April 1 SWE in the state's major river basins show reductions of -5% to -30% for 2050 compared to 1971-2000; the individual projections that show increasing snowpack assume large increases in fall-winter-spring precipitation.
- The seasonal peak of the snowpack is projected to shift earlier by a few days to several weeks by 2050, depending on the amount of warming and the precipitation change. This warming-driven shift could be accelerated by increases in dust-on-snow events.

Streamflow

- Since 2000, annual streamflow in all of Colorado major river basins has been 3% to 19% lower than the 1951-2000 average.
- Modeling studies have attributed up to half of the observed decrease in streamflow since 1980 in Colorado river basins to warming temperatures.
- Future warming will act to reduce annual streamflows. Most climate model projections of annual streamflows in the state's major river basins for 2050 show reductions of 5% to 30% compared to 1971-2000.
- Higher future streamflow would require large overall increases in precipitation to offset the effects of warming, an outcome that appears unlikely.
- Summer and fall streamflows are projected to decline significantly by 2050 as the seasonal runoff peak shifts earlier, by 1-4 weeks, due to warming.

Soil Moisture

- Modeled soil moisture based on meteorological observations suggests overall declines in high-elevation soil moisture from 1980-2022.
- Future warming will lead to declines in summer (June-August) soil moisture throughout the state. Spring (March-May) soil moisture will likely increase at higher elevations as snowmelt shifts earlier.
- Rapid depletion of soil moisture under warm conditions exacerbates warming. When summer sunshine hits a landscape with dry soil a greater fraction of solar energy directly heats the surface, leading to even warmer conditions.

Evapotranspiration

- The evaporative demand ("thirst") of the atmosphere—as measured by potential evapotranspiration (PET) and Reference ET—has increased across Colorado since 1980, mainly due to the warming trend. Statewide, growing-season PET increased by 5% from 1980-2022.
- Additional future warming will drive greater evaporative demand; all climate model projections show statewide annual PET increasing by 8-17% by 2050, compared to 1971-2000.

3.1 Overview

Colorado is known as a ‘headwaters’ state because four major river systems have most of their mountain headwaters within its borders: the Colorado River, the Rio Grande, the Arkansas River, and the Platte River. All of these major rivers, and all of their tributaries with headwaters above 8,000 feet, have a snowmelt-dominated hydrology: most of their annual streamflow (~60-80%) originates as meltwater from the seasonal snowpack (*Li et al. 2017*). Streams whose watersheds are entirely at lower elevations, whether on the eastern plains or in the western plateau region, have flows driven more by rainfall in the warmer months, with less contribution from snowfall and snowmelt.

Most of the water use in Colorado (83%) depends on surface water supply from streams and rivers, often stored in reservoirs (*CWCB 2023*). The remaining 17% of water supply comes from groundwater wells that tap either alluvial aquifers that are strongly connected to a river or stream, or deeper aquifers that are replenished over much longer time periods.

In this chapter, we describe recent trends and likely future changes in four related dimensions of Colorado’s water resources: snowpack, streamflow, soil moisture, and evapotranspiration. To summarize observed trends, we rely on both recent research studies and new analyses using observations from key datasets. For likely future changes, we rely on recent studies and new analyses using the ensemble of CMIP5-LOCA-VIC hydrologic projections (*Vano et al. 2020*). See Appendix A for more information about these hydrologic projections.

3.2 Snowpack

Overview

Colorado’s snowpack serves as a huge seasonal reservoir that stores about 15 million acre-feet of water on average at the spring peak and then makes that water available later in the year when water demands for agricultural uses and outdoor watering are higher. Precipitation that falls and is stored as snow is also more likely to end up as runoff than precipitation that falls as rain (*Li et al. 2017*). Colorado’s seasonal snowpack begins accumulating in late fall and typically peaks in April or May. Once rising spring temperatures warm all of the snowpack to 32°F (0°C), the sun’s energy can more effectively drive snowmelt. The snowmelt leads to an abrupt peak in streamflow, typically in May or June. On most streams and rivers in Colorado fed by mountain snowmelt, about 70-80% of the annual runoff comes in the four months from April to July.

Snow-water equivalent (SWE) refers to the amount of liquid water that would result if the snowpack were melted down. SWE is a better measure for hydrologic monitoring than total snowfall or snow depth, since the latter measures don’t account for the highly variable density of snow. The amount of SWE around the seasonal peak (usually April 1 to May 15) is a very useful predictor of the spring and summer runoff. The peak SWE in Colorado’s mountains is typically 10” to 50”, depending on location, elevation, and year. Note that the snow and rain that falls after peak SWE (in April, May, and June) can dramatically shift the runoff outcomes in years with anomalous spring precipitation, such as 2020 (low) and 2015 (high). In Colorado, SWE is measured hourly at 114 automated SNOTEL (SNowpack TELemetry) sites, and monthly at 81 snow courses, all maintained by the Natural Resources Conservation Service (NRCS) Colorado Snow Survey and its cooperators. Nearly all of these SNOTEL and snow course sites are between 8,500’ and 11,500’.

Similar to weather station data, snow data are subject to non-climatic influences (especially changes in vegetation over time, such as beetle-kill or wildfire) that affect snow deposition at the site (*Kampf et al. 2022*; *Julander and Bricco 2006*; *Pugh and Small 2012*; *Giovando and Niemann 2022*). Thus, monitoring and trend analysis based on multiple sites is more representative of basin-wide conditions compared to single site monitoring and analysis.

Observed snowpack changes

Several recent studies have documented widespread declining trends in April 1 SWE across the West over the past 40 to 70 years ((*Fyfe et al. 2017*), (*Mote et al. 2018*), (*Zeng et al. 2018*), (*Siler et al. 2019*), (*Musselman et al. 2021*)). These studies showed that SWE has decreased in most sites in Colorado’s major river basins, though the percentage declines in SWE in Colorado were generally smaller than in most other regions of the West due to Colorado’s relatively high elevations and colder winter climate. These studies also found that warming temperatures were an important cause of the observed SWE declines, while below-normal fall and spring precipitation in the past few decades has also played a role.

An analysis of Colorado’s snowpack updated from the 2014 report is consistent with these recent West-wide studies. Figure 3.1 shows basin-wide SWE from SNOTEL sites and snow courses starting in the 1940s to 1960s for eight of Colorado’s river basins. Note that the year-to-year variability, especially drought years, is highly correlated among the basins. The 21st century (2001-2022) average April 1 SWE for all eight basins is lower, by 3% to 23%, than the 1951-2000 average (Figure 3.1). The largest decreases occurred in the southwestern portion of the state, specifically in the San Juan and Rio Grande basins. Figure 3.1 shows that years with very large snowpacks (>140% of median)—important for refilling reservoirs—have been less frequent since the 1980s. Though as 2023 demonstrates, these big snowpacks can still occur.

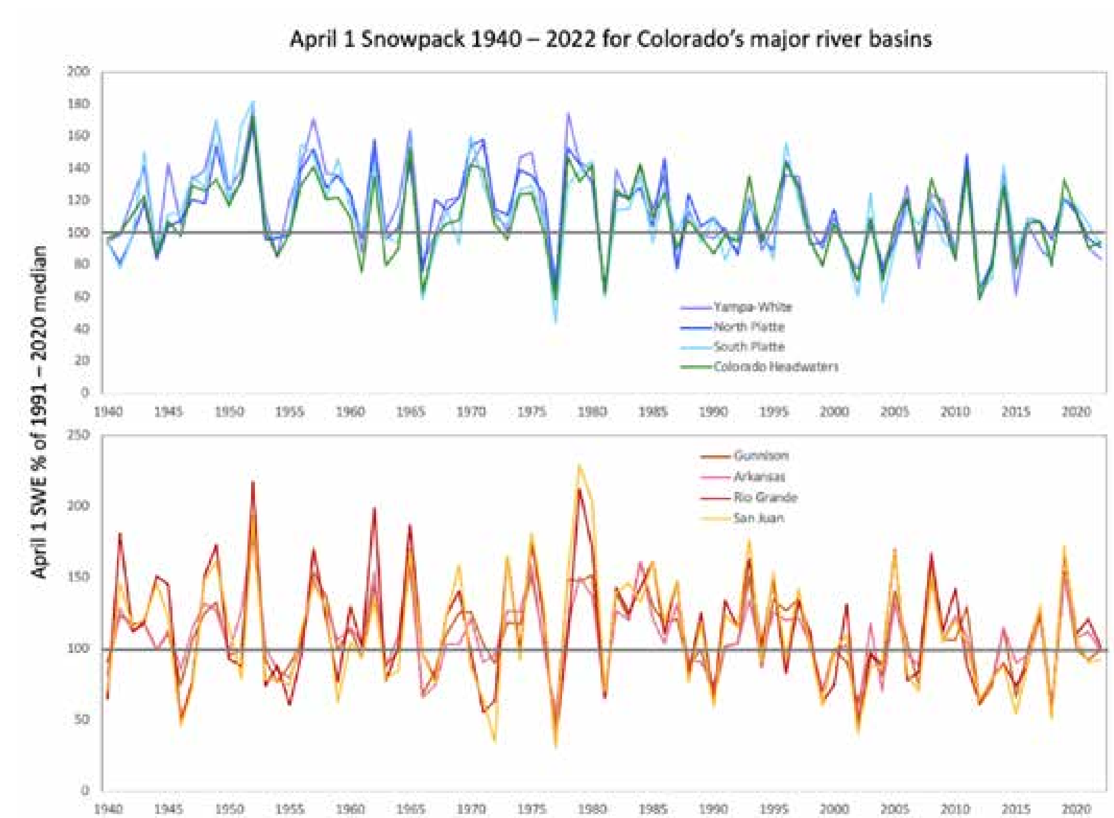

Figure 3.1: Observed April 1 snow water equivalent for northern basins (top) and southern basins (bottom) compared to 1991-2020 median.

Future snowpack projections

Many previous studies have used climate projections (Chapter 2) in combination with hydrologic models to simulate future changes in the hydrology of river basins in Colorado and elsewhere in the interior West. They show that April 1 SWE is likely to decline across Colorado's river basins due to the systemic impacts of warming temperatures, despite the projected increases in winter and spring precipitation ((*Battaglin et al. 2011*), (*Lukas et al. 2014*), (*Lute et al. 2015*), (*Alder and Hostetler 2015*), (*Lukas et al. 2020b*), (*Reclamation 2021*)).

For this report, we analyzed the CMIP5-LOCA-VIC hydrologic projections as noted in Section 3.1. Figure 3.2 shows the projected change in April 1 SWE, under RCP4.5, between the historical baseline (1971-2000) and the 2050-centered period (2035-2064) for the watersheds above key gages within seven major Colorado river basins. In all of the basins, most projections indicate decreased April 1 SWE in the 2050-centered period.

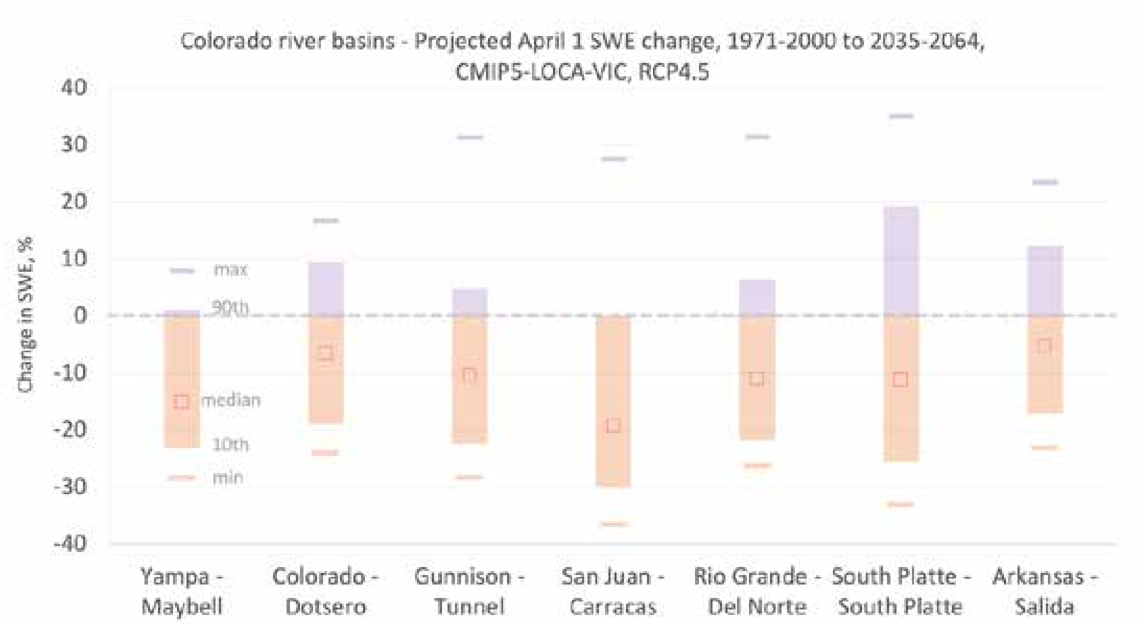

Figure 3.2: Projected future change in April 1st snow-water equivalent (SWE) in watersheds above key gages in seven Colorado river basins for a 2050-centered period (2035-2064) relative to 1971-2000, from an ensemble of 32 CMIP5-LOCA-VIC hydrology projections under a medium-low emissions scenario (RCP4.5). The solid purple and red bars show the middle 80% of the projections (10th-90th percentiles); the two dashes show the minimum and maximum projections; the open squares show the median projections. (Data: GDO-DCP, https://gdo-dcp.ucllnl.org/)

While April 1 SWE is a very commonly used indicator of snowpack and a good predictor of April-July streamflow, it is also a single snapshot in time. Figure 3.3 shows the projected monthly SWE, under RCP4.5, for the 2050-centered period (2035-2064) compared with the historical baseline (1971-2000) for the watershed above the Colorado at Dotsero gage. From November to April, most of the projections for 2050 show lower first-of-month SWE than the historical baseline, reflecting reductions in snow accumulation due mainly to warmer temperatures. For May 1, nearly all projections for 2050 show lower SWE than the historical baseline; the decreases in SWE are greater for April 1. This indicates that snowmelt is starting earlier in the future period. For June 1, all 32 projections show lower SWE than the historical baseline, including projections that showed increased SWE on April 1.

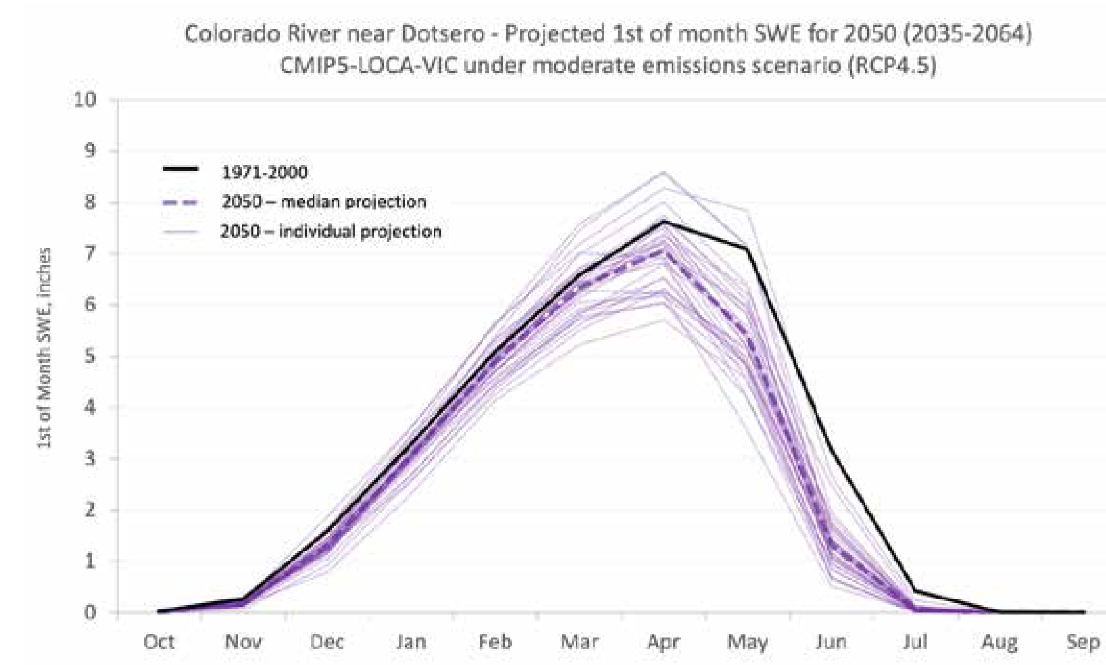

Figure 3.3: Projected future 1st-of-month snow-water equivalent (SWE) for the basin above the Colorado River at Dotsero gage for a 2050-centered period (2035-2064) from an ensemble of 32 CMIP5-LOCA-VIC hydrology projections (purple) under a medium-low emissions scenario (RCP4.5), and the simulated mean monthly SWE for the 1971-2000 period (black). The plotted monthly values are for the 1st of the month. (Data: GDO-DCP, https://gdo-dcp.ucllnl.org/)

Examination of the daily data underlying Figure 3.3 shows that the seasonal peak SWE during the 1971-2000 historical period occurred, on average, on April 9. For the 2050-centered period, 27 of the 32 projections indicate seasonal peak SWE occurring earlier than April 9, by as much as 38 days. The median projection suggests peak SWE will occur 11 days earlier, on March 29.

3.3 Streamflow

Overview

The high mountains of Colorado form the headwaters of major rivers and their tributaries that provide water supply for Colorado and over two dozen downstream states and Mexico, including the Colorado, Rio Grande, Arkansas, and North and South Platte rivers. Water from the Colorado River alone is relied upon by over 40 million people. Accurate forecasts of the volume and timing of streamflow are crucial on a daily- to-annual basis for reservoir managers, irrigators, municipal water providers, and flood-warning systems. Similarly, understanding historical variability in streamflow and any potential future changes in streamflow is critical to long-term water planning.

As discussed in the previous section, seasonal (e.g., April-July) and annual streamflows in most of the state's streams and rivers are driven by snowmelt, so the year-to-year variability in surface water supply in Colorado is strongly related to the variability in the snowpack (e.g., April 1 SWE). Accordingly, seasonal and annual streamflow can be skillfully (though not perfectly) predicted 1-5 months ahead of peak runoff, primarily using

SWE and precipitation data. However, precipitation that falls before the start of the snowpack season and after the seasonal SWE peak contributes to runoff as well. The largest source of uncertainty in streamflow forecasts made between January and May is how the subsequent weather will evolve.

The large magnitude of interannual streamflow variability is an ongoing challenge for water managers. As seen in figure 3.4, water year streamflows in Colorado's river basins vary by up to six-fold from year to year—more than the relative variability in precipitation and snowpack. This is because the fraction of precipitation and snowpack lost to evapotranspiration (see later in this chapter) is greater than average in dry years and less than average in wet years, magnifying the difference in runoff outcomes between dry and wet years. For example, a basin snowpack that is 90% of normal will tend to produce streamflows that are only around 80% of normal (*Vano et al. 2012*).

Observed streamflow changes

Since 2000, the average annual naturalized streamflows in all of Colorado's major river basins have been lower than the 1951-2000 period (Figure 3.4). Naturalized streamflows are gaged streamflows that have been corrected for upstream diversions, depletions, and reservoir operations, making them more appropriate for monitoring long-term change. The largest relative reductions in flow have been seen in the Arkansas (-19%), South Platte (-18%), San Juan (-15%), and Gunnison (-13%), with smaller reductions in the Yampa (-3%), Colorado headwaters (-5%), and Rio Grande headwaters (-8%). A growing body of evidence indicates that the recent lower streamflows in Colorado have been driven not just by below-normal precipitation, but also by anthropogenic warming ((*Udall and Overpeck 2017*), (*McCabe et al. 2017*), (*Xiao et al. 2018*), (*Hoerling et al. 2019*), (*Albano et al. 2022*; *Milly and Dunne 2020*). While most of these studies have focused on the Upper Colorado River Basin (i.e., Yampa, Colorado, Gunnison, San Juan) the general findings are applicable to Colorado's other river basins. The rough consensus that emerges from these studies is that 20-50% of the observed reduction in streamflows since 2000 has been due to warmer temperatures. As discussed in Chapter 2, anthropogenic atmospheric changes may also have some role in the reduced precipitation since 2000, alongside natural variability.

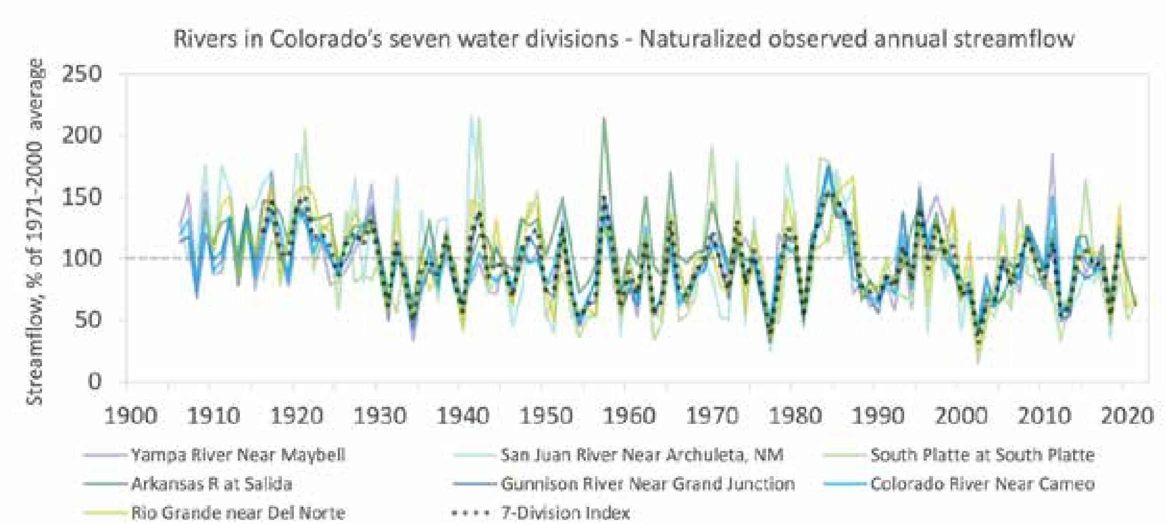

Figure 3.4: Observed naturalized annual (water-year) streamflows for key gages in seven river basins, one from each of Colorado's water division, from the early 1900s through 2019 or 2021, depending on the gage. The gage records have been corrected for upstream diversions and depletions to reflect the natural hydrology of the watershed. (Data sources: Yampa, Gunnison, San Juan, Colorado: Reclamation; South Platte: Denver Water; Rio Grande: CO DWR; Arkansas: J. Lukas based on Hydrosphere/Aurora Water)

Future streamflow projections

As Colorado's climate continues to warm over the next several decades (Chapter 2), the warmer temperatures will have increasing systemic impacts on the hydrologic cycle. Given the same amount of precipitation, annual runoff will be lower in a warmer climate—an effect that is already occurring as described above. It is uncertain how much Colorado's climate will warm (Chapter 2), and it is not precisely known how sensitive the streamflow in Colorado's river basins is to each increment of warming. However, the science is clear: further warming alone will push the water cycle towards reductions in streamflow and water supply.

Due to the pervasive impacts of warming, most of the plausible climate and hydrologic futures for Colorado's river basins show decreasing annual runoff. Increases in runoff will occur only if there is a large future increase in precipitation. This general finding has been seen across many studies, using different sets of climate models, different downscaling methods, and different hydrologic models ((*Nash and Gleick 1991*), (*Christensen et al. 2004*), (*Christensen and Lettenmaier 2007*), (*Reclamation 2011*), (*CWCB 2012*), (*Woodbury et al. 2012*), (*Lukas et al. 2014*), (*Alder and Hostetler 2015*), (*Harding 2015*), (*Lukas et al. 2020b*), (*Reclamation 2021*)). In studies that have projected future changes in streamflow for multiple basins across Colorado, besides the Colorado River and headwaters, the overall tendency towards lower future flows is not as strong in the northwestern basins (*Yampa and White*), while it is strongest in the southern basins (San Juan, Rio Grande) ((*CWCB 2012*), (*Lukas et al. 2014*), (*Harding 2015*)).

Figure 3.5 shows the projected annual streamflow change under RCP4.5 between the historical baseline (1971-2000) and the 2050-centered period (2035-2064) for gages within seven major Colorado river basins, based on the set the hydrologic projections (CMIP5-LOCA-VIC) described above under future snowpack projections. In every basin, a large majority (65-80%) of the 32 projections indicate decreased streamflow in the 2050-centered period, even though most of the underlying climate model projections show at least slightly higher annual precipitation in the future period (Chapter 2). This difference between the precipitation outcomes and the streamflow outcomes reflects the impact of warming in reducing streamflow for a given amount of precipitation.

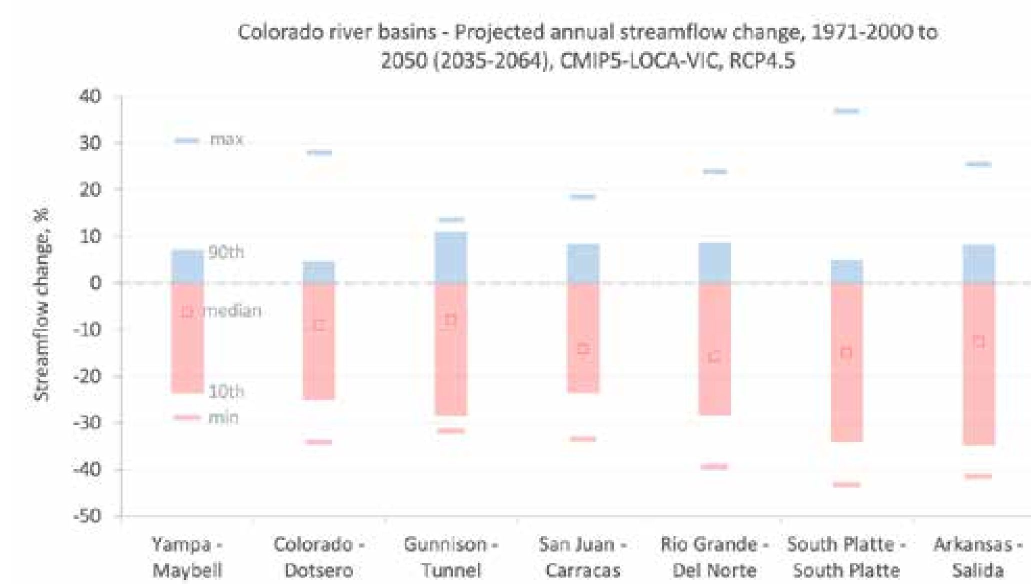

Figure 3.5: Projected future annual streamflow change for key gages in seven Colorado river basins for a 2050-centered period (2035-2064) relative to 1971-2000, from an ensemble of 32 CMIP5-LOCA-VIC hydrology projections under a medium-low emissions scenario (RCP4.5). The solid blue and red bars show the middle 80% of the projections (10th-90th percentiles); the two dashes show the minimum (red) and maximum (blue) projections; the open squares show the median projections. (Data: GDO-DCP, https://gdo-dcp.ucllnl.org/)

The relative impacts of warming and precipitation change on projected streamflow can be seen in Figure 3.6, which shows the 32 CMIP5-LOCA-VIC projections of streamflow change for the Colorado River near Dotsero as a function of that projection's temperature increase and precipitation change. From the statistical relationships between streamflow change, temperature change, and precipitation change underlying this chart, we can estimate that an ensemble-average warming (~4°F) for 2050, relative to 1971-2000, coupled with no precipitation change would result in a streamflow decline of ~13%. Since about 1.5°F of warming has already occurred beyond the 1971-2000 average, this implies that a ~5% streamflow decline has already occurred, with another ~8% decline taking place by 2050, under the 4°F overall warming scenario. These estimates are consistent with previous studies suggesting that each 1°F increment of warming results in a streamflow reduction of 3-5% in Colorado river basins ((*Woodbury et al. 2012*), (*Vano and Lettenmaier 2014*), (*Milly and Dunne 2020*)). The minority of the projected climate futures that show increased streamflow in the 2050 period (Figure 3.6; blue bubbles) are all predicated on an increase in annual precipitation of at least 5%, enough to overcome the impacts of warming. Previous studies have found that a precipitation change of 1% results in a streamflow change of 2-3% (*Vano and Lettenmaier 2014*), consistent with what is seen here.

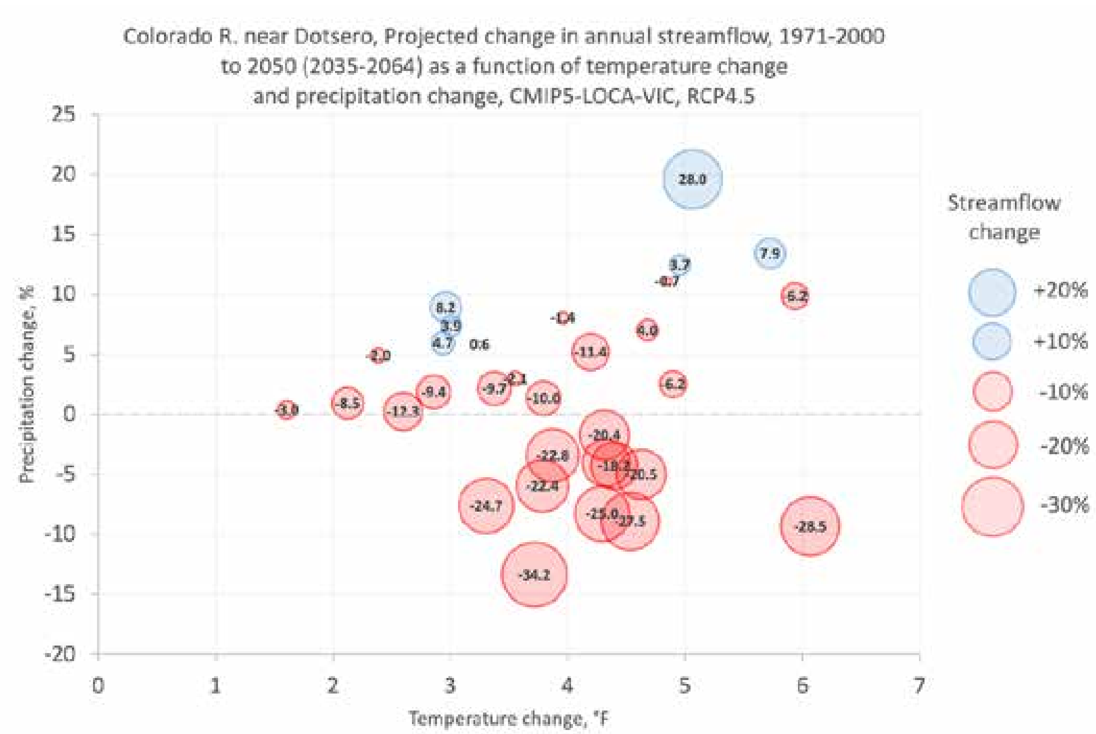

Figure 3.6: Projected change (%) in annual streamflow (values inside the circles) for the Colorado R. near Dotsero gage, as a function of the projected temperature increase (x-axis) and precipitation change (y-axis), for a 2050-centered period (2035-2064) relative to 1971-2000, from an ensemble of 32 CMIP5-LOCA-VIC hydrology projections under a medium-low emissions scenario (RCP4.5). (Data: GDO-DCP, https://gdo-dcp.ucllnl.org/)

The same analysis of CMIP5-LOCA-VIC projected streamflow, temperature, and precipitation for the South Platte River at South Platte shows a similar pattern as for the Colorado River, though with greater sensitivity to warming. For the South Platte, an ensemble-average warming (~4°F) for 2050 relative to 1971-2000, coupled with no change in precipitation, is associated with a streamflow decline of ~18%. If 1.5°F of that warming has already occurred, that implies a warming-driven streamflow reduction of ~7% to date, with ~11% yet to come by

2050 under the +4°F scenario. The magnitudes of these estimates are consistent with previous studies that have examined climate change impacts for the South Platte ((*Woodbury et al. 2012*), (*Harding 2015*)).

As noted earlier in section 2.2, most CMIP5 projections show increased interannual variability in future precipitation for Colorado, implying that streamflow variability would also increase. The projections for the Upper Colorado River Basin (Lees Ferry) as analyzed for *Lukas et al. (2020)*, also from the CMIP5-LOCA-VIC dataset, show increases in the coefficient of variation (CV) of annual streamflows from the late 20th century (1950-1999) to the mid-21st century (2025-2074) in about 70% of the projections.

Future changes in the annual volume of streamflow due to warming will also be accompanied by changes in the timing of streamflow, consistent with the shifts in timing that have already been observed in the past few decades. For streamflow timing, projections based on climate models show near-unanimity regarding the direction of change towards even earlier snowmelt, runoff, and peak streamflow.

Figure 3.7 shows the CMIP5-LOCA-VIC projections of monthly streamflow for the Colorado River near Dotsero for the 2050-centered period compared to the 1971-2000 baseline. There are systematic shifts in the streamflow for almost all months. For March, April, and May, monthly streamflow increases across the model projections as snowmelt and runoff is initiated earlier, and the hydrograph shifts from a sharp peak in June to a more of a "plateau" across May and June, with a May peak in some cases. Flows in June decrease in most projections, and then as the declining limb of the hydrograph shifts and steepens, flows in July, August, and September decrease sharply in all projections. Late fall and winter baseflows (Oct-Feb) are also lower in nearly all projections.

Note that this modeled shift in the hydrograph does not consider the effects of dust-on-snow deposition (Chapter 4), which also acts to shift snowmelt and runoff earlier in the spring. Especially in the southwestern basins of Colorado, which have experienced greater dust-on-snow impacts, a future increasing trend in dust-on-snow events and dust deposition could have a larger effect on shifting the runoff timing than climate change alone and would compound the warming-related shift ((*Deems et al. 2013*), (*Painter et al. 2018*)).

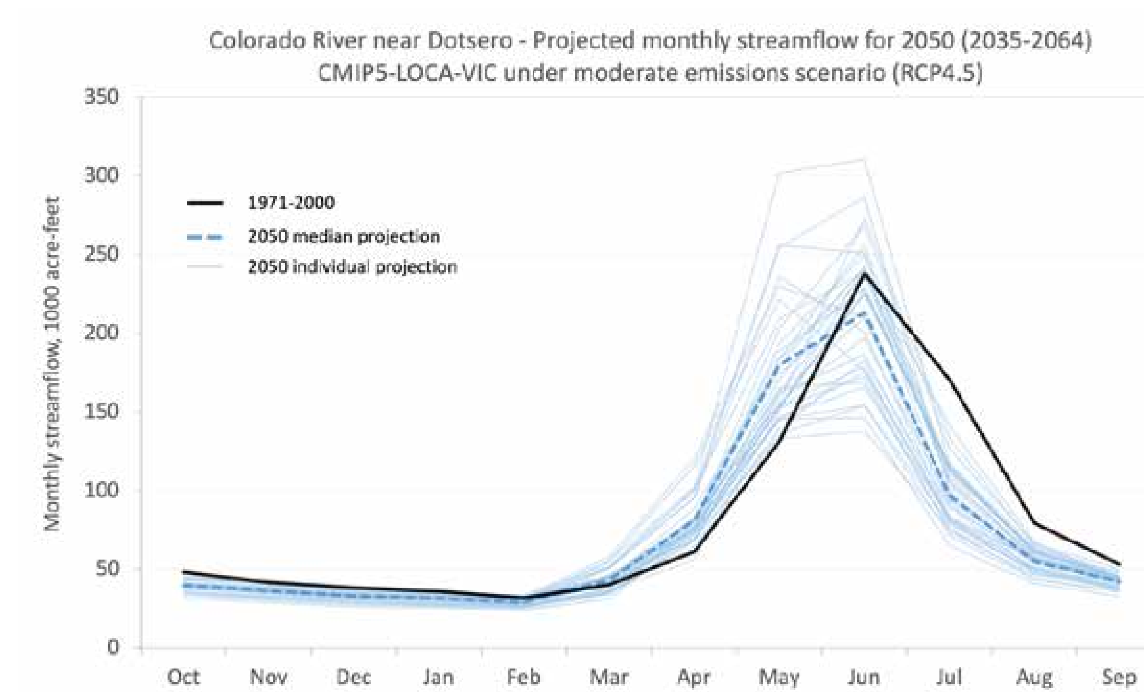

Figure 3.7: Projected future monthly streamflows for the Colorado River at Dotsero for a 2050-centered period (2035-2064) from an ensemble of 32 CMIP5-LOCA-VIC hydrology projections (thin blue) under a medium-low emissions scenario (RCP4.5), and the simulated mean streamflow for the 1971-2000 period (black). (Data: GDO-DCP, https://gdo-dcp.ucllnl.org/)

3.4 Soil Moisture

Overview

Soil moisture is an important component of Colorado's hydrologic cycle. Balanced soil water content is essential for the health of agricultural and natural ecosystems. Persistent low soil moisture levels will reduce agricultural yields, stress native vegetation, and reduce both the amount and predictability of Colorado's water supply ((*Livneh and Badger 2020*), (*Goble et al. 2021*), (*Sazib et al. 2020*)). Extreme wet soil moisture anomalies, which are much less common in Colorado, are associated with increased flooding and pest and disease issues (*Javelle et al. 2010*; *Chuang et al. 2012*).

Soil moisture has an important feedback effect on weather. Part of the sun's incoming energy evaporates water from bare soil and leads plants to transpire water from their leaves while carrying out photosynthesis. When soil moisture is unavailable, this fraction of the sun's energy instead will directly heat the earth's surface. Low soil moisture also limits atmospheric water vapor near the ground, an important ingredient for generating thunderstorms. Particularly during summer, dry soils will act to sustain hot, dry atmospheric conditions until a large-scale weather system breaks the pattern (*McKinnon et al. 2021*)

Much of Colorado is classified as a semi-arid climate, which means some soil moisture limitations are to be expected in a normal year. Surface soil moisture gets recharged only after rain events and then used by plants for transpiration. Plants with access to only shallow soil moisture (less than 36") must be able to survive for days-to-weeks during the growing season without water. Trees and deep-rooted plants can make use of deeper soil moisture supplied primarily from snowmelt.

In Colorado our understanding of soil moisture averages, seasonal variation, interannual variation, and trends at large spatial scales comes mainly from modeling. Land surface models (e.g., Noah, VIC), which use observed weather data as inputs, are often relied upon to enhance our understanding of Colorado soil moisture. The combination of the Snowpack Telemetry Network (SNOTEL) and Colorado Agricultural Meteorological Network (CoAgMET) offer a limited (< 20 years) observational record at high (8000+ feet) and low elevations. Additionally, it is difficult to interpolate between observations because soil moisture is dependent on soil type, which can change over short distances.

Root-zone soil moisture in Colorado typically peaks in the spring both at high and low elevations. High-elevation soil moisture increases sharply as the snowpack melts. Lower elevation soil moisture, particularly on the eastern plains, remains low through the dry season in winter but increases in response to cool, soaking rains in the spring. During the summer season, soil moisture decreases overall due to evapotranspiration but spikes in response to convective rain events. Soil moisture is typically lowest at the end of the growing season (early fall).

Observed soil moisture changes

Soil moisture models typically do a poor job detecting long-term trends in soil moisture. *Fan et al. 2004* showed that on a global scale, soil moisture models capture the seasonal cycle and spatial variability of soil moisture better than trends. Even so, *Andreadis and Lettenmaier, (2006)* found significant decreases in soil moisture in southern Colorado from the mid-20th century to the early 21st century. *Tobin et al. (2020)* showed significant decreases in soil moisture for eastern Colorado in summer and fall.

Like precipitation, snowpack, and streamflow, soil moisture varies considerably from year to year based on weather patterns. Based on the North American Land Data Assimilation System (NLDAS) Noah model analyses for elevations above 8000' in Colorado, soil moisture in the uppermost 2 m (80") has declined from 1980-2022 (Figure 3.8). Water year 2021 saw record-low fall soil moisture conditions following a poor snowpack year and a hot and dry summer, including a record-warm August for western Colorado (*NOAA National Centers for Environmental Information 2023*)

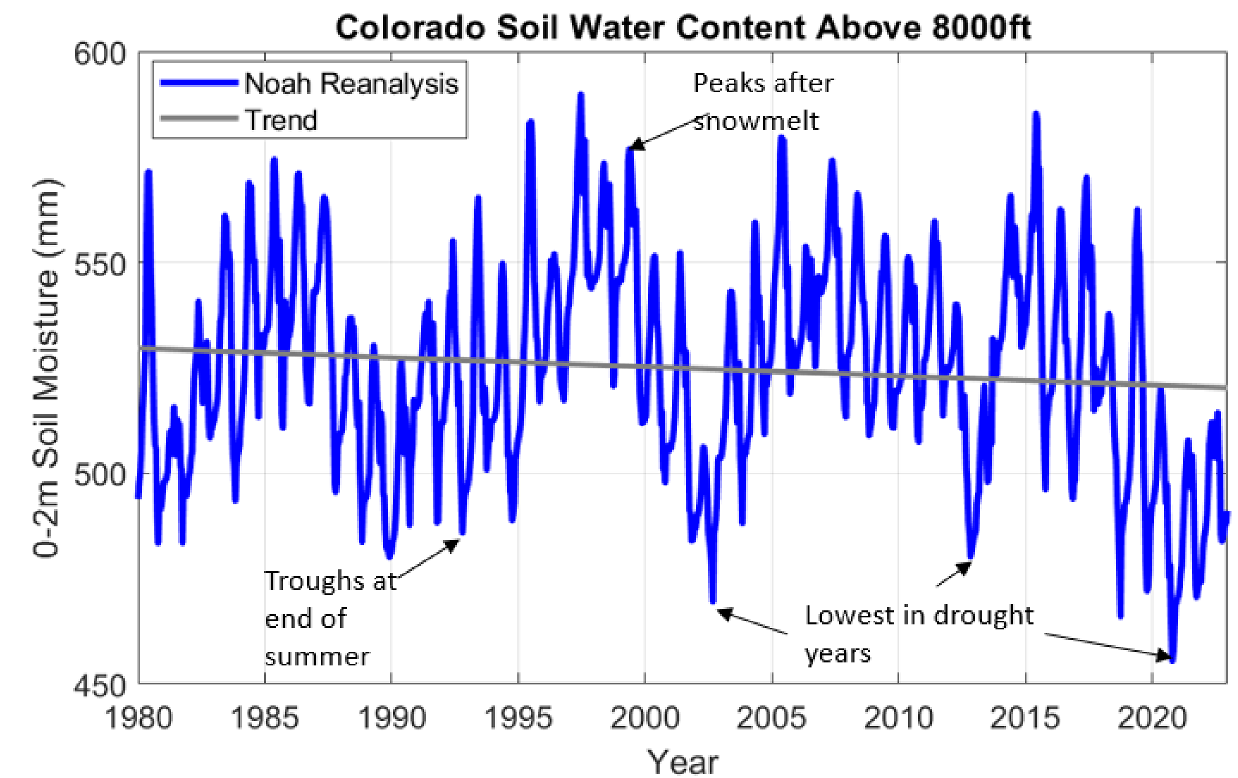

Figure 3.8: Colorado volumetric water content in top 2m soils above 8000ft, for 1980-2022. NLDAS Noah model reanalysis soil moisture in blue, with trend line in gray.

Future soil moisture projections

As the climate continues to warm, the evaporative demand of the atmosphere increases (see section 3.5), which will tend to drive more moisture from soils through both direct evaporation and transpiration from plants, i.e., evapotranspiration. In high-elevation areas where most soil moisture derives from snowmelt, warming temperatures will act to reduce the snowpack through sublimation even before that snow water has a chance to enter the soils.

Previous studies projecting future (~mid-21st century) soil moisture for Colorado's key runoff-producing basins have consistently shown widespread declines in summer (June-August) soil moisture (typically, down to 2 m/80") regardless of the ensemble of climate models and hydrologic models used ((*Ray et al. 2008*), (*Reclamation 2012a*), (*Ayers et al. 2016*)). These analyses also showed increases in spring (March-May) soil moisture as snowmelt shifts earlier (see Snowpack, above) and leads to a saturated soil column earlier in the year relative to historical conditions.

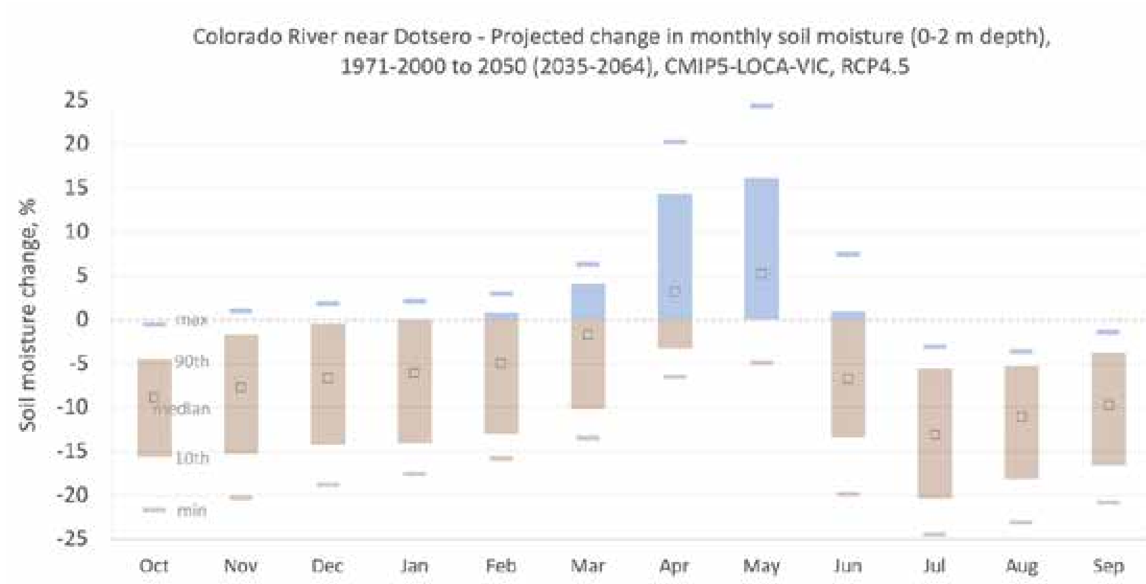

Figure 3.9: Projected future changes in monthly soil moisture (0 - 2 m depth) for the watershed above the Colorado River near Dotsero for a 2050-centered period (2035-2064) from an ensemble of 32 CMIP5-LOCA-VIC hydrology projections under a medium-low emissions scenario (RCP4.5). The solid blue and brown bars show the middle 80% of the model projections (10th-90th percentiles); the two dashes show the minimum and maximum projections; the open squares show the median projections. (Data: GDO-DCP, https://gdo-dcp.ucllnl.org/)

Figure 3.9 shows the CMIP5-LOCA-VIC projections of change in monthly total soil moisture (0-2 m/0-79" depth) for the watershed above the Colorado River near Dotsero for the 2050-centered period, compared to the 1971-2000 baseline. The pattern in monthly and seasonal changes is consistent with the previous studies: Most of the individual projections show increases in spring (April-May) soil moisture, due to earlier snowmelt, but nearly all projections show decreases in the summer, fall, and winter months, driven by warming temperatures. Since soil moisture—along with the snowpack—acts as the interface between the atmosphere and streamflow, it is not surprising that these projected changes in soil moisture appear very similar to the projections of change in monthly streamflow (Fig 3.7 above).

3.5 Evapotranspiration

Overview

Evapotranspiration (ET) encompasses evaporation from soils and open water, transpiration from plants and crops, and sublimation from the snowpack. On a statewide basis, about 80% of the precipitation that falls on Colorado returns to the atmosphere through ET before reaching a stream or aquifer. The relatively cool and wet high mountain areas experience smaller fractional ET losses, but typically amount to 30-50% of annual precipitation (*Sanford and Selnick 2013*).

ET technically refers to the actual loss of water from the land surface—thus, the alternative abbreviations AET (actual evapotranspiration) and ETa are used for clarity. The magnitude or rate of AET is constrained by the water that is available to evaporate or transpire (Figure 3.10). After soils and vegetation are fully dried out, no

more AET can occur. So cumulative AET over an extended period (e.g., 12 months) will not exceed cumulative precipitation—or in the case of irrigated cropland, precipitation plus the depth of irrigation water.

Evaporative demand (E0) and its equivalent, Potential Evapotranspiration (PET), are measures of the atmosphere's "thirst" for surface moisture, and thus the potential loss of water from the land's surface. E0 and PET can exceed and often do exceed AET over any given period. The conceptually similar Reference ET (ET0) is an estimate of the upper bound of ET losses given a particular crop that is fully irrigated. Reference ET is the measure of evaporative demand that is usually reported by ag-weather station networks such as CoAgMET.

Evaporative demand increases with warmer temperatures, greater solar radiation, lower humidity, and higher winds. Of these, temperature is usually the most important in explaining the level of evaporative demand. PET, E0, and Reference ET are best estimated using a "fully physical" equation such as Penman-Monteith that inputs all four variables: temperature, solar radiation, humidity, and winds; methods using only temperature (Thornwaite, Hargreaves, Blaney-Criddle) have larger errors in real-time monitoring (*Sentelhas et al. 2010*) and are also problematic for modeling future conditions (*Reclamation 2012b*).

The tight coupling between temperature and evaporative demand reflects a basic physical relationship, as well as an important feedback mechanism. First, warmer air can hold more moisture than cooler air, as governed by the Clausius-Clayperon equation. This means that under warmer temperatures—if nothing else changes—evaporative demand increases. This general increase in evaporative demand (PET) with warmer temperatures is clearly seen in the seasonal cycle shown in Figure 3.12. Second, when the soils and vegetation dry out seasonally or periodically (i.e., drought)—which often involves elevated evaporative demand—a feedback mechanism occurs: More of the sun's energy heats the surface and the atmosphere above it, rather than going towards evaporating moisture. This drives faster warming, and lower humidity of the air, thus increasing evaporative demand more rapidly (Figure 3.10, right panel).

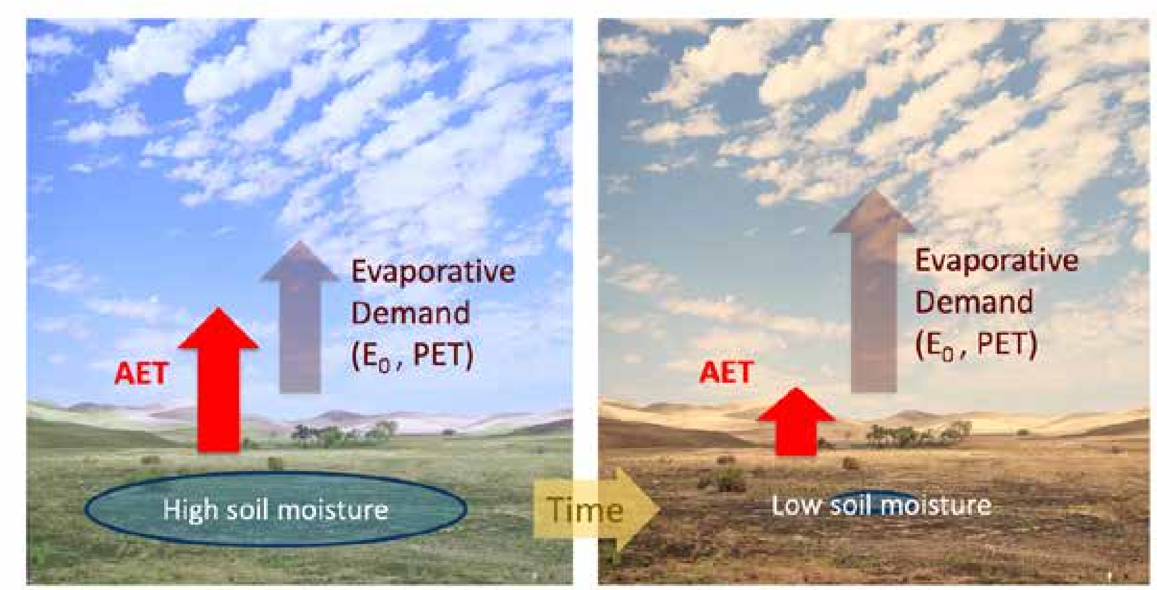

Figure 3.10: Schematic showing how under high soil moisture and water availability, Actual Evapotranspiration (AET) can have the same magnitude as evaporative demand. With time, if the soils dry out, evaporative demand will often increase (as air temperature rises and humidity decreases in response to the now-dry land surface) but AET decreases, limited by the lower amount of water available at the surface to evaporate and transpire. (Modified from Lukas et al. 2017, The EDDI User Guide).

AET is much more challenging to measure than evaporative demand. AET can be estimated using a land-surface (hydrology) model with meteorological inputs, or by assimilating satellite observations of land-surface temperature (which reflects evaporation losses) into an energy-balance model. In-situ measurements of AET can be made using Eddy Covariance (EC) methods, in which several instruments at different heights on a tower measure the vertical transfer of energy and moisture between the surface and the atmosphere.

Observed evapotranspiration changes

Since warming temperatures, all else equal, will lead to higher evaporative demand (E0, PET, Reference ET), it is reasonable to expect that trends in evaporative demand would reflect the strong warming trend in Colorado over the last several decades. And in fact, upward trends in evaporative demand for Colorado have been found in several studies, using different observational datasets ((*Ficklin et al. 2015*),(*McCabe and Wolock 2015*),(*Vicente-Serrano et al. 2020*),(*Albano et al. 2022*)).

Most recently, a comparison of recent U.S. trends in Reference ET (1980-2020), using five gridded observational datasets, found that the average of the datasets show increasing Reference ET trends across all of Colorado, with the largest increases seen in southeastern Colorado, moderate increases in the northeastern and far southwestern parts of the state, and the smallest increases in the northwest part of the state (*Albano et al. 2022*). Examination of the four meteorological components of evaporative demand shows that decreased humidity and increases in solar radiation only contributed a small amount to the observed increase in evaporative demand.

Figure 3.11 shows Colorado statewide PET for the growing season (April-September) since 1980, from the gridMET gridded observational dataset, one of the five used in the *Albano et al. (2022)* study, and whose results are closest to the average across all five datasets. While there is large variability from year to year, the upward trend is clear; statewide PET has increased about 5% over the 1980-2022 period.

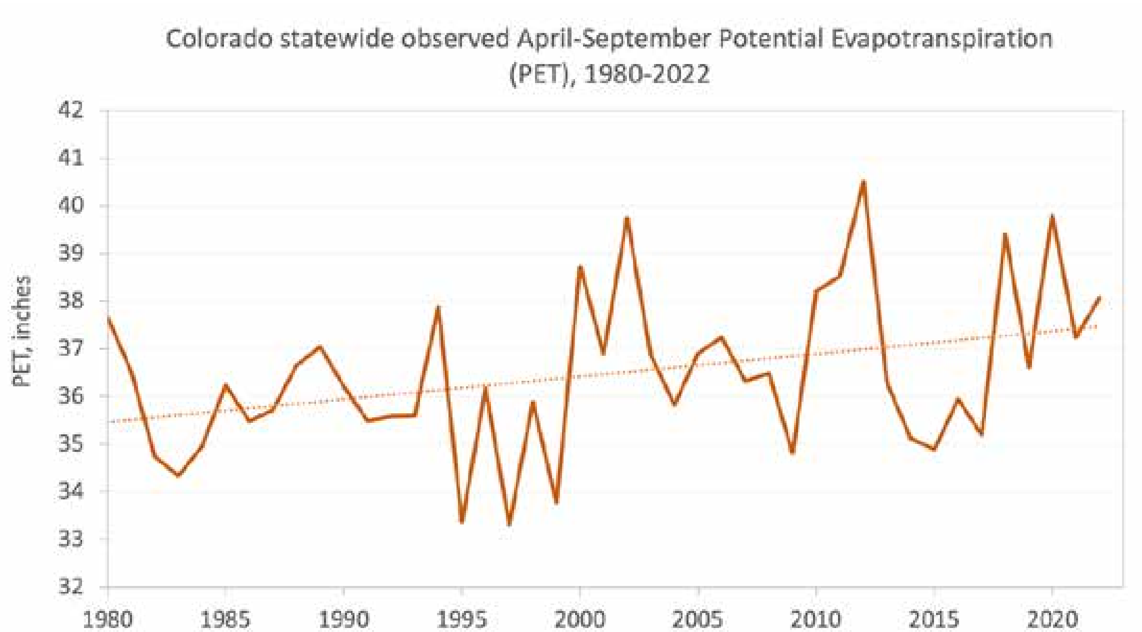

Figure 3.11: Observed Colorado statewide Potential Evapotranspiration (PET) over the April-September growing season, 1980-2022. Dashed line shows the linear trend over that period. (Data: gridMET via Climate Toolbox; https://climatetoolbox.org/tool/historical-climate-tracker).

Future evapotranspiration projections

Given the continued and substantial warming projected for Colorado over the next several decades, further increases in evaporative demand in Colorado are extremely likely. Figure 3.12 shows the projected changes monthly PET under RCP4.5 between the historical baseline (1971-2000) and the 2050-centered period (2035-2064) for the watershed of the Colorado River above Dotsero, using the same projection dataset (CMIP5-LOCA-VIC) in the preceding sections.

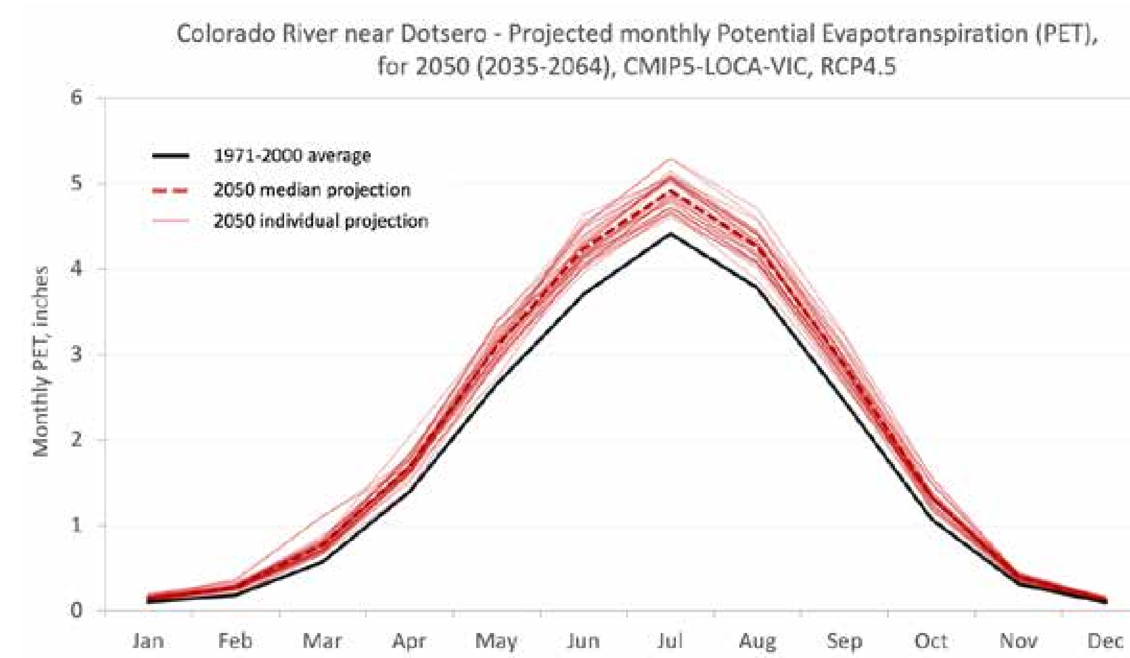

Figure 3.12: Projected future monthly Potential Evapotranspiration (PET) for the watershed above the Colorado River at Dotsero for a 2050-centered period (2035-2064) from an ensemble of 32 CMIP5-LOCA-VIC hydrology projections (thin red) and median (thick red dashed) under a medium-low emissions scenario (RCP4.5), and the simulated mean streamflow for the 1971-2000 period (black). (Data: GDO-DCP, https://gdo-dcp.ucllnl.org/)

Note the extreme seasonality in PET; about 90% of annual PET occurs from April through September. In each month of the year, all 32 projections show increased PET; total April-September PET increases 10% to 20% by 2050 compared to the 1971-2000 baseline. Comparing the PET change with the temperature change in the same 32 model runs, it is clear that temperature is the primary driver of increased PET. Each 1°F of warming leads to about a 4% increase in PET, with a 4°F warming associated with a 15% increase in PET. A similar downscaled projection dataset (CMIP5-MACA), also paired with the VIC hydrologic model, suggests that increases in PET of roughly similar magnitude (~4%) for each 1°F of warming will occur across all elevations both east and west of the Continental Divide.

Chapter 4 | Climate Extremes and Hazards

KEY MESSAGES

Climate variable/event	Recent trend	Projected future change	Confidence in change
Heat waves	**More frequent/intense**	**More frequent/intense**	**Very High**
Cold waves	**Fewer**	**Fewer**	Medium
Droughts	**More frequent/intense**	**More frequent/intense**	**High**
Wildfires	**More and larger**	**More and larger**	**High**
Extreme precipitation	**More intense**	**More frequent/intense**	Medium
Flooding	Mixed	**Higher**	Medium
Windstorms	Uncertain	Uncertain	Low
Severe thunderstorms	Uncertain	More frequent?	Low
Hail	Uncertain	More large hail?	Low
Tornadoes	Uncertain	Uncertain	Low
Winter storms	Uncertain	Larger storms?	Low
Dust on snow events	**Greater dust levels**	**Greater dust levels**	Medium

Table 4.1: Summary of the observed and projected changes in climate extremes and hazards for Colorado, as detailed in the following sections.

Heat waves and cold waves

- Hot days and heat waves have become more common, and the number cold nights and cold waves has decreased across Colorado in recent decades, but the changes have not been equal. There have been significant increases in extreme heat across most of the state, whereas the decrease in extreme cold has been more modest.
- Projected future changes are similarly asymmetric: Heat waves are projected to increase in frequency by as much as ten-fold by the middle of the 21st century, whereas the frequency of cold waves is projected to decrease by less than half.

Wildfire

- Since 2000, Colorado has experienced a large increase in the number of large wildfires and in the annual area burned by all wildfires; on average, fires have burned at higher elevations and with higher intensity than in the late 20th century. While several factors have contributed to these trends, warming temperatures are a major driver.
- Future warming is expected to lead to further increases in the occurrence of large wildfires and in annual area burned by all fires, especially in forest ecosystems, according to multiple studies. A greater percentage of fires will occur in the fall, winter, and spring than at present.

Heavy and extreme rainfall

- There are some indications of recent increasing trends in heavy and extreme rainfall in Colorado, but these are not consistent across all indicators and time periods, unlike in other regions of the U.S.
- Atmospheric moisture (precipitable water; PW) has generally increased over Colorado, but not by as much as one would predict from the warming atmosphere alone.
- Future warming, by increasing the moisture-holding capacity of the atmosphere, will make heavy and extreme rainfall more likely unless counterbalanced by declining trends in other storm “ingredients”. Climate-model projections for Colorado show overall increases in the magnitudes of heavy and extreme rainfall events.

KEY MESSAGES CONTINUED:
Drought, Floods, Thunderstorm hazards, Non-convective windstorms, Winter storms, Dust-on-snow

KEY MESSAGES

Drought

- Warming temperatures have increased the severity of 21st century droughts in Colorado.
- Regardless of changes in precipitation, it is likely that warmer temperatures will contribute to more frequent and severe droughts. Warmer temperatures will also decrease the benefit of wetter years.

Floods

- Gaged streamflow records show no widespread, consistent trends in the magnitude of flood events in Colorado of different frequencies (e.g., 1-year, 20-year, 50-year, 100-year).
- The expectation that heavy and extreme rainfall events will increase in Colorado implies increases in future flood risk as well, but there are many factors influencing how rainfall is translated into runoff. Increased exposure to flooding through floodplain development may be more important than climate-driven changes in risk.

Thunderstorm hazards

- Because of the relatively short data record for thunderstorm hazards and the influences of changing observation systems, the sign and magnitude of any long-term changes is unclear.
- Some studies have suggested increases in the average size of hail in a warmer climate, with smaller hail becoming less frequent but larger hail more frequent. Overall, however, there remain large uncertainties regarding future changes, as data limitations and the infrequent and localized nature of these storms makes them challenging to study in the context of a changing climate.

Non-convective windstorms

- Colorado is prone to intense winds in the mountains and from downslope windstorms along the Front Range. These windstorms can cause considerable damage, and can exacerbate wildfires, such as in the 2021 Marshall Fire. Long-term changes in extreme winds have not been extensively studied, and potential future changes are highly uncertain.

Winter storms

- Despite warming temperatures in the winter, there are no detectable trends in winter severity across the Colorado Front Range and Eastern Plains. There are also minimal trends in large snowfall events.
- Several notable and high impact winter storm events have occurred over eastern Colorado in the last decade, including extreme cold, high winds, strong cold fronts, and large accumulations of snow.
- Future trends in winter storms remain highly uncertain, but the risk of high-impact winter events is likely to remain.

Dust-on-snow

- Dust-on-snow events have emerged as a concern since 2000 due to better understanding of its hydrologic effects, as well as an overall increase in the occurrence of dust-on-snow. Dust-on-snow causes earlier melt and runoff and may reduce annual runoff.
- It is likely that in a future warmer climate, drier conditions in the dust-source regions will allow for greater dust emission and thus deposition on snowpacks. Dust-on-snow and warming will both drive earlier snowmelt and runoff.

4.1 Overview

This chapter assesses recent trends and likely future changes in climate extremes and climate-driven hazards in Colorado. While it is true that anthropogenic climate change is increasing the overall risk of impacts across the various extreme weather and climate events and natural hazards, both globally and in Colorado, this generalization does not necessarily apply to each type of extreme or hazard. Each type has different climatic drivers, and there may also be non-climatic factors that act to increase (or decrease) their risk and impacts, such as with floods and wildfires.

In general, extremes and natural hazards that have strong physical linkages to warming temperatures are the ones most likely to have already increased and to increase further in the future. At the top of this list are heat waves; droughts and wildfires are also worsened in a warmer climate. All three have shown clear recent upward trends in Colorado. Extreme precipitation also has a direct physical linkage with temperature and is expected to become more frequent and severe with warming, yet this has not been clearly seen in our region. Severe thunderstorms and their related hazards—tornadoes, hail, and winds—have more complex linkages with warming. Due to observational challenges, it is difficult to assess recent trends and future projections for thunderstorm hazards.

In the sections below, for each type of climate extreme or hazard, we describe its drivers, examine recent variability and trends to the extent that observed datasets can support that assessment, highlight recent high-impact events, and then summarize the likelihood of future changes and the evidence for that assessment. This chapter emphasizes the observed and potential future changes of these extremes and hazards, with limited references to the impacts from these events. The update to the Colorado Vulnerability Study will provide greater detail on Colorado's vulnerabilities, documented impacts, and risk of future impacts to these types of events.

4.2 Heat Waves and Cold Waves

Overview

As the climate warms, periods of extreme heat are expected to become more frequent, while periods of extreme cold become less frequent (*USGCRP 2017*). Two different approaches can be employed to investigate changes in temperature extremes. One is to consider the exceedance of absolute temperature thresholds (e.g., exceeding 95°F or dropping below 0°F). The advantage of this method is that these thresholds are familiar to people, and they generally correspond to some kind of impact (e.g., heat stress to humans and animals increases at higher temperatures). The disadvantage is that, in a state as diverse as Colorado, some areas surpass these thresholds many times per year, whereas other areas may never experience those temperatures. Another method is to consider temperatures that are rare for that location (e.g., a temperature that occurs on average only once per year, or that exceeds a percentile, etc.). Furthermore, when considering heat waves and cold waves, many different definitions have been proposed in the literature (e.g., (*Perkins and Alexander 2013*)). Regardless of the specific methods used, available data show that heat waves are generally becoming more frequent, and cold waves less frequent, in Colorado. However, the details of the results vary, as shown below.

Observed heat and cold wave changes

Changes in exceedance of high and low absolute temperature thresholds

Comparing the most recent two decades (2001-2020) to the 1971-2000 period shows that in eastern Colorado and the valleys in western Colorado, the number of hot days (95°F or higher) has increased. Some areas experienced over 10 more hot days per year during the period from 2001-2020 than during the period from 1971-2000 (Fig. 4.1a). Other thresholds such as 90°F show similar spatial patterns; although many areas in Colorado, especially at high elevations, rarely or never reach 90°F.

Very cold nights are becoming less frequent across Colorado but generally at a slower pace than hot days are increasing. Fig. 4.1b shows that the San Luis Valley has experienced the greatest reduction in sub-zero temperatures, by a few days per year. Most other parts of the state have relatively small reductions of 1-2 nights per year, whereas a few pockets in Gunnison, Fremont, and Rio Blanco Counties have seen small increases in the frequency of sub-zero temperatures. In some areas of southeastern Colorado, temperatures below zero are very rare.

Calculations at individual stations (not shown) are generally consistent with the findings from the gridded dataset used in Fig. 4.1. However, this gridded dataset only has daily data available back to 1951, and long-term stations in southeastern Colorado show that the dust bowl era in the 1930s had more frequent occurrence of extreme heat than even the first two decades of the 2000s. Nonetheless, recent trends in this part of the state are toward more frequent hot days.

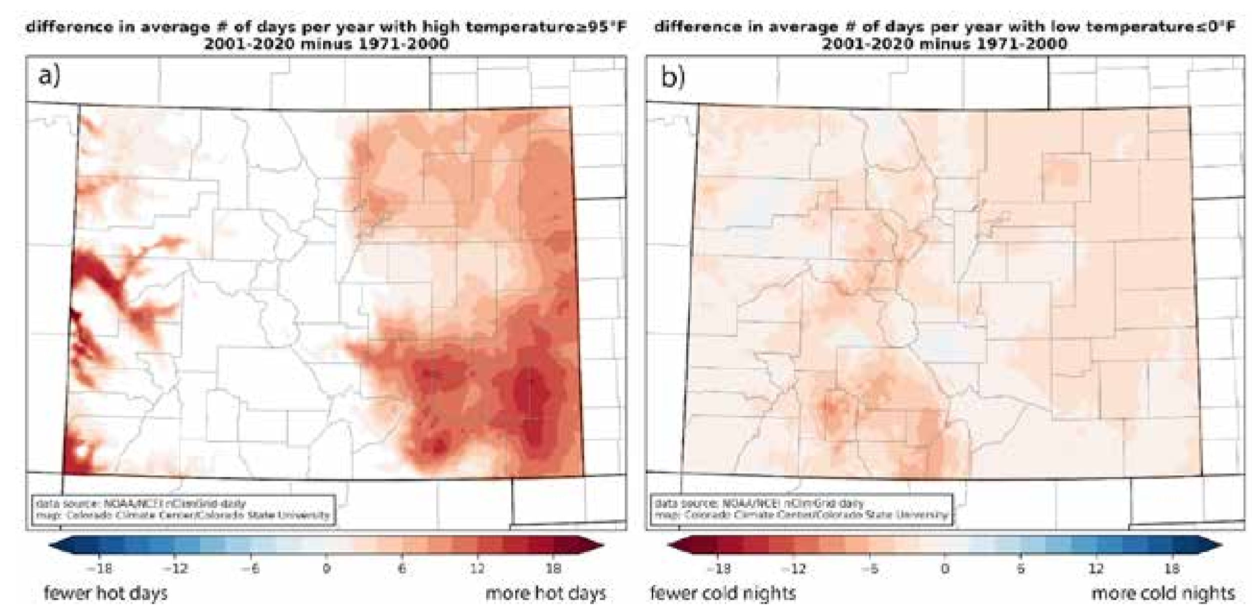

Figure 4.1: Differences in the number of days per year with (a) daily maximum temperature ≥ 95°F, and (b) daily minimum temperature ≤ 0°F, comparing the period 2001-2020 to 1971-2000.

Changes in occurrence of heat waves and cold waves

In contrast to the absolute temperature thresholds presented above, heat waves and cold waves are generally defined relative to the historical temperature ranges for an area. Some studies consider heat/cold waves as consecutive days exceeding a threshold ((*Perkins and Alexander 2013*), (*Keellings and Moradkhani 2020*), (*Domeisen et al. 2023*)), whereas others consider the average temperature over a period of days (*Peterson et al. 2013*). Here, we will use a definition for heat and cold waves that is similar to *Peterson et al. (2013)*. Specifically, a heat wave or cold wave is defined using a 4-day averaged daily mean temperature (daily mean is the average of the high and low for the day). The 4-day average temperature that was exceeded on average once per year during 1971-2000 was defined as a heat or cold wave (in other words, the average hottest or coldest 4-day period per year during 1971-2000). This calculation is done for each alternate climate division, and then the number of heat/cold waves in each year and decade over the full dataset (1951-2022) were calculated. Other definitions of heat/cold waves, including different lengths and requiring consecutive days exceeding a threshold, showed qualitatively similar results. The benefits of this calculation are 1) it includes both maximum and minimum temperature in the analysis, 2) the four-day average indicates a sustained period of hot or cold (thus a "wave"), and 3) the extreme threshold is uniquely defined for each climate division.

Heat waves have increased in frequency from the 1950s to present in all climate divisions (Fig. 4.2), though the upward trend is statistically significant in only 8 of the 11 divisions. In particular, the decades of the 2000s and 2010s had substantially more heat waves than the preceding decades in nearly all divisions. The increases are especially large in the Northwest and Mesas & Valleys divisions, where very few heat waves occurred in the 1950s and 60s, and then 2-3 per year occurred on average in the 2000s and 2010s. The increase in heat waves has been less prominent in the Northeast and Southeast divisions (Fig. 4.2), despite the total number of hot days increasing (Fig. 4.1a).

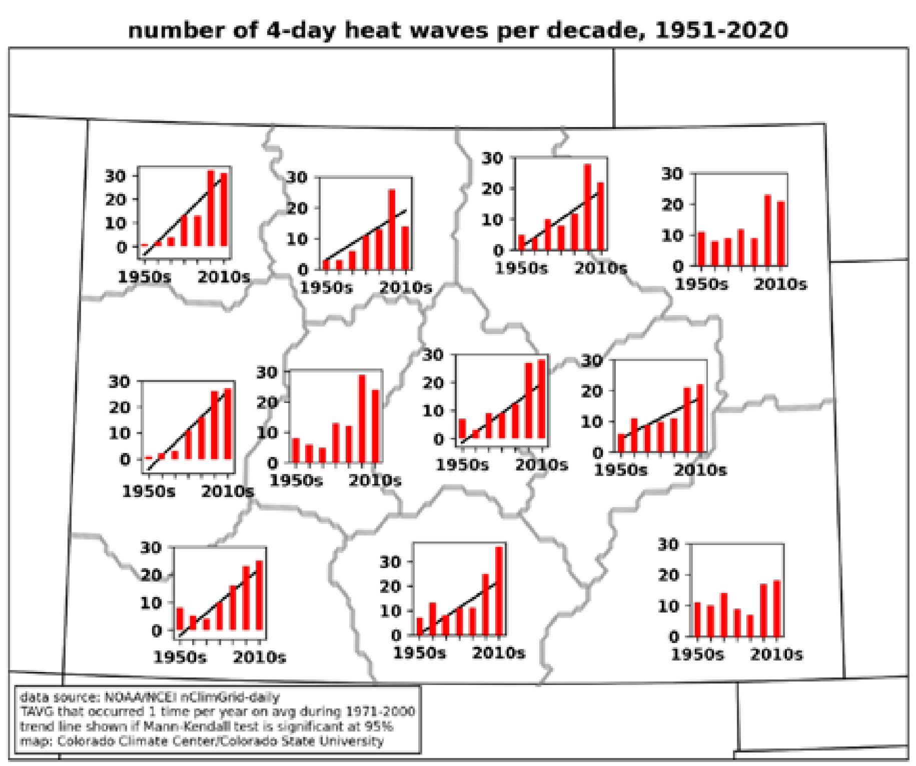

Figure 4.2: Time series of the number of 4-day heat waves per decade from 1951-2020 for each climate division. (See Fig. 2.2 for the names of the divisions.) Heat waves are defined as a 4-day period in which the daily mean temperature (the sum of the daily maximum and minimum temperatures divided by two), averaged over the four days, exceeds the 4-day average temperature that was exceeded on average once per year during 1971-2000.

Data for 2021-22 (not included in the decadal analysis above) revealed a large number of heat waves in all parts of the state; in some divisions, there were more heat waves in the first two years of the 2020s than in some entire decades in the 20th century.

Cold waves have generally declined in frequency across Colorado from 1951-2020, but the decline is much less pronounced than the increase in heat waves (Fig. 4.3). The decrease in 4-day cold waves was not found to be statistically significant in any of the climate divisions. In most divisions, the 1970s and 80s had a large number of cold waves; then, they declined in the 1990s and 2000s before increasing slightly in the 2010s.

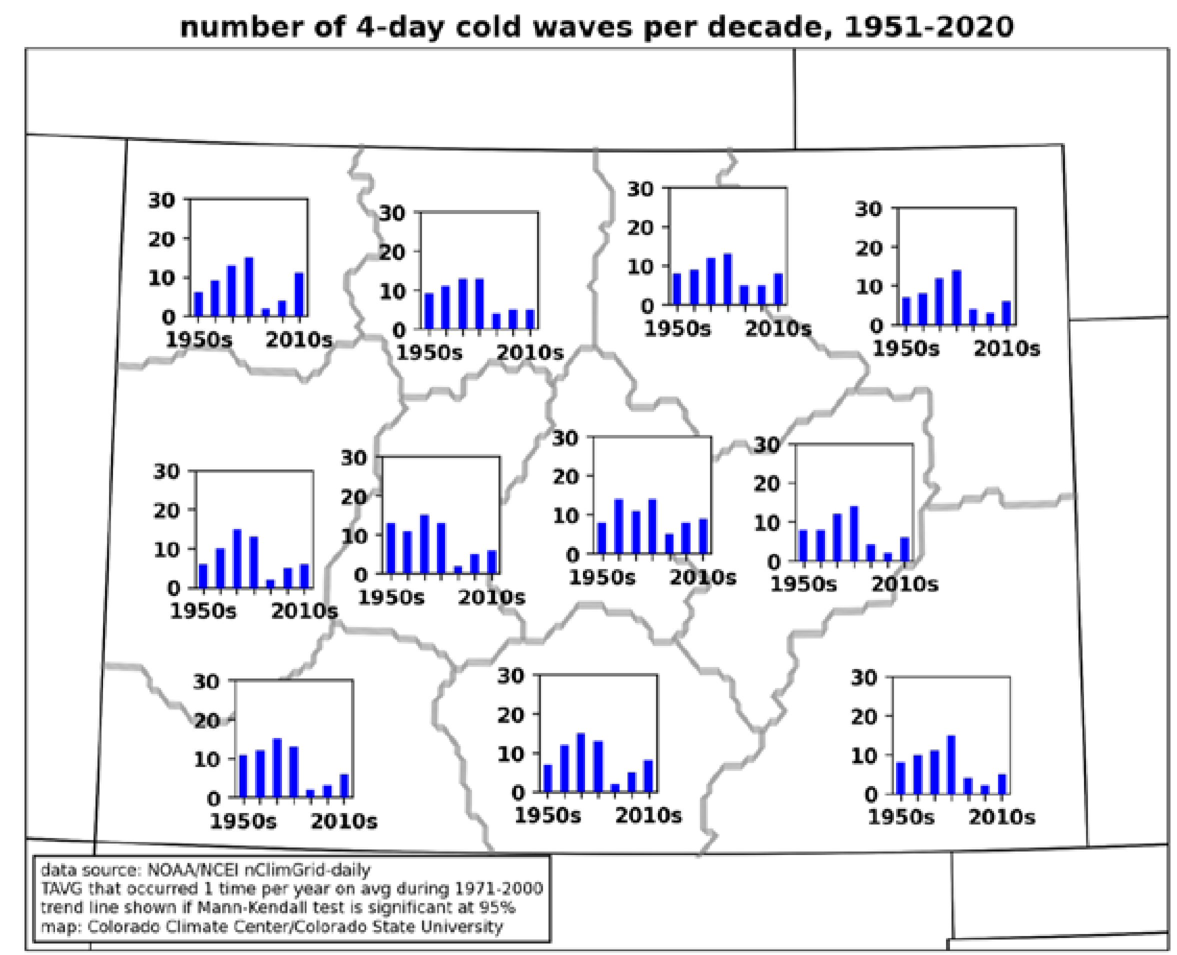

Figure 4.3: As in Fig. 4.2, but for 4-day cold waves.

Future heat and cold wave projections

Research has consistently indicated that heat waves are likely to increase in frequency and intensity in a warmer climate (*Domeisen et al. 2023*). In one study relevant to Colorado, *Cowan et al. (2020)* examined what would happen if the anomalous conditions associated with the Dust Bowl-era heat waves occurred in the present-day climate. They found that those 1930s heat waves that had a probability of around 1 in 100 years, would have a probability closer to 1 in 40 years today (and a higher probability in an even warmer climate). They also illuminate the impact of dry springs, noting that summer heat waves are generally more frequent and intense following a dry spring as compared to a wet spring.

The 32 CMIP5-LOCA model projections for medium-low emissions scenario RCP4.5 (described in Chapter 2.2) were analyzed using the same definitions of heat waves and cold waves that were used for observed conditions. Specifically, the 4-day average temperature (hot or cold) that was exceeded on average once per year during 1971-2000 was identified in each individual model run, and then occurrences of those temperatures in daily CMIP5-LOCA output from 1951-2090 were tabulated.

Heat waves are projected to increase at a rapid pace in all parts of Colorado as the climate warms. In most regions, the median number of projected heat waves is expected to increase from 1 per year during 1971-2000 (by definition; not shown), to approximately 10 per year by the 2060s (Fig. 4.4). Some projections show a smaller increase in the number of heat waves, others a much larger one. All model projections show a statistically significant increase in heat waves from the 1950s to the 2080s in all regions; at least 90% of the model projections show a significant increase in heat waves from the 2000s to the 2080s in all regions except the Southeast (where there is 87.5% agreement among models for a significant increase). To put these results in other terms: what would have been the hottest 4-day period of each year during 1971-2000 is projected to occur approximately 10 times--spanning 40 days per year--by the 2060s.

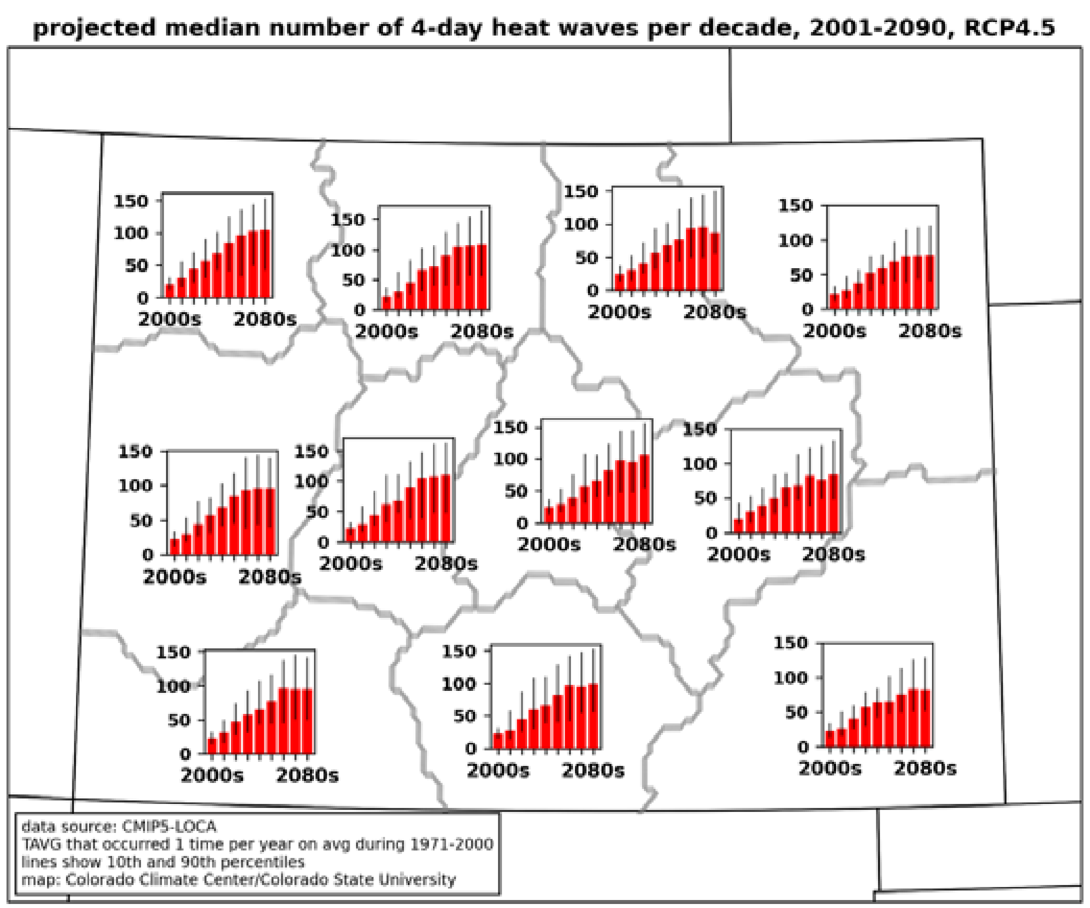

Figure 4.4: Time series of the number of 4-day heat waves per decade from 2001-2090 in CMIP5-LOCA projections for each climate division. (See Fig. 2.2 for the names of the divisions.) The red bars indicate the median projection for each decade, and the lines indicate the 10th and 90th percentile of the 32 projections. Heat waves are defined as a 4-day period in which the daily mean temperature (the sum of the daily maximum and minimum temperatures divided by two), averaged over the four days, exceeds the 4-day average temperature that was modeled on average once per year during 1971-2000 in each individual model projection.

Although extreme cold is also generally expected to decrease in frequency as the climate warms (e.g., *USGCRP 2017*), in Colorado, both observations (Fig. 4.3) and future projections (Fig. 4.5) indicate that cold waves will not decrease nearly as much as heat waves increase. Whereas model projections indicate that heat waves will increase in frequency by as much as ten-fold, similarly defined cold waves are projected to decrease in frequency by half, or even less, depending on the region (Fig. 4.5). There is also much less agreement on the robustness of the trend: fewer than half of CMIP5-LOCA projections show a statistically significant decrease in 4-day cold waves across the 21st century. In most regions, the frequency of cold waves decreases from roughly once per year in the early 21st century, to roughly once per two years by late century.

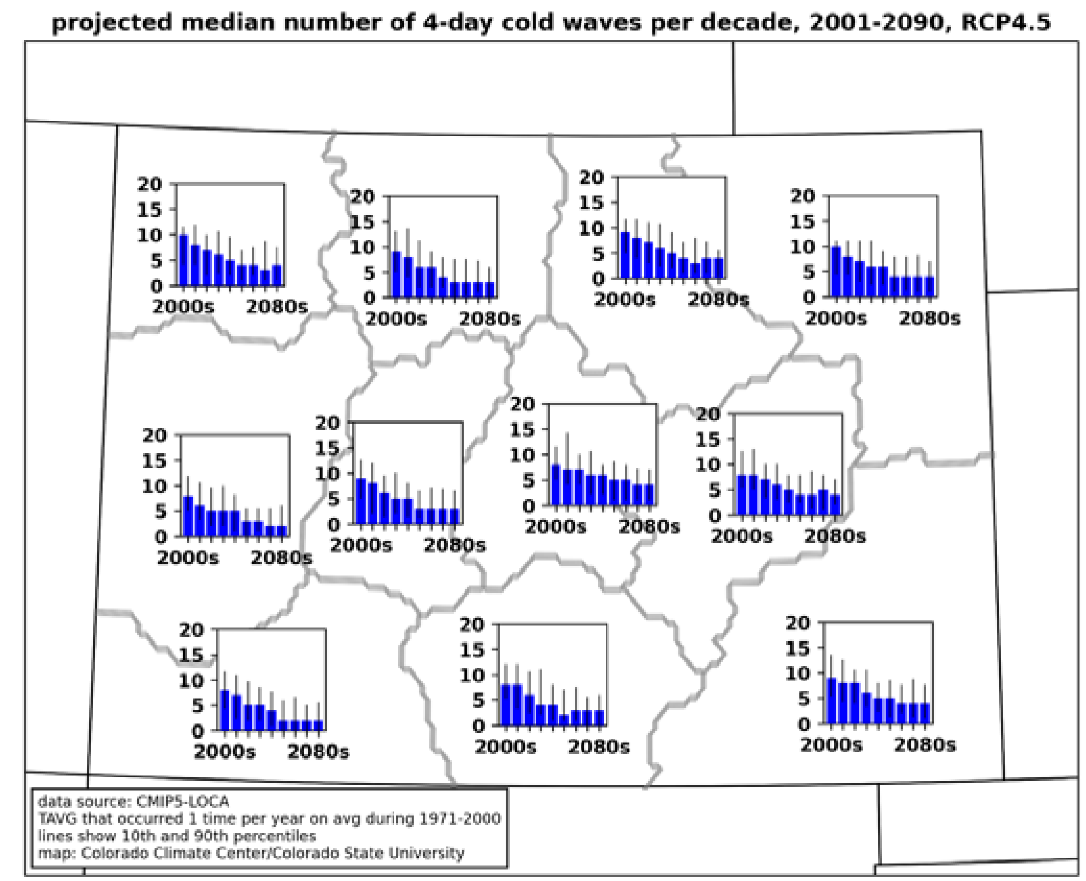

Figure 4.5: As in Fig. 4.4, but for cold waves.

The strong asymmetry in the projections of heat waves and cold waves in a warmer climate is likely to have impacts on the agricultural sector in Colorado. As one example, western Colorado has had several instances in the early 21st century of extremely hot summers punctuated by strong cold waves in the fall and spring that have led to the loss of fruit crops (*NOAA 2020a*). Challenges such as these may become more acute in the future, as periods of extreme heat become much more frequent, but the risk of extreme cold remains.

4.3 Drought

Overview

Most simply defined, drought is insufficient water to meet demands. Drought is most commonly assessed as a deficit of precipitation, snowpack, soil moisture, and/or streamflow across timescales from months to years. Temperature has played a critical role in increasing the severity of recent droughts in Colorado and the Southwest U.S.

Conventional monitoring of droughts has focused on defining extreme deficits in each of the water variables. Historically, the Palmer Drought Severity Index was widely used and included both temperature and precipitation. However, it was insufficient for certain regions of the country and fixed on one time scale (correlating well with 9-month analyses). For precipitation, the Standardized Precipitation Index (SPI) introduced methods to assess the severity of drought on varying timescales (*McKee et al. 1993*). Because of its versatility to work well both spatially and temporally, it became a primary tool for monitoring drought, but it did not consider the temperature aspect of drought.

Warmer temperatures during drought result in higher evaporative demand. Evaporative demand describes the atmosphere's "thirst" for moisture. Drought severity can be exacerbated by high evaporative demand; in conjunction with moisture deficits, the atmosphere is trying to take more water away from the surface (through evaporation and transpiration). To better capture this phenomenon, new indicators and indices have been introduced into regular drought monitoring, including the Standardized Precipitation Evapotranspiration Index (SPEI) (*Vicente-Serrano et al. 2010*), the Evaporative Demand Drought Index (EDDI) (*McEvoy et al. 2016*), and vapor pressure deficit (VPD) (*Lowman et al. 2023*).

Observed drought changes

The Standardized Precipitation Evapotranspiration Index has expanded the utility of the SPI by adding a temperature component to the index. The distinction between SPI and SPEI over longer time periods illustrates the differences between precipitation-driven droughts that occurred historically and the droughts driven by the combination of low precipitation and warmer temperatures since 2000.

Looking at a time series of 24-month SPI since 1895 (Fig. 4.6), there are 8 significant dry periods, including the drought at the turn of the 20th century, the Dust Bowl in the 1930s, major droughts in the 1950s, 1960s, and 1970s, and three periods since 2000. The SPEI time series suggests nearly continuous drought since 2000 (Fig 4.7). This illustrates that because of higher temperatures, not only are times of drought more severe, there may be less benefit and recovery during wetter times. This phenomenon, increasingly prevalent in the 21st century, has been termed "hot drought" (*Udall and Overpeck 2017*).

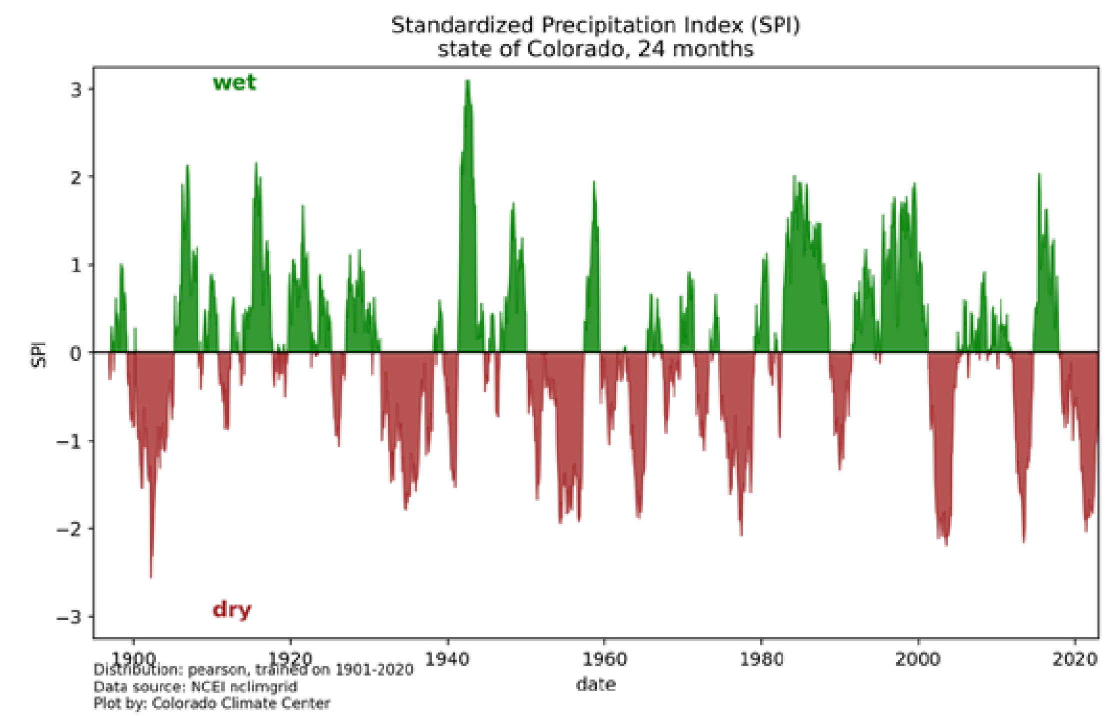

Figure 4.6: 24-month Standardized Precipitation Index for Colorado. Data were fit to a Pearson distribution using NOAA nClimGrid data from 1901-2020.

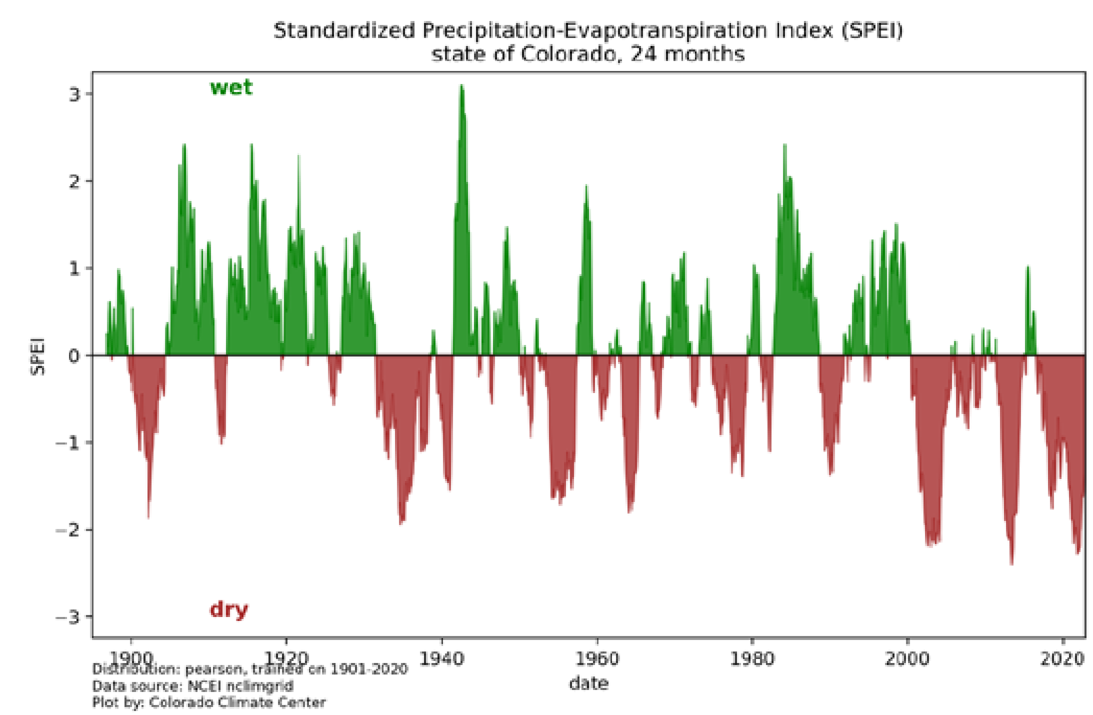

Figure 4.7: As in Fig. 4.6 but for Standardized Precipitation-Evapotranspiration Index. Potential evapotranspiration was calculated using the Thornthwaite method.

Each of the significant drought periods of the 21st century – centered around 2002, 2012, and 2020 – exhibited the indicators that we typically expect with droughts: low peak snowpack and early runoff, decreased streamflows, dry soils accompanying very hot summers, and high evaporative demand. Subsequent studies of these drought periods find that certain events would not have been as severe if the climate were not warming. In addition to *Udall and Overpeck (2017)*, (*Williams et al. 2020*) and (*Williams et al. 2022a*) found that the 21st century megadrought over the Southwest would not have been a megadrought in terms of duration or severity without climate change. A NOAA Drought Task Force assessed conditions in the Southwest during the 2020-2021 drought period (*Mankin et al. 2021*). They found that precipitation deficits over those two years, although exceptionally low, had the same likelihood of occurring in past decades (1950-2000). They also evaluated VPD, which (Lowman et al. 2023) simply describes as "high atmospheric aridity." VPD tends to be elevated during drought, ultimately impacting plants' growth and photosynthetic activity. Observed VPD during the 2020-2021 drought had virtually no chance of occurrence in the 20th century but is more likely to occur in future climate scenarios. (*Mankin et al. 2021*) concluded that the VPD observations in 2020-2021 made the drought worse. Regardless of changes in precipitation, warmer temperatures are making droughts more severe and frequent.

Sidebar: Flash Drought

New studies have also emerged on the topic of flash droughts (*Otkin et al. 2018*). Flash droughts indicate a rapid intensification of drought during the growing season, with primary impacts on agriculture. The Eastern Plains of Colorado are vulnerable to flash droughts, observed in the summers of 2012 and 2020. Typical onset and intensification of drought stemming from precipitation and soil moisture deficits differ from flash droughts, which are primarily initiated in the atmosphere with hot temperatures, low humidity, higher winds, and high VPD. This rapid increase in evaporative demand quickly outpaces evolution from precipitation deficits, thus becoming more "flashy" in behavior.

Future drought projections

Williams et al. (2020, 2022) found that anthropogenic climate change in the CMIP6 (CMIP5) climate models contributed 42% (46%) to soil moisture deficits in the Southwest U.S for the 2000-2021 time period. Precipitation simulations are a large source of uncertainty in the models, but there is strong agreement that warmer temperatures (where confidence in future scenarios is much higher) result in a net drying effect across the Southwest (including Colorado). This drying effect, shown in soil moisture anomalies, reduction in snowpack, and increased evaporative demand, increases the likelihood of widespread and severe droughts over the region (*Williams et al. 2022b*).

Future projections of VPD (*Mankin et al. 2021*) highlight the relationship between atmospheric demand and temperatures. Future VPD increases can be attributed to increasing temperatures. The high VPD observed from 2011-2020 over the Southwest (and specifically during the 2020-2021 drought) is likely to occur more frequently in future projections (2030-2050).

Despite uncertainty in future precipitation projections, droughts are projected to increase in frequency and severity for Colorado (and the Southwest in general) because of warmer temperatures.

4.4 Wildfire

Overview

The occurrence and behavior of wildfires in the western U.S. are strongly influenced by weather and climate, and they are especially linked to drought conditions ((*Littell et al. 2009*), (*Hostetler et al. 2018*)). Below-normal winter and spring precipitation and early meltout of the snowpack are linked with dry fuels and greater fire activity in subsequent months. Shorter periods of far-below-normal precipitation can lead to dry fuels and increased fire activity at any time of the year. High temperatures—whether as part of a drought or a long-term trend—hasten the drying of fuels, making fire ignition, fire spread, and intense fire behavior more likely. Fires are also much more likely to spread and exhibit intense behavior on days with high winds and low humidity. Note that in some vegetation types, such as grasslands and shrublands, wet growing seasons that lead to temporarily high fuel loads may be required for fire to spread during subsequent drier periods.

Wildfire occurrence and behavior are also driven by several non-climatic factors, such as the legacies of historical forest and land management (e.g., fire suppression) and resulting changes in fuel loads. Additionally, increasing human activity and development of houses and other structures within fire-dependent forest, shrublands, and grasslands leads to more ignitions year-round.

Observed wildfire changes

Over the past 20 to 40 years, the Western U.S. has experienced several linked trends in wildfires: large increases in annual area burned, number of very large fires (>10,000 acres), fraction of fire area burned at high severity, and length of the fire season ((*Dennison et al. 2014*), (*Abatzoglou and Williams 2016*), (*Westerling 2016*), (*Parks and Abatzoglou 2020*), (*Higuera et al. 2021*) (*Parks et al. 2023*)). While these trends are also affected by non-climatic factors ((*Balch et al. 2017*), (*Radeloff et al. 2018*)) and by multidecadal variability in precipitation, a critical common thread is the role of increasing temperatures. Two recent studies found that anthropogenic climate change, via warmer temperatures and resulting increases in fuel dryness across the region, could account for half or more of the recent increase in annual area burned ((*Abatzoglou and Williams 2016*), (*Zhuang et al. 2021*)). However, *Holden et al. (2018)* found that, while acknowledging the role of warming temperatures, a declining trend in summer precipitation was the primary driver.

These West-wide increasing trends in wildfire are very clearly expressed in Colorado. Figure 4.8 shows the number of very large Colorado wildfires (over 10,000 acres), and the total area burned in those fires, from 1984 through 2020. From 1984-1999, there were 8 wildfires larger than 10,000 acres, and records suggest that only two additional fires that size occurred from 1950 to 1983. Since 2000, there have been 60 wildfires larger than 10,000 acres, including six fires larger than 100,000 acres; all but one of the latter occurred after 2017. The annual area burned by wildfires in the forested areas of Colorado, and adjacent areas of New Mexico and Wyoming, increased by over 300% from the 1984-2000 period to the 2001-2017 period. The average elevation at which these wildfires occurred shifted upwards by over 1000' between 1984 and 2017, which is consistent with how warming is shifting temperature regimes upslope (*Alizadeh et al. 2021*).

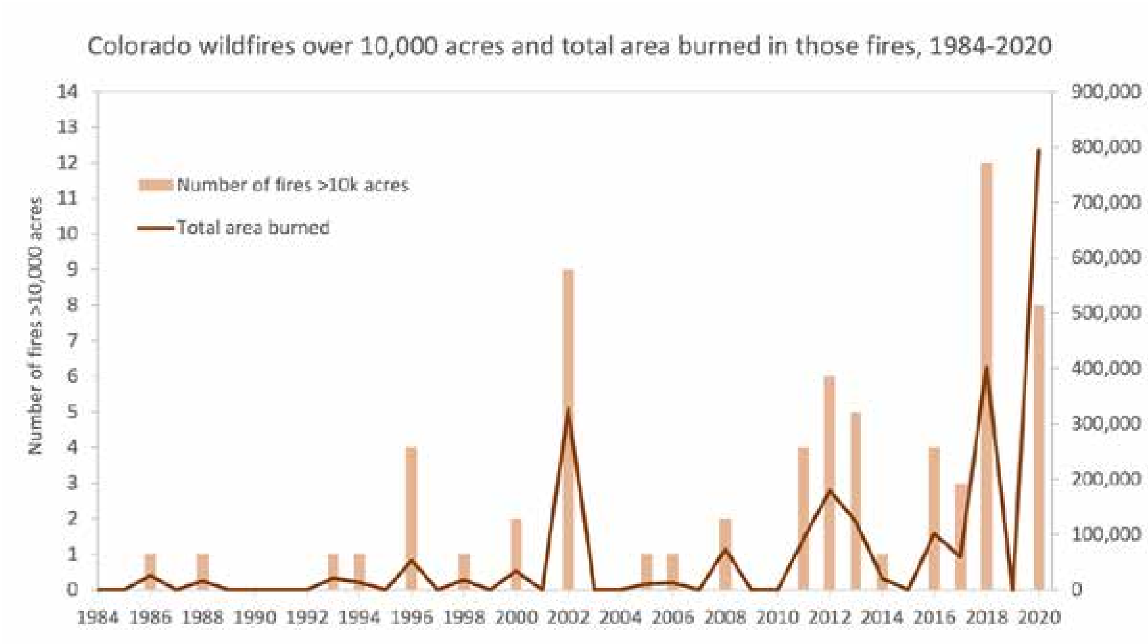

Figure 4.8: Number of Colorado wildfires that burned over 10,000 acres, 1984-2020, and total area burned in those fires each year. (Data: Monitoring Trends in Burn Severity (MTBS), https://www.mtbs.gov/direct-download)

Future wildfire projections

Many studies have combined climate model projections with observed fire-climate relationships to estimate the impacts of future climate change on wildfires in Colorado and the Rocky Mountain West. These studies have uniformly indicated substantially worsened wildfire risk for Colorado by the mid-21st century compared to the late 20th-century, as additional warming further increases fuel dryness and enhances fire ignition and spread ((*Liu et al. 2015*; *Brey et al. 2021*), (*Moritz et al. 2012*), (*Pechony and Shindell 2010*), (*Spracklen et al. 2009*), (*Litschert et al. 2012*), (*Yue et al. 2013*), (*Abatzoglou and Williams 2016*), (*West et al. 2016*), (*Kitzberger et al. 2017*), (*Littell et al. 2018*), (*Abatzoglou et al. 2021*), (*Brown et al. 2021*)).

Most of these studies quantified potential changes in annual area burned, collectively indicating a 100-500% increase under a warming of 2.5°F to 5°F (equivalent to RCP4.5 projections for mid-century). Under the same level of warming, *Stavros et al. (2014)* projected a 400% increase in the occurrence of very large wildfires (>50,000 acres). In short, studies consistently project a continuation of the recent increasing statewide trends in wildfire, given the near-certain continuation of the recent warming trend. However, some grassland and shrubland ecosystems in which fire is fuel-limited could see reduced fire occurrence as warming leads to overall lower fuel accumulation and continuity (*Littell et al. 2018*).

While post-fire changes to vegetation type, structure, and fuels could eventually limit how much new fire can occur on the landscape in each year or decade (*Westerling et al. 2011*), such feedback mechanisms will not prevent large, climate-driven increases in average annual burned area from occurring over the next several decades (*Abatzoglou et al. 2021*).

4.5 Heavy and Extreme Rainfall

Overview

Heavy and extreme precipitation events occur when three main storm "ingredients" are at unusually high levels, including atmospheric moisture, the transport of moisture into the storm (convergence), and upward motion (lift) within the storm. During the warm season (April-September), most heavy and extreme precipitation events in Colorado occur in convective storms, such as supercell thunderstorms and larger mesoscale convective systems (MCS). They can also occur in larger-scale systems with front-driven lift and orographic (terrain-driven) lift, such as during the Front Range floods in September 2013 (*Gochis et al. 2015*). The precipitation in warm-season storms usually falls as rain or hail, leading to flooding risk. During the cold season (October-March), heavy and extreme precipitation is associated with strong mid-latitude cyclonic storms with both frontal and orographic lift. While precipitation in cold-season storms generally falls as snow at all elevations (see Winter Storms, section 4.9), heavy rainfall and flooding risk can occur at lower elevations (~6000' and below), especially in the 'shoulder' months (October and March).

There are substantial differences between the eastern and western slopes of Colorado in the frequency, magnitude, and seasonality of heavy and extreme precipitation events, along with the prevalent storm types associated with these events. In particular, eastern Colorado is much more prone to strong convective storms; thus, rainfall events of a given frequency (e.g., 1-year) are generally much larger than in western Colorado (*Mahoney et al. 2013*).

Of the main storm ingredients, only atmospheric moisture has a direct physical link to temperature, through the Clausius-Clayperon (C-C) equation. The application of the C-C equation to water vapor says that for every 1°C rise in temperature, the moisture-holding capacity (saturation vapor pressure) of the atmosphere increases by 6.5%--or 3.5% for every 1°F rise (*Brune 2023*). Not every storm in a warmer climate will necessarily drop more precipitation than previously; but in general, with other factors held the same, storms will have access to more moisture in a warmer climate. Atmospheric instability, which influences the lifting of air parcels in convective storms, also tends to be greater under warmer temperatures, although the relationship is not as direct or as strong as with moisture (*Mahoney et al. 2018*).

Definitions can vary; here we use "heavy" to refer to events expected to occur in a given location once per year or less frequently (annual return interval = >1), and "extreme" to refer to events expected to occur every 20 years or less frequently. Thus, depending on the location in Colorado, a "heavy" event is at least 1"-2" of precipitation over 24 hours, while an "extreme" event is at least 2"-4" of precipitation over 24 hours.

Observed extreme rainfall changes

In the southwestern U.S., including Colorado, there have been some indications of increasing trends in heavy and extreme precipitation over the past several decades ((*Westerling et al. 2011*), (*Kunkel et al. 2020*)). For other metrics and time periods that were analyzed, increasing trends have not been observed ((*Bonnin et al. 2011*), (*Hoerling et al. 2010*), (*Lehmann et al. 2015*)). By comparison, in the Eastern and Midwest regions of the U.S., increasing trends are stronger and more consistent across different metrics of heavy and extreme precipitation and across different time periods.

The total from heavy and extreme precipitation events as a fraction of annual precipitation has increased since the 1950s in the six-state Southwest region (CO, UT, NM, AZ, CA, NV). Over the same region, the magnitude of every-20-year, 24-hour event has increased (USGCRP 2017). Across a range of event durations (1-day to 30-day), ***Kunkel et al. (2020)*** found that for the four-state Southwest (CO, UT, NM, AZ), the amount of precipitation falling in heavy (1-, 2-, 5-, and 10-year) and borderline extreme (20-year) events had generally increased from 1949-2016 and from 1979-2016. These increases were larger and more consistent in the warm season than the cold season.

Atmospheric moisture (precipitable water; PW) over Colorado and the surrounding states is observed to have increased from 1979 to 2016 by 0-8%, overall less than C-C scaling would suggest (***Kunkel et al. 2020***). It is possible that over the southwestern U.S., multi-decadal natural variability in the climate has suppressed the general effect of warming temperatures and increased regional precipitable water on heavy and extreme precipitation (***Hoerling et al. 2016***). Specifically, the prevalence of La Niña conditions since 2000 may have led to fewer such events in our region.

Future extreme rainfall projections

Given the near-certain continuation of warming for the rest of the 21st century, the C-C equation points to continued increases in atmospheric moisture globally (by 3.5% per 1 degree F) and a strong potential for increases in heavy and extreme precipitation. A very basic assumption is that the amount of precipitation in those events would increase, on average, according to C-C scaling. Under this assumption, 4°F of additional warming would lead to heavy and extreme precipitation events that are about 15% larger than without any warming. Whether that C-C-based "juicing" ultimately leads to that level of overall increase in extreme precipitation for Colorado depends on whether the future frequency of the different types of weather patterns that produce extreme precipitation, and other storm "ingredients" such as moisture convergence and lift, also change. Some observational studies have found evidence of "super-C-C scaling," i.e., that convergence and/or lift have changed or interacted with warming so that the overall effect is to increase precipitation amounts beyond the C-C relationship, especially for short-duration (< 3-hour) events (***Fowler et al. 2021***).

The ability of climate models to simulate these other storm ingredients is limited by the relatively coarse spatial resolution of the models, especially for convective storms. A review of the different mechanisms by which climate change could affect extreme precipitation in Colorado and New Mexico concluded that that the C-C-driven increase in atmospheric moisture with warming temperatures is likely to take precedence over the other effects (***Mahoney et al. 2018***).

Studies based on climate model projections (CMIP5 and CMIP6) for Colorado and the Southwest have consistently indicated overall future increases in the magnitudes of heavy and extreme precipitation events for our region, generally following the C-C scaling ((***Kharin et al. 2013***), (***Wuebbles et al. 2014***), (***Janssen et al. 2016***), (***Lynker 2019***), (***Swain et al. 2020***), (***Rupp et al. 2022***), (***Pierce et al. 2023***). Again, even when downscaling, these studies based on global climate models poorly represent the shorter-duration convective storms that are important sources of extreme rainfall events in Colorado. The only recent study specific to Colorado, conducted on behalf of CWCB, projected the future change in the 24-hour, 100-year precipitation event for 28 grid boxes (1° by 1°) covering Colorado (***Lynker 2019***). This analysis found that under RCP4.5, most of the grid boxes over the state would see 2% to 12% increases in 24-hour, 100-year events by 2050. Additionally, under RCP8.5 with higher warming, most grid boxes would see increases of 8% to 20% by 2050. The upper ends of these changes are approximately equivalent to C-C scaling. This study did not show any consistent discrepancies between different parts of Colorado with respect to future changes in extreme precipitation.

4.6 Floods

Overview

Flood events are very obviously linked to heavy and extreme precipitation, but they are also influenced by many factors, including characteristics of the watershed (geology, slope angles, vegetation, soil texture and depth, extent of impervious (e.g., paved) surfaces, urban drainage system). They are also influenced by the stream channel itself, which is often modified extensively by human activity (dams, diversions, channelization). Other factors that vary more over time, such as the level of soil moisture or the presence and depth of snowpack, can also play an important role. As a result, the intensity of a flood event may not match the intensity of the underlying precipitation event; a '100-year' rainfall can produce a 10-year flood, a 100-year flood, or a 1000-year flood, depending on these other factors.

In Colorado, floods occur almost entirely during the warmer half of the year (April-September), driven by either short-duration (< 6 hours) convective storms or longer-duration, broader-scale storm systems. Especially on the Western Slope, flooding also occurs from the melting of unusually large snowpacks. Such snowpacks typically arise from multiple heavy or extreme precipitation (i.e., snowfall) events during the cold season.

Watersheds that have recently burned in a wildfire, especially if the burn severity was high, are at much greater risk of flooding than unburned watersheds. Fire-induced changes to vegetation and soil properties mean that surface runoff and flooding can initiate at much lower precipitation intensities and total amounts, as little as 0.25" in one hour.

Historical flood marker near the lagoon on the Colorado State University Fort Collins campus.

Observed flood changes

There is limited evidence suggesting increases in flooding in Colorado in recent decades. A recent global analysis of trends in flooding examined over 10,000 gaged streamflow records, including about 40 in Colorado (*Slater et al. 2021*). Most of those gages in Colorado showed declining trends since 1970 in the size of the 20-year, 50-year, and 100-year flood events; however, many of these gages reflect extensive human modification of the streamflow regime. Increasing trends in floods were seen at about one-third of the gages, mainly on the Front Range and in northwestern Colorado. Two earlier studies that looked at U.S. trends in the 1-year flood event (i.e., annual peak daily discharge), but only in near-natural gaged streamflow records, found no increasing trends at any of the eight gages in Colorado they examined (*Villarini et al. 2009*),(*Hirsch and Ryberg 2012*)). Note that analyses of gaged stream and river flows may not capture changes in flash flooding involving overland flow outside of channels or in smaller basins without gages, such as in the 2013 Front Range floods.

Future flood projections

As described earlier, climate model projections indicate the likelihood of increased frequency and severity of extreme precipitation events for Colorado in the next several decades. Considered in isolation, these projected increases in extreme precipitation would lead to increased frequency and severity of flooding (*Swain et al. 2020*). However, the many factors that affect how rainfall is translated into runoff complicate the picture. In particular, the projected declines in summer soil moisture could be a countervailing factor. One study has found that semi-arid and semi-humid regions show smaller future increases in flooding than humid regions; in their model analysis, Colorado generally sees future declines in the intensity of the 30-year flood, despite increasing intensity of extreme precipitation (*Tabari 2020*).

Similar modeling by (*Brunner et al. 2021*) for river basins in Europe found a threshold effect in the future translation of precipitation into flooding. This same effect may play out in Colorado: The drying of soil moisture and snowpack losses resulting from warming temperatures could counterbalance the increased magnitudes of the less-extreme precipitation events (< 10-year), leading to little or no change in less-extreme flood events. For more extreme precipitation events (> 50-year), the increased precipitation magnitudes with climate change could overwhelm the effect of soil drying and translate into increases in the largest flood events. In the September 2013 Front Range flood event, whose intensity was likely exacerbated by warming (*Trenberth et al. 2015*),(*Pall et al. 2017*), very extreme precipitation (50-year to ~1000-year) overcame dry antecedent soils to cause extreme flooding (*Gochis et al. 2015*).

4.7 Thunderstorm Hazards: Tornadoes, Hail, and Winds

Colorado regularly experiences severe convective weather, defined by the National Weather Service as a tornado, hail at least 1" in diameter, or thunderstorm wind gusts of at least 58 mph. Although severe storms can occur anywhere in the state, the vast majority of the impacts are along the Front Range and eastern Plains (Fig. 4.9). Nearly all thunderstorm hazards occur between March and October, with a peak in early June. Severe thunderstorms are very rare outside of these months. Notable recent severe thunderstorms in Colorado include the EF-3 tornado in Berthoud in 2015 (*NOAA 2015*), the state-record hailstone with diameter of 4.83" in August

2019 near Bethune (*Childs and Schumacher 2019*), and the wind damage from a derecho and a macroburst, two days apart in eastern Colorado in June 2020 (*Childs et al. 2020*). Tornadoes in Colorado are frequent, but the vast majority are relatively weak. Although strong and damaging tornadoes (rated 2-3 on the Enhanced Fujita scale) occur occasionally in Colorado, violent tornadoes (rated EF-4 or EF-5) have not been observed in Colorado. Eastern Colorado, along with the adjacent states in the Great Plains, is one of the global "hot spots" for large hail (*Raupach et al. 2021*).

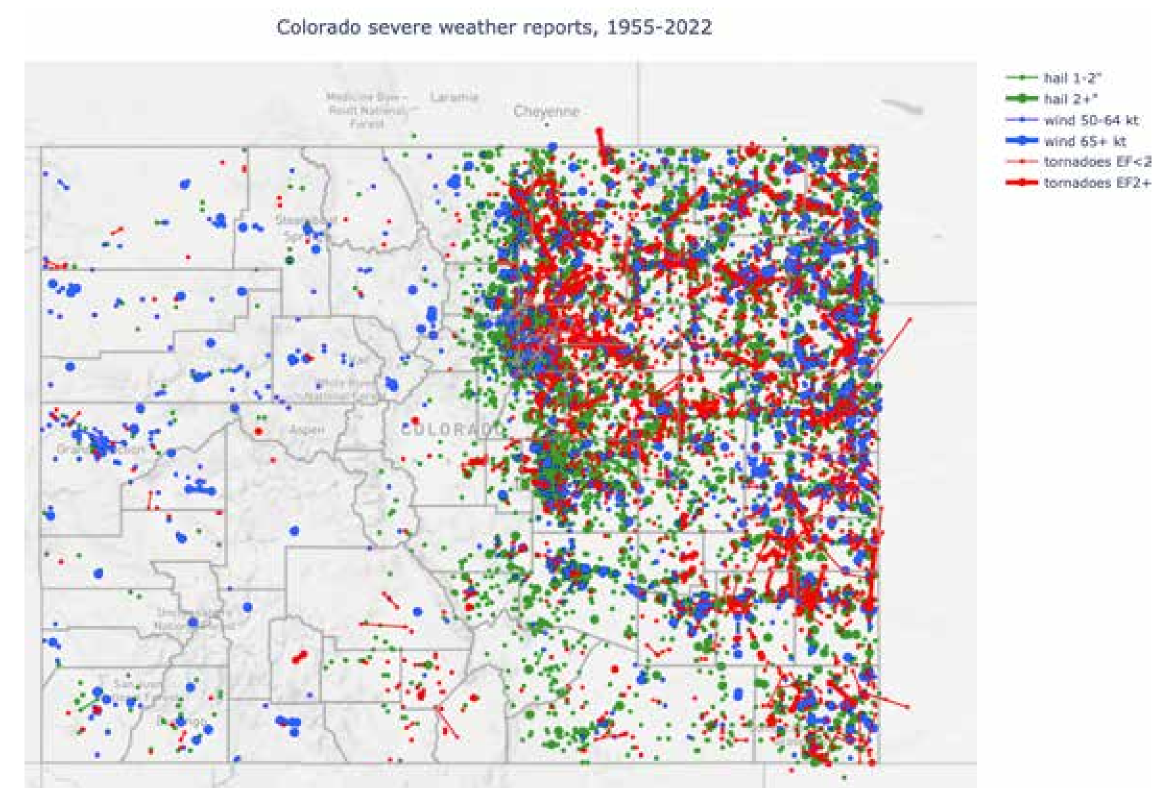

Figure 4.9: Map of severe weather reports from 1955-2022, based on data from the NOAA Storm Prediction Center. See https://climate.colostate.edu/severe_wx_climatology.html *for an interactive version.*

Long-term trends in hazardous convective weather are very challenging to identify because the data largely come from reports from storm spotters and the public. As the population of Colorado has grown, awareness of severe weather has increased, and the ability to easily submit reports has expanded. There are upward trends in severe weather reports that result from these non-meteorological factors. *Childs and Schumacher (2019)* closely examined the observed trends in tornadoes and severe hail and connected them to both meteorological and non-meteorological causes. They found that from 1997-2019, when severe weather reports have been more systematically collected, there was a slight downward trend in tornadoes in Colorado but an increasing trend in severe hail. They also found an upward trend in the ratio of "significant" severe hail (at least 2" in diameter) reports to those of 1" in diameter. Using a different method, (*Tang et al. 2019*) showed that from 1979-2017, most of the continental US experienced an increase in the number of days with the potential to produce large hail, but in eastern Colorado, there was actually a significant decrease in the number of days. The decrease in eastern Colorado was noted to be "puzzling" and worthy of further investigation. Overall, because of the relatively short data record for these hazards and the influences of changing observation systems, the sign and magnitude of long-term changes remains uncertain (*Raupach et al. 2021*).

The influences of climate change on hazardous convective weather in the future are also uncertain. (*Mahoney et al. 2012*) used numerical model simulations to show that in a warmer climate, despite increased intensity of thunderstorms overall, the occurrence of hail will be greatly reduced owing to an increase in the height of the melting level. The review by *Raupach et al. (2021)*, as well as (*Brimelow et al. 2017*) and (*Trapp et al. 2019*), similarly concluded that the average size of hailstones reaching the ground will increase in a warmer climate. In other words, hail frequency may decline, with what would have been small hail instead falling as rain, but when hailstorms do occur, they are more likely to produce large hail. Using various proxies for hail in downscaled climate simulations, *Childs et al. (2020)* found that in northeast Colorado, environments supporting severe hail will occur on 2-3 additional days per year in the future compared to the late 20th century, with smaller increases along the Front Range and southeastern Colorado. They also found that the changes in the impacts of severe hail (e.g., human exposure and damage) will be more sensitive to future changes in population than to changes in hailstorms themselves—something that is true of many weather and climate hazards. If Colorado's population continues to grow rapidly and the climatology of hailstorms remains similar to the present day, then exposure could more than double. However, if hailstorms shift to occur more frequently over eastern Colorado where population is projected to decline, then overall human impacts from hail could decline in the future but impacts to agriculture could increase.

Regarding tornadoes, the results from *Childs et al. (2020)* echo those for hail in Colorado: In the future, a modest increase in days favorable for tornadoes in northeast Colorado is likely, with future trends in impacts driven much more by population changes than changes in tornado occurrence. The influence of climate change on convective wind events in Colorado has not been systematically studied. The derecho of 6 June 2020 (*NOAA 2020b*) across the western US produced the largest number of severe wind reports on a single day in Colorado history, but it is unclear whether this event can be attributed to climate change in any way. (See section on non-convective windstorms for discussion of other types of wind hazards.)

In summary, for all three hazards (hail, tornado, and winds), there remain large uncertainties regarding future changes, as data limitations and the infrequent and localized nature of these storms makes them challenging to study in the context of a changing climate.

4.8 Non-convective Windstorms

Colorado's topography, and a location that often intercepts the midlatitude jet stream, makes it prone to extreme wind. In particular, the Front Range from Fort Collins to Pueblo is prone to downslope windstorms, where air flowing eastward over the mountains rapidly descends and results in extreme gusts (*American Meteorological Society 2022*). Several damaging windstorms in Boulder, such as 11 January 1972, which had gusts of nearly 100 mph (*Lilly and Zipser 1972*) and 17 January 1982, which had a gust measured at 137 mph at the NCAR Mesa Lab (*Zipser and Bedard 1982*), motivated extensive research on the causes of downslope winds. The devastating Marshall Fire in December 2021 was also fueled by a downslope windstorm with gusts up to 115 mph (*NOAA 2022*). (See section below on compound events.)

Other areas in Colorado's high country are also prone to extreme winds. Longs Peak had a wind gust of 201 mph in 1981, which is unofficially considered the state record, but it was measured at a temporary weather station as part of a research project. Other mountain areas routinely experience wind gusts exceeding 100 mph. The eastern plains can also experience extreme non-convective winds, such as a 107-mph gust at Lamar that occurred in December 2021.

Unfortunately, long-term changes in wind are difficult to quantify because data records for wind, especially wind gusts, are generally much shorter and less complete than records for temperature and precipitation. Detailed wind measurements generally require automated instrumentation, which only came into widespread use in the 1990s. Worldwide, there was some evidence for a "global stilling" trend (i.e., a slowing of average wind speed) that began in the 1980s, but this trend was found to have reversed after 2010 (*Zeng et al. 2019*). Using data from the Colorado Agricultural Meteorological Network, (*Goble 2018*) found that from 1996-2018 average wind speeds declined in all seasons and all parts of the state, except for the western slope in spring. However, this study did not address windstorms specifically and was based on a relatively short data record. Future changes in extreme winds are highly uncertain, but changes notwithstanding, the threat for extreme winds in Colorado will remain.

4.9 Winter Storms

While we've observed increasing trends in cold season temperatures (Chapter 2) and fewer cold waves (Chapter 4.1) in recent decades, it is more challenging to assess how winter storms have changed, or may change in the future. "Winter storms" encompasses a broad range of natural hazards such as heavy snowfall, ice accumulations, high winds, and cold temperatures. The physical mechanisms required for most winter storms are large-scale in nature – associated with the troughs along the polar jet stream, low pressure centers, and cold fronts. These large-scale events can leave a trail of impacts that extend across the entire country. For example, in February 2021, a major winter storm brought extreme cold, snow, and ice accumulations that impacted states from Oregon to Alabama (*Bolinger et al. 2022*). In Colorado, record-low temperatures were observed across many parts of the eastern plains, with the primary impact being power outages.

Due to the complexity of winter storms, identifying trends (both historic and projected) is difficult. Changes in large scale factors are one option. For example, (*Cohen et al. 2021*) found that Arctic amplification – where the higher latitudes are warming at a faster rate than the tropics, thus weakening the jet stream and resulting in a wavier pattern – is evident in observations and connected with changes in mid-latitude winter weather patterns. In theory, the wavier pattern of the jet stream would have more ridges and troughs, potentially increasing the frequency of winter storms. These connections are not represented in climate models, and the dynamic mechanisms are still being debated (*Moon et al. 2022*). Additionally, (*Blackport and Screen 2020*) found that Arctic amplification does not necessarily mean more waviness, and recent reported trends toward a wavier circulation had reversed.

Identifying trends at a local level can also be challenging. Each winter storm is the collation of several different variables. Some characteristics of winter storms – cold fronts, freezing rain, high winds – are difficult to measure and assess over time. Variables estimated from well measured observations of temperature and precipitation (such as cold waves or snowfall accumulations) can provide some insight.

The Accumulated Winter Season Severity Index – AWSSI – uses temperature, snowfall, and snow depth observations to monitor winter severity accumulated throughout the season (*Boustead et al. 2015*). While they find that warming temperatures result in overall decreasing trends in historic accumulations of AWSSI, we find no significant trends in winter severity at eastern Colorado stations (Fig 4.10). Large accumulating snow events can still occur frequently across the Front Range Urban Corridor and Eastern Plains. For example, the largest annual 2-day snow events since 1951 exhibit high variability with minimal detectable trends (Fig 4.10). The number of 2-day events that exceed 3 inches may be decreasing slightly, with Denver observing a decreased frequency in seasons with more than 10 events since 2000. However, Fort Collins continues to experience between 10 and 15 of these events each year.

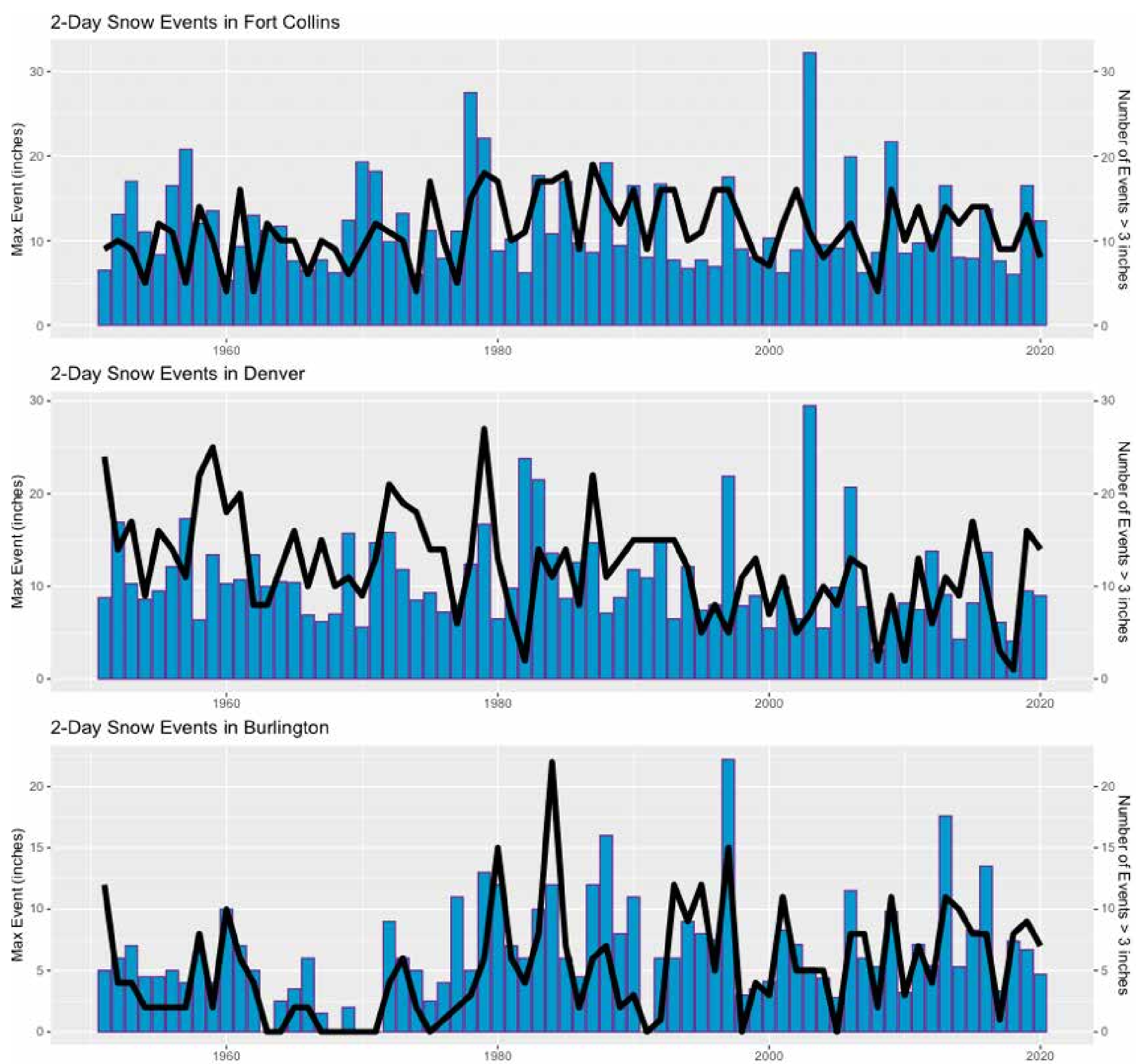

Figure 4.10: Maximum 2-day snow event per year in inches (blue bar) and total number of 2-day snow accumulations greater than 3 inches per year (black line) for Fort Collins (top), Denver Central-Park (middle), and Burlington (bottom), 1951-2020.

Several recent notable winter storms have impacted Colorado's Front Range and Eastern Plains. A heavy snowstorm over southeastern Colorado in late April 2017 covered and killed hundreds of livestock. A 'bomb cyclone' passed over southeastern Colorado in March 2019, bringing destructive winds (Colorado Springs airport

reported a 96-mph wind gust), snow, and low visibility across eastern Colorado. In March 2021, 20-30" of widespread snow blanketed northern Colorado. In December 2022, a powerful cold front moved across the region; the temperature in Fort Collins fell 37°F in 20 minutes, to 6°F. These events indicate that Colorado's susceptibility to severe winter storms remains.

4.10 Dust-on-snow

Over the past 20 years, the phenomenon of dust-on-snow deposition in Colorado and the West has shifted from a periodic curiosity to a chronic concern for water managers and water users. This shift is due to both a much better understanding of the significant hydrologic effects of dust-on-snow, and an overall increase in the occurrence of dust-on-snow events. Dust-on-snow is also unusual in that the visual appearance is an accurate gauge of the eventual impact on snowpack and runoff; the darker the snow surface, the stronger the dust's radiative forcing (i.e., enhancing the sun's energy) on snowmelt.

Dust-deposition events in Colorado typically occur during large-scale storms that move in from the southwest, most frequently in the spring (*Painter et al. 2018*). Strong winds in these storms pick up fine soil particles in the Colorado Plateau from lands that have been disturbed by grazing, oil and gas drilling, dryland agriculture, and off-road vehicle use (*Duniway et al. 2019*). Dust deposition on snowpacks and its impacts, are usually greatest in the San Juans, closest to this primary source ((*Painter et al. 2012*), (*Skiles et al. 2015*)). Yet, the dust may be transported hundreds of miles to all of Colorado's mountains, including the east slope of the Front Range. The dust layers from each event are often buried by subsequent snows, but then reemerge and coalesce at the snow surface as the snowpack compacts and melts down in late spring.

Lake-sediment cores from the San Juans show a several-fold increase in dust deposition starting in the mid-1800s through the 20th century (*Neff et al. 2008*). Dust mobility and deposition increased again around 2000, due to increasing aridity in the source areas and more widespread disturbance of the soils (*Brahney et al. 2013*).

Multiple studies have shown that dust loading in the snowpack alters the energy balance of snowmelt, enhances melt rates, and advances the timing of spring runoff by up to 3-6 weeks (*Painter et al. 2007*; *2012*; *Skiles et al. 2012*, (*Painter et al. 2010*), (*Deems et al. 2013*)). Modeling studies suggest that dust-on-snow deposition over the 20th and early 21st centuries has reduced natural streamflows from the Upper Colorado River Basin by about 5%, or 800,000 acre-feet, compared to pre-1800s low-dust conditions (*Painter et al. 2010*). This is mainly due to earlier meltout of snowpacks and increased evapotranspiration from soils and vegetation that are exposed and growing earlier in the season.

In a warmer future climate, overall drier soil conditions in the dust source region are very likely, which will tend to reduce vegetation cover and allow for greater dust emission, given the same level of disturbance (*Munson et al. 2011*). Further warming, like dust-on-snow, will tend to drive even earlier snowmelt and runoff. The only study to jointly model dust-on-snow and warming found that runoff timing remains strongly affected by dust under a variety of future warming scenarios (*Deems et al. 2013*). However, in a significantly warmer mid-century climate, going from "moderate" dust to "extreme" dust has no additional effect on runoff volume.

4.11 Compound Events

With the increase in the area burned annually by wildfires in the 21st century, attention to the issue of flash flooding and debris flows in burned areas has also increased. When the landscape is burned by wildfire, especially by a high-intensity fire, the soil often becomes hydrophobic, instead of being able to soak up rainwater (*NOAA 2023*). As such, flash floods and debris flows can develop in recently burned areas with much less rainfall than would be needed in non-burned areas. For example, a rain rate of 0.25" in 15 minutes is used as a general guideline for the potential of flash flooding on a burn scar, whereas such rain rates would be very unlikely to produce flash flooding in non-burned areas (*COMET MetEd*).

While burn-scar flash flooding occurred after the large wildfire seasons in 2002, 2012, and 2018, the concerns became particularly acute after the record 2020 fire year. Several major floods and debris flows occurred in the summer of 2021. In the Poudre Canyon in northern Colorado, intense rain fell on the Cameron Peak burn scar on the evening July 21, and a devastating flash flood occurred, killing four people and destroying several homes (*Whitehead 2021*). Again in 2022, heavy rain on the Cameron Peak burn scar resulted in a deadly flash flood when a camper was washed away in Buckhorn Canyon (*Tabachnik 2022*).

Farther south, the Grizzly Creek burn scar was the site of numerous debris flows following intense monsoon rains in July 2021. The largest of these occurred on July 31, when interstate 70 in Glenwood Canyon was overtopped with debris and heavily damaged. The important western Colorado highway was closed for over two weeks for repairs (*Nicholson 2021*).

As discussed in section 4.4, area burned by wildfires has increased in the 21st century in Colorado and is expected to increase further in a warming climate. Although trends in extreme rainfall have not yet been robustly detected in Colorado, it is expected that the heaviest rain rates will generally increase as the climate continues to warm (see section 4.5 on extreme rainfall). Even if extreme precipitation remains unchanged, an increase in burned area increases the risk of burn-scar flooding during the intense thunderstorms that have regularly been observed historically. Then, if short-term rain rates also increase, the frequency and intensity of compound flood-after-fire hazards will increase significantly. *Touma et al. (2021)* projected large increases in future extreme rain events occurring within one year of intense wildfires in the western US. Although their results were for a high-emissions scenario, even more modest increases in each individual hazard (i.e., with less extreme future emissions) would lead to much higher future risk for these compound events.

4.12 Air Quality

Overview

There are several different air quality issues that impact Colorado. Each may exhibit varying trends around the state. While most air quality issues are anthropogenic (with the exception of smoke from naturally caused wildfires), they may or may not be influenced by climate change. The primary issues that may be impacted by climate change are discussed below.

Ground-level ozone

Traffic, industry, oil and natural gas production, and wildfire smoke can all contribute to ozone formation and abundance in the state. Currently, the Northern Front Range exceeds the ozone National Ambient Air Quality Standard (*Bien and Helmig 2018*), and despite decreasing ozone in other areas of the country, some Northern Front Range sites have exhibited increases in ozone between 2000 and 2015 (*Abeleira and Farmer 2017*). While it is essential to reduce precursor emissions, ozone's temperature dependence (warmer temperatures increase ozone) means climate change will exacerbate the issue (*Crooks et al. 2022*).

Smoke and debris fill the air in Northern Colorado from the Cameron Peak and East Troublesome wildfires in October 2020.

Wildfire smoke

During the summer, the largest smoke-plume source regions are located in the Western U.S. and Rocky Mountains (*Brey et al. 2018*). More local wildfire smoke (which will have a more significant impact on Colorado from Rocky Mountain wildfires) tends to stay lower in altitude and have higher PM2.5 concentrations. As noted in the Wildfire section, wildfire activity (both acres burned and number of fires) is expected to increase with climate change. It is likely that air quality in Colorado (particularly in the summer) will subsequently continue to degrade.

Appendix A

About the data used in this report

Observed temperature and precipitation trends

Gridded temperature and precipitation data

Since the 2014 Climate Change in Colorado report, several gridded datasets for temperature and precipitation have become available that are based on observations from long-term climate stations, but also apply homogenization methods that account for changes in observation time, station location, and so forth. Throughout this report, we use NOAA's nClimGrid dataset (*Vose et al. 2014*), which includes monthly temperature and precipitation information on a 4-km latitude/longitude grid across the contiguous United States, and whose underlying station data and methods are similar to the NOAA nClimDiv dataset used in the 2014 report. The nClimGrid dataset is regularly used as an official source for climate monitoring by NOAA and by the Colorado Climate Center.

All climate datasets have uncertainties and limitations, and to explore these, we compared the nClimGrid monthly temperature data to a gridded climate dataset independently developed by the Berkeley Earth project (*Rohde et al. 2013*). Figure A.1 shows that these two datasets provide remarkably similar estimates of the temperature change over Colorado during the period 1985-2022. Although differences exist month-to-month and year-to-year, the two temperature datasets have a correlation of r = 0.984. This provides confidence that the temperature changes presented in this report are robust and are not simply an artifact of the choice of dataset.

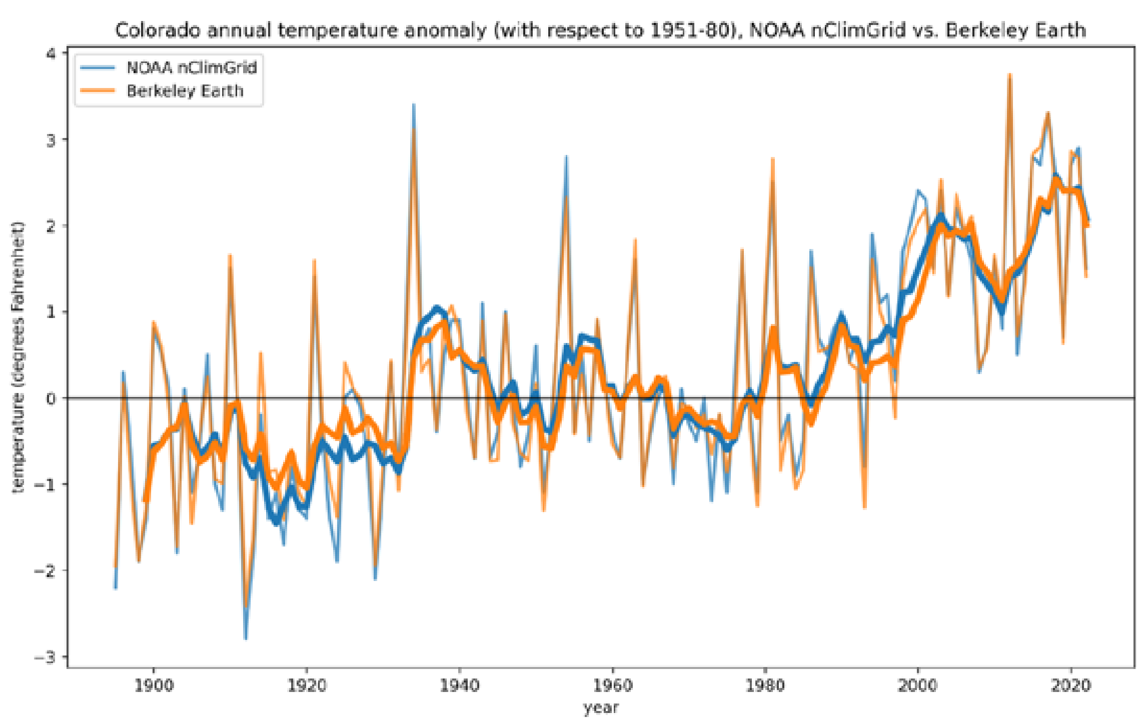

Figure A.1: Annual temperature anomalies (degrees Fahrenheit) for Colorado, with respect to a baseline of 1951-80, for the NOAA nClimGrid and Berkeley Earth datasets. The thick lines show a 5-year running mean.

Projected temperature, precipitation, and hydrology changes

Climate projections from global climate models (GCMs) - CMIP5 and CMIP6

Projections (i.e., simulations) by global climate models (GCMs) are the foundational data for assessing the direction and magnitude of physically plausible future climate changes at global, regional, and local scales. This report uses two sets of climate model data assembled by the Coupled Model Intercomparison Project (CMIP), incorporating the efforts of dozens of climate modeling groups around the world. CMIP is an organized "round-up" of several dozen of the latest generation of climate models conducted every 7 years or so to support policy-relevant climate assessments as well as climate research more broadly. (We acknowledge the World Climate Research Programme (WCRP), which supports and coordinates CMIP, the climate modeling groups for producing and making available their model output, the Earth System Grid Federation (ESGF) for archiving the data and providing access, and the multiple funding agencies who support ESGF.)

The CMIP5 (Coupled Model Intercomparison Project, Phase 5) multi-model ensemble was previously used in the 2014 Climate Change in Colorado report and was used again in this report. CMIP5 data for Colorado regridded to a common 1-degree grid, but not downscaled (see section on downscaling below), were obtained through the LLNL GDO-DCP server (https://gdo-dcp.ucllnl.org/) and used to evaluate statewide temperature and precipitation change (e.g., Figures 2.5, 2.6, 2.7, 2.12, 2.13). The CMIP5 ensemble used in this report encompasses 37 projections, one each from 37 models.

In 2020 and 2021, the data from CMIP6 (Coupled Model Intercomparison Project, Phase 6) were released, representing a new generation of climate models. Because of their relative newness, CMIP6 climate projections have only recently been added to public-facing climate portals. Only a handful of datasets of downscaled CMIP6 projections have been produced (as of July 2023), and no watershed-scale CMIP6-based hydrologic projections for the U.S. have yet been produced.

For this report, the CMIP6 multi-model ensemble was used to supplement and compare with the CMIP5 projections. CMIP6 data for Colorado regridded to a common 1-degree grid, but not downscaled, were obtained through the KNMI Climate Explorer (https://climexp.knmi.nl) and used to evaluate statewide temperature and precipitation change alongside CMIP5 (e.g., Figures 2.5, 2.6, 2.12). The CMIP6 ensemble used in this report initially encompasses 37 projections, one each from 37 models, but then was screened to a final ensemble of 22 projections, one each from 22 models, as detailed below.

GCMs have improved by many measures from one generation to the next, but since CMIP3, the improvements have diminished, indicating that climate modeling is maturing. While the CMIP6 models do show general improvements over CMIP5 in reproducing many features of the climate system and regional climate statistics, the assessed skill of the models by these benchmarks across the CMIP5 and CMIP6 ensembles show substantial overlap (e.g., *Pierce et al. 2021*). In practical terms, CMIP6 does not make CMIP5 obsolete--in fact, an issue emerged with CMIP6 models for which the IPCC applied an adjustment that was not done for previous CMIP ensembles.

When researchers first examined projections across the CMIP6 models, a number of models showed higher rates of global and regional warming than the upper end of the CMIP5 models; that is, unexpectedly high climate sensitivity or climate response to a given increment of greenhouse-gas emissions. Since these models also appear to simulate excessive warming in recent decades (~1980-present), it is plausible that these "hot" models' estimates of future warming are unrealistically high. Accordingly, the IPCC AR6 report (*IPCC 2021*) deemphasized the "hot" CMIP6 model projections, using additional modeling and analysis to develop an "assessed" range of future global temperatures that ended up very close to what had come directly from the CMIP5 model ensemble, given a similar emissions scenario.

Since then, a simpler method has been proposed for screening CMIP6 models to deemphasize the hot CMIP6 models in projecting future warming at regional scales (*Hausfather et al. 2022*). That method was used for this report to screen the CMIP6 ensemble from 37 models down to 22 models. If the same method were applied to the CMIP5 ensemble, none of the models would be screened out.

For Colorado, after the 12 "hot" CMIP6 models are screened out (along with 3 other models that are too "cold", according to the screening criteria) CMIP6 still shows greater warming than CMIP5 for the same emissions increment, though the two ensembles mostly overlap (Figures 2.6 and 2.7). The reduced range across the CMIP6 temperature projections relative to CMIP5 primarily results from the screening of CMIP6 and the resulting smaller ensemble. In any case, there is much more difference among the models within each CMIP ensemble, than there is between the two CMIPs. The screening of CMIP6 models has virtually no impact on the projections of precipitation change as shown in Figure 2.13. Note that there is still considerable discussion within the climate science community regarding for what applications one should screen out or otherwise deemphasize the hot models in CMIP6 (*Rahimpour Asenjan et al. 2023*). For this report, on balance, we believed it was appropriate to screen out hot models, consistent with the latest global-scale climate assessment (*IPCC AR6*).

Emissions scenarios

A major uncertainty in how climate change will unfold in the coming decades stems from society, not the climate system: How annual global emissions of greenhouse gases, and thus their atmospheric concentrations, will change in the future. For the CMIPs and the IPCC reports, the climate modeling community has collectively adopted sets of assumptions, known as emissions scenarios, whose broad range is intended to capture this uncertainty (Figure A.2). For the most recent three CMIPs and IPCC report cycles, three sets of emissions scenarios have been used:

- CMIP3 – Special Report on Emissions Scenarios (SRES) scenarios
- CMIP5 – Representative Concentration Pathways (RCP)
- CMIP6 – Shared Socioeconomic Pathways (SSP)

For CMIP5 (RCP) and CMIP6 (SSP), each of the scenarios is tagged with a number (e.g., 2.6, 3.4, 4.5, 6.0, 7.0, 8.5) that represents the total radiative forcing in watts per square meter (W/m2), the extra energy that will be trapped in the climate system under that scenario, beyond pre-industrial levels.

The 2014 Climate Change in Colorado report focused on outcomes under the medium-low RCP4.5 emissions scenario, while also reporting selected results under the high-end RCP8.5 scenario. Since 2010, the year-on-year increase in global fossil-fuel CO2 emissions—and thus total anthropogenic CO2 emissions—has slowed

such that the trajectory of those emissions through 2022 is on track with the RCP4.5 scenario, and about 20% below what the RCP8.5 scenario assumes for 2022 (*Global Carbon Project 2022*). Fossil-fuel CO2 emissions currently represent about 90% of all CO2 emissions from human activities, and about 70% of all anthropogenic greenhouse gas emissions. The current emissions policies enacted by the major emitting countries indicate a path of global fossil-fuel and total anthropogenic CO2 emissions through 2050 that is more consistent with the RCP4.5 trajectory, and well below the RCP8.5 trajectory (Figure A.2; (*Hausfather and Peters 2020*)). While current trends are encouraging, emitting countries may reverse policies or fail to meet targets. It is also possible that the total emissions of greenhouse gases through mid-century would end up being closer to RCP8.5 even if fossil-fuel emissions track RCP4.5, if unexpectedly large carbon-cycle feedbacks occur, e.g., releases of methane from permafrost (*Schwalm et al. 2020*).

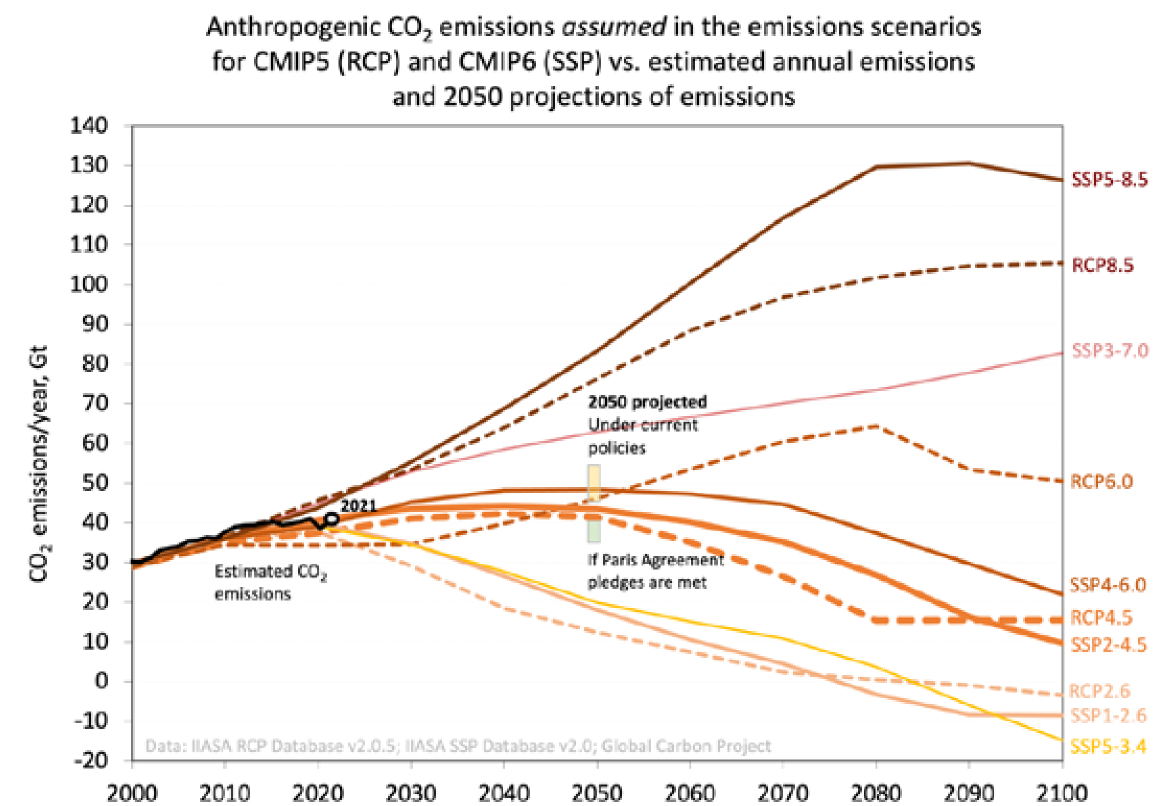

Figure A.2: Annual total anthropogenic CO2 emissions--about 90% of which are from fossil fuel burning--assumed in the emissions scenarios used to drive climate model projections in the CMIP5 and CMIP6 ensembles. The black line shows estimated actual annual CO2 emissions through 2021. This report focuses on projections driven by the RCP4.5 scenario (thick dashed orange) and similar SSP2-4.5 scenario (thic k solid orange). (Data: IIASA RCP Database v2.0.5; IIASA SSP Database v2.0; Global Carbon Project)

As in the 2014 report, we again focus here on RCP4.5, and also SSP2-4.5, the comparable scenario used for the CMIP6 projections; both scenarios are approximately in line with the upper end of combined national pledges under the 2015 Paris Agreement (green box in Figure A.2; *IPCC 2021*). While this focus on 4.5 scenarios excludes an assessment of high-end warming outcomes seen only under RCP8.5 and its CMIP6 analog SSP5-8.5, Figures 2.6 and 2.7 showed that under the 4.5 emissions scenarios, there is still a wide range of projected warming outcomes by 2050, overlapping considerably with the range of projected warming under 8.5 scenarios. By 2070, the warming ranges under the 4.5 and 8.5 scenarios overlap less. Both of the full CMIP5 and CMIP6 datasets include projections run under scenarios that are between 4.5 and 8.5 in terms of warming outcomes (e.g., RCP6.0, SSP4-6.0, SSP3-7.0), and these should also be considered for use in future climate vulnerability assessments. The limited availability of downscaled projections under RCP6.0 meant that scenario was not used in this report.

Downscaled climate projections from GCMs

For use at spatial scales smaller than the state of Colorado, GCM output needs to be downscaled through statistical methods (statistical downscaling), or via higher-resolution regional climate models (RCMs; dynamical downscaling), in order to better represent localized changes to weather and climate and to facilitate hydrologic modeling. For this report, we used the CMIP5-LOCA (LOcalized Constructed Analogs) dataset developed by *Pierce at al. (2014)*. Projections from 32 CMIP5 models were statistically downscaling using the LOCA method, in which multiple daily weather patterns from the historical record are selected, adjusted, and blended in order to create fine-scale outputs that are consistent with the coarser-scale weather pattern shown for a given day in the raw GCM output. In this way, a long-term climate projection is built that is faithful to the way weather and climate vary (at least historically) across space and time at local scales.

The CMIP5-LOCA dataset was chosen among several options, including the CMIP5-BCSD (Bias-Correction Spatial Disaggregation) dataset that was used in the 2014 Report. The BCSD method has since been shown to have a statistical artifact that alters the GCM-projected precipitation change, causing "wettening" over the Interior West. Evaluations of downscaling methods have shown that LOCA imposes fewer alterations of the coarse-scale GCM change signals (*Alder and Hostetler 2019*) while increasing the level of local detail in a physically meaningful way based on past weather patterns.

The CMIP5-LOCA projections are a 1/16-degree (~6 km) grid, at a daily timestep. The full CMIP5-LOCA dataset includes 32 projections, one from each of 32 climate models, for each of two emissions scenarios, RCP4.5 and RCP8.5 (so 64 projections total). This report only analyzes the projections under RCP4.5, as discussed above.

Watershed-scale hydrology projections

To generate projections of future hydrology for basins in Colorado and elsewhere, researchers typically take the downscaled future temperature changes and precipitation changes projected by an ensemble of climate models and then run that set of plausible trajectories of future climate through a separate watershed-scale hydrologic model, such as VIC or Noah. That hydrologic model then simulates the changes in snowpack, streamflow, soil moisture, and other variables associated with each climate model's projection of future climate: temperature change and precipitation change.

For this report, we used the set of CMIP5 global climate model (GCM) projections that were downscaled using the LOCA method and then run through the VIC (Variable Infiltration Capacity) hydrologic model. These hydrologic projections (CMIP5-LOCA-VIC) were created by NCAR researchers for a consortium led by the Bureau of Reclamation (*Vano et al. 2020*) and were previously analyzed for some basins in Colorado in *Lukas et al. (2020)* and *Reclamation (2021)*. These projections were obtained through the GDO-DCP server (https://gdo-dcp.ucllnl.org/)

The CMIP5-LOCA-VIC projections are on a 1/16-degree (~6 km) grid, the same resolution as the underlying CMIP5-LOCA projections, at a daily timestep.

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Glossary

Anomaly

A deviation from the expected or normal value.

Bias correction

Adjustments to raw model output (e.g., from a climate model, or streamflow forecast model) using observations in a reference period.

Climate

Climate can be 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 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).

Climatology

In forecasting and modeling, refers to the historical average climate used as a baseline (e.g., "compared to climatology"). Synonymous with climate normal.

Convection

The vertical transport of heat and moisture in the atmosphere, typically due to an air parcel rising if it is warmer than the surrounding atmosphere.

Downscaling

Method to take data at coarse scales, e.g., from a GCM, and translate those data to more local scales.

Dynamical

In modeling, refers to the use of a physical model, i.e., basic physical equations represent some or most of the relevant processes.

El Niño-Southern Oscillation (ENSO)

A coupled atmosphere-ocean phenomenon, with characteristic time scales of two to about seven years. During a warm-phase ENSO event (El Niño), 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 (SST) 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, called La Niña, occurs when the trade winds strengthen, leading to colder-than-normal SSTs in the equatorial tropical Pacific.

Emissions scenarios

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 of emissions, such as demographic and socioeconomic development, technological change, and energy use. The values of the different greenhouse gases and aerosols associated with a given emission scenario are then used as inputs to a climate model to drive projections of climate under that emissions scenario. For the CMIP5 climate models, the four primary emissions scenarios are known as RCPs (Representative Concentration Pathways); for the CMIP6 climate models, there are seven SSPs (Shared Socioeconomic Pathways), four of which are roughly equivalent to those RCPs that share the same number at the end (2.6, 4.5, 6.0. 8.5).

Evapotranspiration

The aggregate of evaporation from the land surface and water bodies and transpiration of water from plant surfaces to the atmosphere. Generally, it includes sublimation from the snow surface as well.

Forcing – *see climate forcing*

Global climate models (GCMs)

Complex, computer-based, mathematical representations of the Earth's climate system based on fundamental scientific principles. They are designed to capture the dynamics and interactions of the main components of the climate system: atmosphere, oceans, land surface and vegetation, sea ice, land ice. GCMs provide realistic simulations of the key physical phenomena at global down to continental scales, including planetary energy balance; large-scale atmospheric and oceanic circulation (like ENSO); broad-scale patterns of temperature and precipitation; and the statistical characteristics of the historical and current climate. Also known as Earth system models (ESMs).

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 (H2O), carbon dioxide (CO2), nitrous oxide (N2O), methane (CH4), and ozone (O3) 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.

Gridded data

Data that is represented in a two-dimensional gridded matrix of graphical contours, interpolated or otherwise derived from a set of point observations.

Humidity

Typically expressed as relative humidity (RH): The amount of moisture in the atmosphere relative to the amount that would be present if the air were saturated. RH is expressed in percent (%) and is a function of both moisture content and air temperature. Absolute humidity is the amount of moisture in a volume of air (e.g., g/m2), without consideration of the air temperature.

Hydrograph

A graph of the volume of water flowing past a location per unit time (hours, days, or months)

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 an assessment of the state of knowledge on climate change based on peer-reviewed and published scientific/technical literature in regular time intervals. The IPCC Sixth Assessment Report (AR6) was released in 2021 and 2022.

Internal variability

Variability in climate that comes from chaotic and unpredictable fluctuations of the Earth's oceans and atmosphere. Synonymous with natural variability

Jet stream

A narrow band of very strong winds in the upper atmosphere that follows the boundary between warmer and colder air masses; low-pressure systems preferentially form along the jet stream and then their motion is guided by the jet stream (i.e., storm track)

Megadrought

A sustained and widespread drought that lasts at least 10-15 years.

Mid-latitude cyclonic storm

A common, large (~500-2000 km) storm system that has a low-pressure center, cyclonic (counter-clockwise) flow, and a cold front. Over Colorado, mid-latitude cyclones almost always move from west to east and are effective at producing precipitation over broad areas, mainly between October and May.

Natural flow

Gaged flow that has been adjusted to remove the effects of upstream human activity such as storage or diversion. Equivalent to naturalized flow, virgin flow, and undepleted flow.

Orographic lift

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

Projection

A long-term (typically 10-100 years) forecast of future climate or hydrology that is contingent on specified other conditions occurring during the forecast period, typically a particular scenario of greenhouse gas emissions. The contingent condition is what differentiates a projection from a forecast, which has no conditions and is typically for a shorter term.

Percentile

A measure of where a particular observation or projection falls within a larger set of data; an observation in the 10th percentile is larger than only 10% all other observations in the dataset, and smaller than 90% of the observations. The median is the 50th percentile; there are equal numbers of observations larger and smaller than the median.

Radiative forcing

A factor causing a difference between the incoming and outgoing energy of the Earth's climate system, e.g., increases in greenhouse-gas concentrations. Synonymous with climate forcing.

Reanalysis

An analysis of historical climate or hydrologic conditions that assimilates observed data into a modeling environment to produce consistent fields of variables over the entire period of analysis.

Reference ET (evapotranspiration)

An estimate of the upper bound of evapotranspiration losses from irrigated croplands, and thereby the water need for irrigation. Equivalent to potential evapotranspiration (PET).

Resolution

Typically refers to the level of spatial detail in model output or other data; the ability to distinguish two points as separate and depict small features. Equivalent to grid cell size.

Runoff

Precipitation that flows toward streams on the surface of the ground or within the ground. Runoff as it is routed and measured within channels is streamflow.

Runoff efficiency

The fraction of annual precipitation in a basin or other area that becomes runoff, i.e., not lost through evapotranspiration.

Solar radiation

Incoming radiation from the sun, consisting of visible (i.e., sunlight), near-ultraviolet, and near-infrared spectra, with wavelengths between 0.2 and 3.0 micrometers. Also known as shortwave radiation, distinguishing it from longwave radiation, which is absorbed energy re-radiated from the earth's surface at longer wavelengths.

Snow-water equivalent (SWE)

The depth, often expressed in inches, of liquid water contained within the snowpack that would theoretically result if one were to melt the snowpack instantaneously.

SNOTEL

An instrumented site with both weather instruments and a snow pillow that provides a value of the water equivalent of snow that has accumulated on it (SWE); typically, the pillow contains antifreeze and has a pressure sensor that measures the weight pressing down on the pillow.

Streamflow

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

Sublimation

When water (i.e., snow and ice) or another substance transitions from the solid phase to the vapor phase without going through the intermediate liquid phase; a major source of snowpack loss over the course of the season.

Transpiration

Water vapor discharged into the atmosphere from the leaf surfaces of plants.

Acronym List

AET	Actual Evapotranspiration
AWSSI	Accumulated Winter Season Severity Index
BCSD	Bias-Corrected Spatially Disaggregated [downscaling method]
C-C	Clausius-Clayperon [equation]
CMIP3	Coupled Model Intercomparison Project – Phase 3
CMIP5	Coupled Model Intercomparison Project – Phase 5 (there was no Phase 4)
CMIP6	Coupled Model Intercomparison Project – Phase 6
CWCB	Colorado Water Conservation Board
DWR	[Colorado] Division of Water Resources
EC	Eddy Covariance
EDDI	Evaporative Demand Drought Index
EF-[0…5]	Enhanced Fujita [scale for tornado severity]
ENSO	El Niño-Southern Oscillation
ET	Evapotranspiration
GCM	Global climate model
GDO-DCP	Green Data Oasis – Downscaled Climate Projections [web portal]
gridMET	Gridded Surface Meteorological [climate dataset]
GHG	Greenhouse Gas
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
KNMI	Royal Netherlands Meteorological Institute
LLNL	Lawrence Livermore National Laboratory
LOCA	Localized Constructed Analogs [downscaling method]
MACA	Multivariate Adaptive Constructed Analogs [downscaling method]
MCS	Mesoscale Convective System
NARCCAP	North American Regional Climate Change Assessment Project
NCA	National Climate Assessment
NCAR	National Center for Atmospheric Research
NCEI	National Center for Environmental Information (at NOAA)
nClimGrid	NOAA U.S. Climate Gridded Dataset
NLDAS	North American Land Data Assimilation System
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resource Conservation Service
NWS	National Weather Service
PET	Potential Evapotranspiration
PDSI	Palmer Drought Severity Index
PW	Precipitable Water
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
SNOTEL	Snowpack Telemetry
SPEI	Standardized Precipitation-Evapotranspiration Index
SPI	Standardized Precipitation Index
SRES	Special Report on Emissions Scenarios
SSP	Shared Societal Pathway
SWE	Snow Water Equivalent
USGCRP	United States Global Change Research Program
VIC	Variable Infiltration Capacity [hydrology model]
VPD	Vapor Pressure Deficit

Acknowledgments

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