

Climate Change in Colorado

A Synthesis to Support Water Resources Management and Adaptation

A REPORT FOR THE COLORADO WATER CONSERVATION BOARD

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A Synthesis to Support Water Resources Management and Adaptation

A REPORT BY THE WESTERN WATER ASSESSMENT FOR THE COLORADO WATER CONSERVATION BOARD

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Funding from the Colorado Water Conservation Board of the State of Colorado to the Cooperative Institute for Research in Environmental Sciences, Western Water Assessment

Produced in cooperation with CU-Boulder University Communications, Marketing & Creative Services.

Photos

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EXECUTIVE SUMMARY

The scientific evidence is clear: the Earth's climate is warming. Multiple independent measurements confirm widespread warming in the western United States; in Colorado, temperatures have increased by approximately 2°F between 1977 and 2006. Increasing temperatures are affecting the state's water resources. (Sections 1, 2, 4, 5, 6)

THIS REPORT is a synthesis of climate change science important for Colorado's water supply. It focuses on observed trends, modeling, and projections of temperature, precipitation, snowmelt, and runoff. Climate projections are reported out to the mid-21st century, because this is a relevant time frame for development of adaptation strategies.

Although many published studies and datasets include information about Colorado, few climate studies focus only on the state. Consequently, many important scientific analyses for Colorado are lacking. This report summarizes Colorado-specific findings from peer-reviewed regional studies, and presents new graphics derived from existing datasets. The state is home to many experts in climate and hydrology, and this report also draws from ongoing work by these scientists.

Observations, Attribution, and Projections

- Changes in Colorado's climate and implications for water resources are occurring in a global context. On a global scale, climate change has been linked to observed and projected changes in the water cycle. By the mid-21st century, average river runoff and water availability are projected to increase at high latitudes and decrease over dry regions at lower midlatitudes such as the western United States. Changes in the quantity and quality of water may occur due to warming even in the absence of precipitation changes. (Section 1)
- The accumulation of greenhouse gases (including carbon dioxide) in the atmosphere is ***very likely*** the cause of most of the increase in global average temperatures (IPCC AR4 WGI 2007). In North America, temperatures have increased by 2°F in the last 30 years, and "human-induced warming has ***likely*** caused much of the average temperature increase over the past fifty years" (CCSP SAP 3.3 2008, p. 3). (Section 5)
- In Colorado, temperatures have increased about 2°F in the past 30 years. All regions examined within the state warmed during the last 30 years, except the far southeast corner, in which there was a slight cooling trend. (Section 2)
- Climate models show a 1°F warming in the West over the last 30 years in response to greenhouse gas emissions from human activities (anthropogenic). However no studies have specifically investigated whether the detected trends in Colorado can be attributed to anthropogenic greenhouse gases. (Sections 2, 4)
- Climate models project Colorado will warm 2.5°F [+1.5 to +3.5°F] by 2025, relative to the 1950–99 baseline, and 4°F [+2.5 to +5.5°F] by 2050. The 2050 projections show summers warming by +5°F [+3 to +7°F], and winters by +3°F [+2 to +5°F]. These projections also suggest that typical summer monthly temperatures will be as warm as or warmer than the hottest 10% of summers that occurred between 1950 and 1999. By way of illustration, mid-21st century summer temperatures on the Eastern Plains of Colorado are projected to shift westward and upslope, bringing into the Front Range temperature regimes that today occur near the Kansas border. (Section 5)
- Winter projections show fewer extreme cold months, more extreme warm months, and more strings of consecutive warm winters. Typical projected winter monthly temperatures, although significantly warmer than current, are between the 10th and 90th percentiles of the historical record. Between today and 2050, typical January temperatures of the Eastern Plains of Colorado are expected to shift northward by ~150 miles. In all seasons, the climate of the mountains is projected to migrate upward in elevation, and the climate of the Desert Southwest to progress up into the valleys of the Western Slope. (Section 5)
- In all parts of Colorado, no consistent long-term trends in annual precipitation have been detected. Variability is high, which makes detection of trends difficult. Climate model projections do not agree whether annual mean precipitation will increase or decrease in Colorado by 2050. The multi-model average projection shows little change in annual mean precipitation, although a seasonal shift in precipitation does emerge. (Sections 2, 5)
- A widespread and large increase in the proportion of precipitation falling as rain rather than snow, and reduction in snow water equivalent (SWE) have been observed elsewhere in the West. In Colorado, however, these changes are smaller and not as significant. Most of the reduction in snowpack in the West has occurred below about 8200 ft.

However, most of Colorado's snowpack is above this elevation, where winter temperatures remain well below freezing. (Section 2)

- Projections show a precipitous decline in lower-elevation (below 8200 ft) snowpack across the West by the mid-21st century. Modest declines are projected (10–20%) for Colorado's high-elevation snowpack (above 8200 ft) within the same timeframe. (Section 5)
- Between 1978 and 2004, the spring pulse (the onset of streamflows from melting snow) in Colorado has shifted earlier by two weeks. Several studies suggest that shifts in timing and intensity of streamflows are related to warming spring temperatures. The timing of runoff is projected to shift earlier in the spring, and late-summer flows may be reduced. These changes are projected to occur regardless of changes in precipitation. (Sections 2, 5)
- Recent hydrology projections suggest declining runoff for most of Colorado's river basins in the 21st century. However, the impact of climate change on runoff in the Rio Grande, Platte, and Arkansas Basins has not been studied as extensively as the Colorado River Basin. (Section 5)
- The lowest five-year period of Colorado River natural flow since records began in the late 1800s occurred in 2000 to 2004 (9.9 million acre feet per year). Recent hydrologic studies of the Upper Colorado River Basin project multi-model average decreases in runoff ranging from 6% to 20% by 2050 compared to the 20th century average, although one statistical streamflow model projects a 45% decline by 2050. The range of individual model projections within a single study can include both increasing and decreasing runoff due to the range of climate model output used to drive the hydrology models. Ongoing studies are attempting to resolve methodological differences in order to reduce the range of uncertainty in runoff projections. (Sections 2, 5)
- Throughout the West, less frequent and less severe drought conditions have occurred during the 20th century than revealed in the paleoclimate records over the last 1000 years. Precipitation variations are the main driver of drought in Colorado and low Lake Powell inflows, including the recent drought of 2000–07, and these variations are consistent with the natural variability observed in long-term and paleoclimate records However, warming temperatures may have increased the severity of droughts and exacerbated drought impacts. (Sections 4, 5)
- Because global climate models do not represent the complexity of Colorado's topography, researchers are using "downscaling" and other techniques to study processes that matter to Colorado water resource managers. Several projects are underway to improve regional understanding: Some use statistical "downscaling" methods, which adjust for the effects of elevation and the mountains on snowfall and temperature; other studies involve compiling, calibrating, and studying historical datasets; others involve enhanced climate modeling efforts to include finer spatial resolution that better represents Colorado's mountainous terrain. (Section 3)

SIDEBAR ES-1. Communicating Uncertainty

Recognizing the difficulty in communicating scientific uncertainty to those outside the community, climate assessments now make statements designed to communicate probability. The so-called likelihood terminology indicates "the assessed likelihood, using expert judgment, of an outcome or a result" (IPCC AR4 WGI 2007, p. 3). The likelihood terminology quoted in this document follows two different but similar conventions, shown below.

It is important to recognize that the likelihood terminology used here is independent of consequence; these are not risk statements and the consequences of potentially cascading effects are not implicit in the likelihood statements.

The authors and editors of this report did not develop likelihood statements independently. Here, all likelihood statements are quoted from three major assessments (IPCC AR4 WGI 2007, IPCC 2008, CCSP SAP 3.3) where long-term processes involving large panels of experts arrived at conclusions based on the best available science.

Statements quoted from IPCC AR4 WGI and the IPCC Technical Paper on Water use this convention:	Statements quoted from CCSP SAP 3.3 use an intentionally less discrete system:
virtually certain (>99%)	
extremely likely (>95%)	
very likely (>90%)	*very likely* (about 75–100%)
likely (>66%)	*likely* (about 60–75%)
*more likely than not** (>50%)	
*about as likely as not** (>33-66%)	
unlikely (<33%)	*unlikely* (about 25–40%)
very unlikely (<10%)	*very unlikely* (about 0–25%)
extremely unlikely (<5%)	
*exceptionally likely** (<1%)	

* these likelihood terms used by IPCC are not quoted in this report

Implication for Water Resource Managers

Climate change will affect Colorado's use and distribution of water. Water managers and planners currently face specific challenges that may be further exacerbated by projected climate changes. The implications of climate change in this report are consistent with the broader conclusions in the CCSP SAP 4.3, the IPCC Technical Paper on Water (2008), and the 2007 National Academy of Science Report "Colorado River Basin Water Management."

This report provides a scientific basis to support further studies of water resources impacts. However, the assessment and quantification of specific climate change impacts on water resources is beyond the scope of this document.

A synthesis of findings in this report suggests a reduction in total water supply by the mid-21st century. When combined with temperature increases and related changes in evaporation and soil moisture, all recent hydrologic projections show a decline in runoff for most of Colorado's river basins by the mid-21st century. (Section 6)

1 Introduction

IN RESPONSE TO THE RISKS associated with global warming, Governor Ritter issued the Colorado Climate Action Plan (CCAP) in 2007. The CCAP sets out a goal to prepare the state to adapt to those climate changes "that cannot be avoided" (CCAP 2007, p. 3). Recommendations in the CCAP include assessing the vulnerability of Colorado's water resources to climate change, analyzing impacts on interstate water compacts, and planning for extreme events such as drought and flooding.

This report is a synthesis of the state of the science regarding the physical aspects of climate change that are important for evaluating impacts on Colorado's water resources. It presents scientific analyses to support future investigations and state efforts to develop a water adaptation plan. Accordingly, the document focuses on observed trends, modeling, and projections of hydroclimatic variables—including temperature, precipitation, snowmelt, and runoff—that are important factors for water supply in the state. However, the geographic scope of the document does not end at the state's borders, because of Colorado's role as a headwaters for supply in the West. Projections focus on the mid-21st century, because this is a relevant planning horizon for adaptation strategies, but some projections are for earlier and later periods (SIDEBAR 1-1). This document is also intended to support other planning in the state including the State Water Supply Initiative, the Colorado River Water Availability Study, the Joint Front Range Climate Change Vulnerability Study, and the Governor's Conference on Managing Drought and Climate Risks.

Changes in Colorado's climate and implications for water resources are occurring in a global context. The IPCC Technical Paper on Water finds that on a global scale, observed warming has been linked to many changes in the water cycle. Climate models project that precipitation will increase at high latitudes and decrease in parts of the subtropics and lower midlatitudes. By the mid-21st century, average river runoff and water availability are projected to elevate at high latitudes and decrease over dry regions at lower midlatitudes such as the western United States. Increased precipitation intensity and variability are projected to elevate risks of floods and droughts. Water supplies in glaciers and snow cover are projected to decline in many areas of the world.

Changes in the quantity and quality of water may occur even in the absence of precipitation change. Current practices may not be robust enough to cope with climate change. The impacts of climate change challenge the

SIDEBAR 1-1. How to Interpret the Timescales in This Report

Many of the graphics and analyses in this report focus on recent trends and mid-21st century projections, but projections for other timeframes are important depending on the type of decision or planning horizon.

2008 (the present): Climate variations such as the recent drought may influence the results of trend analysis of the historical record. Many of the climate projections in this report show changes with respect to 1950–99 averages. During this period global and North American temperatures have already risen about 2°F, some of which can be attributed to anthropogenic causes.

2025: The projected warming in 2025 is roughly half that in 2050 (see FIGURES 5-2 through 5-7). In this timeframe, all greenhouse gas emissions scenarios lead to a similar range of temperature projections. Natural variability will play an important role in determining the climate of the next few decades. However, even relatively small shifts in the average climate can substantially change the risk of extreme events (FIGURE 1-1) such as heat and cold waves and drought.

2050: The climate projections for the differing greenhouse gas emissions scenarios start to diverge by 2050, but all projections still show a quantitatively similar range. Anthropogenic effects on climate variables are projected to be larger in 2050 than 2025 or the present. Therefore, the larger climate change signal will be more easily detected against the background of natural variability, and will further shift the risk of extreme events.

Beyond 2050: The future of Colorado's climate beyond 2050 depends on the greenhouse gas emissions path that the world follows. As the world warms, feedbacks in the climate system may further increase global greenhouse gas concentrations. Warming in Colorado may trigger changes in land cover that would alter regional climate. The possibility has been raised of large, potentially irreversible changes in the climate system particularly if global average temperatures increase more than a few degrees (e.g., Hanson et al. 2007).

FIGURE 1-1. Climate and Extreme Events

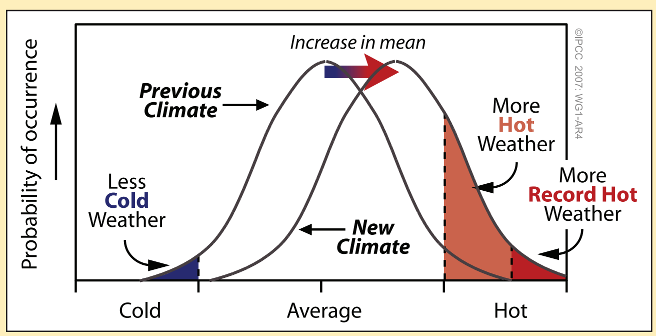


Fig. 1-1. Relatively small shifts in the average climate can substantially change the risk of extreme events such as heat and cold waves and drought. (IPCC AR4 WGI 2007)

assumption that past hydrology provides a good guide to the future. Furthermore, many gaps have been identified in observations, modeling, and applications research (IPCC 2008).

Context

Knowledge about climate and climate change is evolving; thus this report is a snapshot of the state of science at a key point in Colorado's history. The information reported here provides a basis for planning to adapt to higher temperatures and the consequences that will result, especially the impacts related to Colorado's water and forests. Like the Colorado Climate Action Plan, this is a living document, and should be updated as the science progresses.

Although many published studies and datasets include information about Colorado, there are few climate studies that focus on the state. Consequently, many important scientific analyses for Colorado have not been done. This report summarizes Colorado-specific findings from peer-reviewed regional studies, and presents new analyses derived from existing datasets and model projections. The state is home to many experts in climate and hydrology, and this report draws from ongoing work by these and many other scientists who are stepping up to the challenge of providing societally relevant studies to aid decision-makers.

This document takes advantage of recent research and syntheses of climate including the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), the IPCC Technical Paper on Water (2008), and the U.S. Climate Change Science Program (CCSP) Synthesis and Assessment Products (SAP) from 2007 and 2008. The statements within this report that include an expert assessment of the likelihood of occurrence (Sidebar ES-1) have been extracted from these documents.

Water managers have a long history of adapting to changing circumstances, including changes in economies and land use, environmental concerns, and population growth. Climate change will further affect the decisions made about how Colorado uses and distributes its water. The report provides a scientific basis to support further studies of water resources impacts and adaptation efforts called for in the Governor's CCAP; the assessment of specific sensitivities and vulnerabilities of water supply and ecosystem impacts is beyond the scope of this report. Section 6 discusses the potential uses of the information in this report in assessment of climate risks and vulnerabilities and in integrated resource planning and adaptation.

Vulnerability assessments of water resources might include the risks of compact calls in Colorado's river basins, risks to supply within the state, or the risks of drought. Integrated planning processes following on these assessments might include mitigation planning to assess and prepare for drought, and developing mechanisms for each river basin to deal with potential compact calls.

Structure of the Report

Key findings of this report are summarized at the beginning of each section and in the Executive Summary that precedes the main document. You are of course encouraged to read the entire document, but less technical readers may find sufficient information in this Introduction, the Executive Summary, the key findings at the beginning of each section, and the figures.

The report begins with a description of the climate of Colorado, the observing systems and data available for study, and the observed trends in Colorado and the western United States for variables relevant to water resources (Section 2). Section 3 is an overview of climate models and theory intended to provide the background for later sections. Section 4 provides attribution of the principal causes of observed climate conditions including the recent multi-year drought. Section 5 then describes the global modeling projections for Colorado and the surrounding areas of the Intermountain West, and situates Colorado in the context of global climate change. It also describes how the complex topography of the state relates to interpreting and using climate change projections. Recent hydrologic projections for the Colorado River and other state resources are shown. Section 6 discusses the general implications of these findings for Colorado's water resources, although the assessment of specific impacts on water resources is beyond the scope of this report.

A glossary provides descriptions of some key climate terms, as well as an appendix of ongoing research efforts that may contribute in the near term to our understanding of climate change in Colorado. The details of data source and methods for each figure are available at **http://wwa.colorado.edu**.

2
The Observed Record of Colorado Climate

KEY POINTS

- Colorado's highly variable climate is a consequence of high elevations and the complex topography of the mountains, plains, and plateaus. Climate varies spatially and temporally, and different climatic variables fluctuate in distinct ways.
- In Colorado, statewide temperatures have increased about 2°F over 30 years. This synthesis is based on two methods estimating 2.1°F from 1977 to 2006 and 1.7°F from 1977 to 2006.
- In regions of Colorado, widespread warming is evident across most climate divisions in the 30-year period.
- In the last 50 years, the North Central Mountains warmed the most (+2.5°F), while temperatures in southwestern Colorado, including the San Juan Mountains, changed very little (+0.2°F). Minimum temperatures have warmed more than maximum temperatures during this period.
- In all parts of Colorado, no consistent long-term trends in annual precipitation have been detected in the time periods analyzed. Variability is high, which makes detection of trends difficult.
- A widespread and large increase in the proportion of precipitation falling as rain rather than snow and a reduction in snow water equivalent (SWE) have been observed elsewhere in the West between 1949 and 2004. In Colorado, however, these changes are smaller and not as statistically significant (Knowles et al. 2006). Most of the reduction in snowpack in the West has occurred below about 2500 m (about 8200 ft, Regonda et al. 2005). However, most of Colorado's snowpack is above this elevation, where winter temperatures remain well below freezing.
- Peak streamflows in the western United States are occurring earlier in the spring due to warming temperatures during spring months (Stewart et al. 2005, Hamlet et al. 2005). In Colorado, between 1978 and 2004, the spring pulse has shifted earlier by about two weeks (Clow 2007).
- Throughout the West, less frequent and less severe drought conditions have occurred during the 20th century than in the paleoclimate records covering the last 1000 years (Meko et al. 2007).

Observations are the basis for understanding past and recent climate variability, for modeling future climate, and for evaluating future climate scenarios. This discussion of observations is intended to provide a background in how observations are made, the variation inherent in Colorado's climate record, and the challenges in analyzing this record. This information provides a context for climate attribution and projections. This section also presents a brief overview of the climate of Colorado. For a discussion on the difference between climate and weather, see climate in the glossary.

This report describes a number of observational studies. Comparing these studies is inherently complicated because different researchers analyze different periods of record, which are determined in part by the data available, and by the problem they want to study. Extensive effort would be needed to re-analyze and homogenize the results, so we have merely stated the periods that the authors chose.

The results of these observational studies must be taken in the context of the years defining the period and the climatic events that may or may not be included in different records. Colorado's climate has been punctuated by several notable climatic events, including the Dust Bowl years (1930s), a relatively cool period from the 1950s to the 1970s, and the recent severe drought in which eight out of ten years (1999–2008) had below normal April 1 snow water equivalent (SWE). These variations may influence the results of ongoing analyses. This report presents 30-, 50-, 75-, and 100-year trend analyses.

2-1. Observing Systems in Colorado

The earliest instrumental weather observations in Colorado came from some of the early forts built on the western frontier. In 1870, the organization that later became the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) established more weather stations in Colorado including Denver, Pueblo, and Pikes Peak. In the 1880s the Colorado State Legislature authorized the creation of the Colorado Weather Service, with a goal of better defining the weather and climate resources of Colorado. This network of dozens of urban and rural weather stations later became the State of Colorado National Weather Service Cooperative Observer (COOP) Network. NOAA's National Climatic Data Center (NCDC) is also concerned with tracking future climate and has recently deployed a special climate observing network called the Climate Reference Network, including six stations in Colorado (**http://www.ncdc.noaa.gov/oa/climate/uscrn/**).

There are currently ~250 weather stations in Colorado reporting to the NWS. These stations measure and report daily high and low temperatures, precipitation (rain and the melted water from snow and ice), snowfall, and total snow depth. Average daily temperature is computed as the mean of the minimum and maximum temperatures. Some of these weather stations report additional information such as wind, humidity, and cloud cover.

It is important to note that many of these observing systems were not constructed and maintained with the goal of detecting long-term climate trends. In this context, changes in instrumentation, station locations, time of measurement and other factors have affected interpretation of long-term datasets. Changes in the location of observing stations may affect long-term records. Of the ~250 current stations scattered across the state, only two are located in nearly the same place as they were when first established in the 1880s. Station moves can result in slight differences in the local climate observed, and may appear as a spurious "climate change" trend. The widespread transition from glass to electronic thermometers in the 1980s resulted in a cold shift, or bias, of about 0.5°F compared to periods prior to the instrumental change. An even larger cold bias can occur if the daily observing time is changed from the afternoon to the morning (Pielke et al. 2002), as has become more common in recent decades. Land use changes that affect local temperature are also common in Colorado, including year-round urban heat island effects and altered irrigation patterns, which impact temperatures during the growing season (Pielke et al. 2002). To further complicate the matter, changes in these parameters are not always documented (Pielke et al. 2007).

Long-term hydrologic records also face observational challenges. For example, snow data are subject to local weather modification efforts and vegetation growth near the site (Julander and Bricco 2006). Changes in instrumentation and the impact on stream gauges from changes in stream channel geometry and upstream diversions also complicate the picture.

Given the complications introduced by observing stations, climatologists spend a lot of time considering how to work with the best scientific data by routinely quality controlling datasets. Scientists have developed procedures for adjusting and accounting for observational bias (including instrumentation changes and station location) by culling aberrant records and applying calibration measures. It is important to note that the methodological processes meant to improve observational datasets are subject to scrutiny in the peer review process and have been vetted by the scientific community.

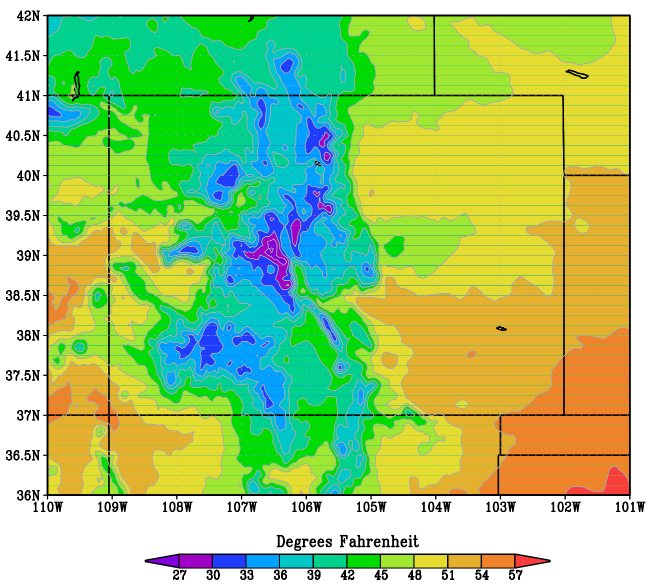
An extensive discussion of the records at some Colorado climate stations is provided in Pielke et al. (2002), who caution that, given local variability and station issues, trends at individual stations may not be representative of regional trends. Section 2-4 presents data from some individual stations, then analysis of regions of the state.

2-2. The Climate of Colorado

Colorado's climate is unlike that of any other state—it is characterized by the high elevations and complex topography of the Rocky Mountains, the Colorado plateau and valleys of the West Slope, and the high plains falling off from the Continental Divide towards the east (FIGURE 2-1). Climate varies in Colorado spatially across many regions, temporally across years and decades, and its temperature and precipitation histories differ across the state.

FIGURE 2-1. Annual Average Temperature and Precipitation in Colorado (1950–99)

TEMPERATURE



PRECIPITATION

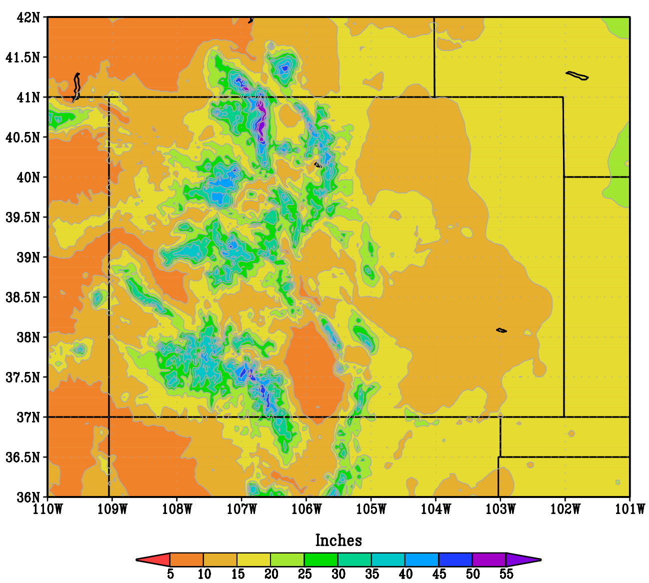


Fig. 2-1. Annual climatology (1950–99) of daily average temperature (°F) and precipitation (inches). See FIGURES 5-2 and 5-3 for January and July temperature climatologies. (Data: PRISM)

Different climate drivers influence temperature variability in different parts of the state. Western Colorado and interior mountain valley temperatures are greatly affected by the presence or absence of snow cover. In a year with deep and early snows, winter temperatures can dip to 6–10°F below average (N. Doesken, pers. comm.). The opposite (i.e., above average temperatures) may occur during winters with limited snow cover. For the high mountains, the influence of persistent upper-level ridges and troughs (regions of high and low atmospheric pressure, respectively) dominate temperature anomalies. East of the mountains the battle among subtropical, Pacific, and polar continental air masses determines which years are warmer or colder than average (Pielke et al. 2003).

The annual cycle dominates temperature variability (see FIGURES 5-2 and 5-3). Statewide, January is typically the coldest month of the year and July or August is the warmest. Temperatures vary widely from day to day and week to week, especially during the cooler months from mid-autumn to late spring. Winter temperatures are more variable than summer temperatures, and daytime temperatures are more variable than nighttime readings. The least variability occurs with summer minimum temperatures.

It is against the background of variability in temperature and precipitation (discussed in Section 2-6)that long-term climate records are analyzed to detect trends. Time series analysis, including trend analysis, uses statistical methods to analyze records spanning a period of time in order to assess whether or not there is a detectable trend. To determine whether there is an anomaly in one period of interest compared to another, scientists may compare a year or period of years to a base period or reference period climatologies. This reference period depends on the process or issue being studied, and the variability in the datasets. The IPCC used various periods, including 20- and 30-year averages; these data were global averages and included a considerable number of data points, therefore reducing variability (IPCC AR4 WGI 2007). For a smaller region or one with greater variability, a longer period may be needed in order to detect trends in a statistically robust way. Analyses generated for this report use 50-year (1950–99) climatologies where possible.

2-3. Local and Regional Climates of Colorado

Sections 2-3 and 2-4 describe Colorado's climate from the standpoint of individual stations, experimental Colorado climate divisions, and the official National Climatic Data Center (NCDC) divisions. All these analyses are based on data from the NWS COOP Observing Network.

An effort has been underway for several years to carefully scrutinize all of Colorado's long-term weather stations and identify which are best for historic time series analysis and trend detection. In collaboration with the Western Water Assessment (WWA), the Colorado Climate Center has categorized each station in Colorado according to suitability for trend analysis and detection. The Colorado Climate Center has developed a website specifically to view temperature and precipitation variations and trends for the best long-term datasets at stations in Colorado, including the data shown in FIGURES 2-2, 2-3, and 2-4 (**http://ccc.atmos.colostate.edu**).

To illustrate local variability in Colorado, nine stations were selected from 38 "better quality" stations through Colorado (FIGURES 2-2 and 2-3). These stations have 90-year or longer records in both temperature and precipitation, and comparatively fewer identified problems with station relocation, instrument changes, and missing observations, according to analysis by the Colorado Climate Center and the WWA. In contrast, stations in Denver, Colorado Springs, and throughout the central mountains relocated too frequently, or had other problems limiting their use in long-term analysis. The temperature records show

FIGURE 2-2. Temperature at Nine Observing Stations

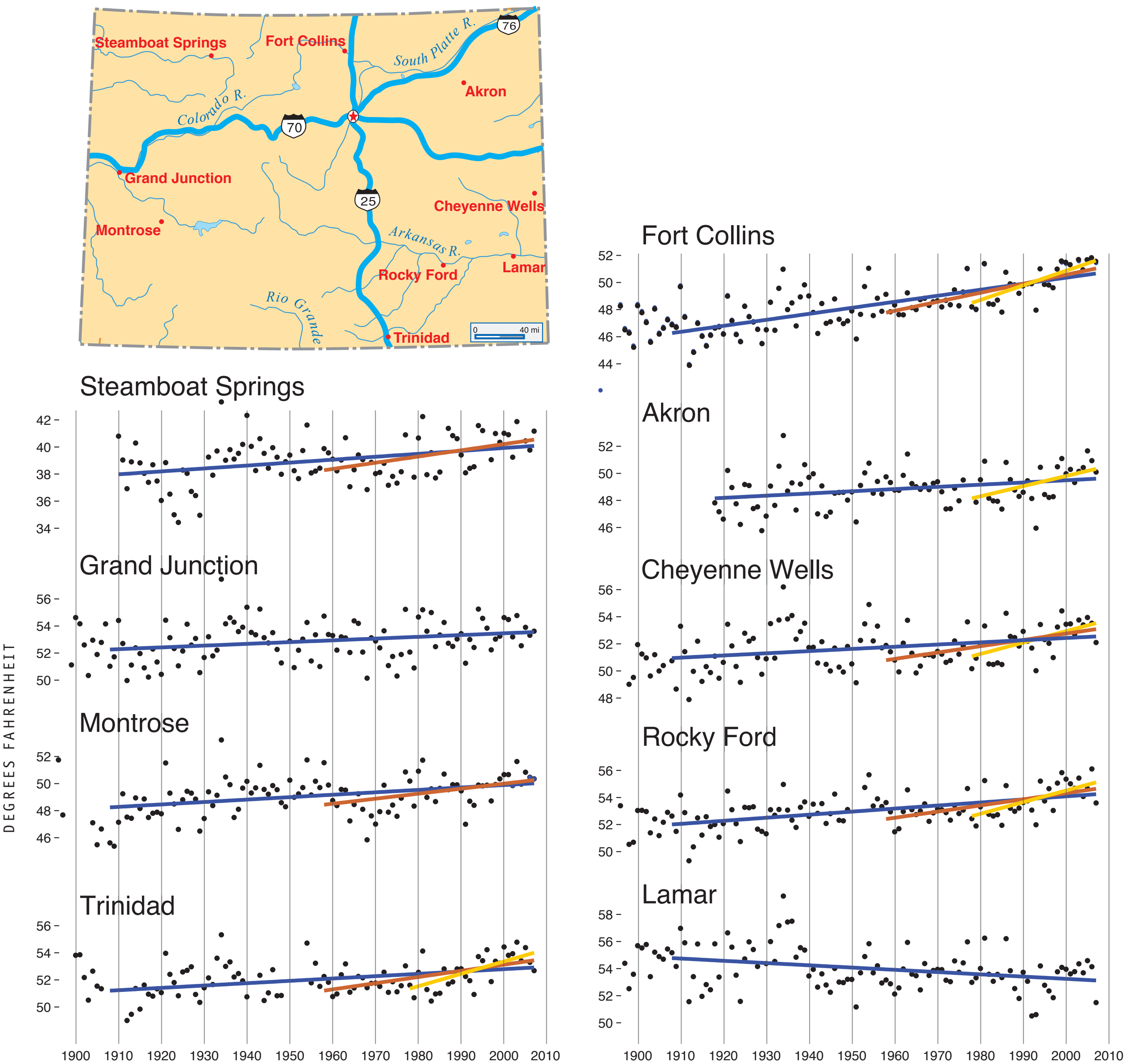


Fig. 2-2. Daily average temperature (°F), annually averaged, at nine observing stations in Colorado. Station locations are shown on the map of Colorado (top left). The 100-, 50-, and 30-year linear trends shown in blue, red, and yellow, respectively, are statistically significant (>97.5%); linear trends that are not significant are not shown. If less than 100 years of data were available, the full period of record was used to calculate the trend shown in blue. Of the 27 trends generated, 19 are increasing, one is decreasing (100-year trend at Lamar), and seven were not statistically significant.

the linear regression for the 30-, 50-, and 100-year trends in the mean (Figure 2-2), and the precipitation records (Figure 2-3) show the 10-year moving average.

Variability is apparent at all locations, and is comparatively smaller in the temperature record than the precipitation record. When added up over an entire year, the mean temperature at each location falls within a few °F of its long-term average. Statistically significant trends are detected in the temperature record when the trend emerges from the variability. Of 27 trend lines computed (100-, 50-, and 30-year time periods, at nine stations), 19 are increasing, one is decreasing (100-year trend at Lamar), and seven were not statistically significant. In all parts of Colorado, no consistent long-term trends in annual precipitation

FIGURE 2-3. Water Year Precipitation at Nine Observing Stations

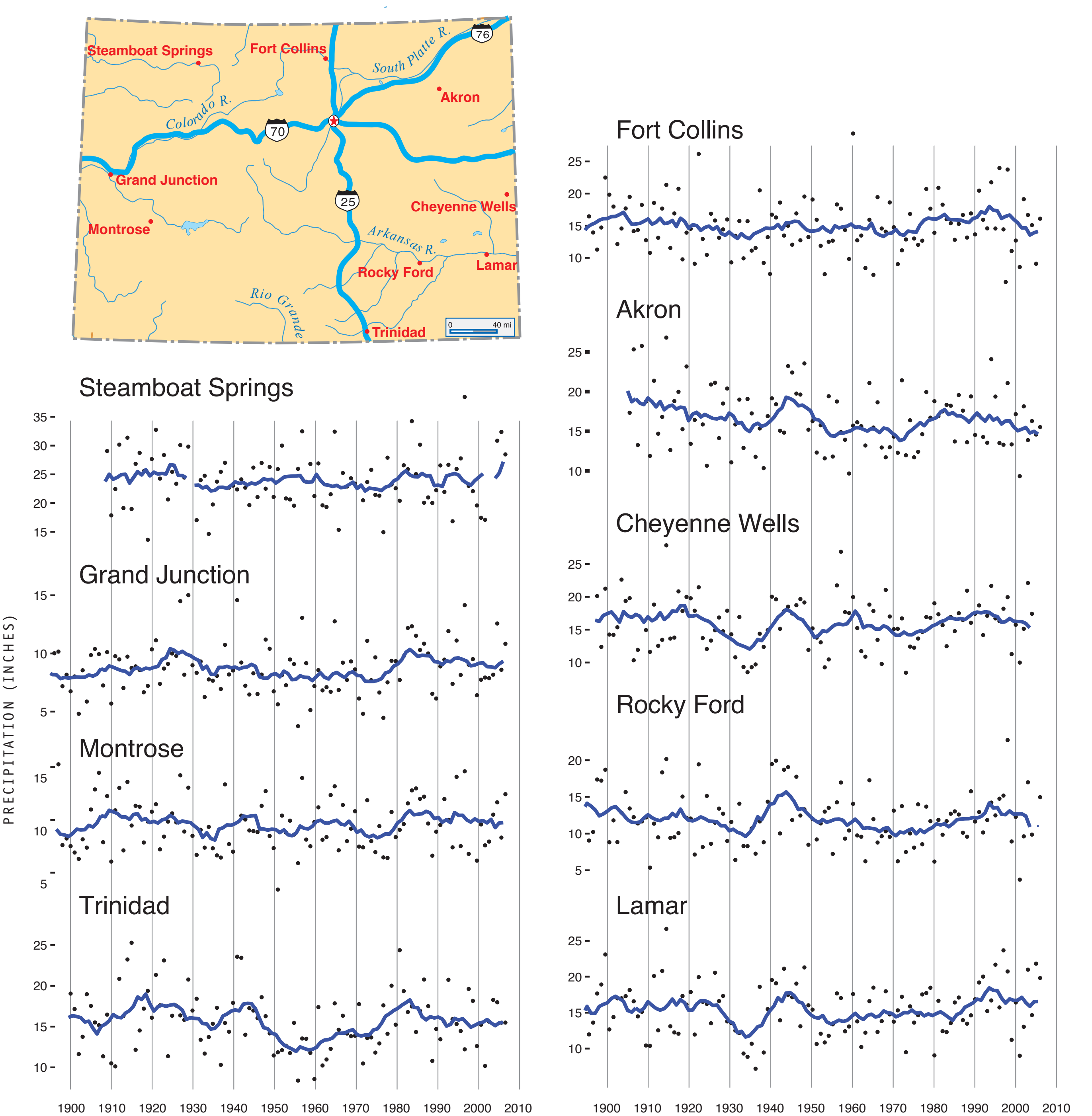


Fig. 2-3. Water year precipitation (inches) at nine observing stations around Colorado. Station locations are shown on the map of Colorado *(top left)*. Overall long-term trends are not detectable at the stations. The 10-year moving average of available data *(solid blue line)* is shown to emphasize decadal variations. Shorter-term changes, such as the droughts of the 1930s, 1950s, and the early 2000s, are apparent at some stations.

have been detected in the time periods analyzed. Seasonal trends have not been analyzed at these locations, but may be of interest to water managers.

Climatic trends at individual stations may not be representative of regional climate because of local processes at those stations (Figures 2-2 and 2-3). For this reason, climatologists assess long-term regional variability by grouping observing stations together. Regional trends may emerge (e.g., be statistically detectable) when the records from these stations are averaged together.

The NOAA National Climatic Data Center (NCDC) five official climate divisions group Colorado climate data into regions by river basins, but these divisions are not necessarily representative of the complex regional climates in the state. A new set of climate divisions has been developed (Wolter and Allured 2007). These new divisions are based on groups of observing stations that vary in a similar manner from year to year, and are thought to reflect similar regional climate processes. Sufficient data are available to construct time series of temperature for most of these new climate divisions back to the early 1930s. The averages calculated from the better quality observing records within each division help to detect regional temperature trends by eliminating local processes that are not indicative of regional climate at each observing station.

Temperature trends were computed for these new climate divisions for selected time periods (75-, 50-, and 30-year periods) or the whole record (Figure 2-4). Regionally, the north-central part of the state has been warming the fastest (a +2.5°F change in the annual average over the past

FIGURE 2-4. Colorado Regional Temperature Trends

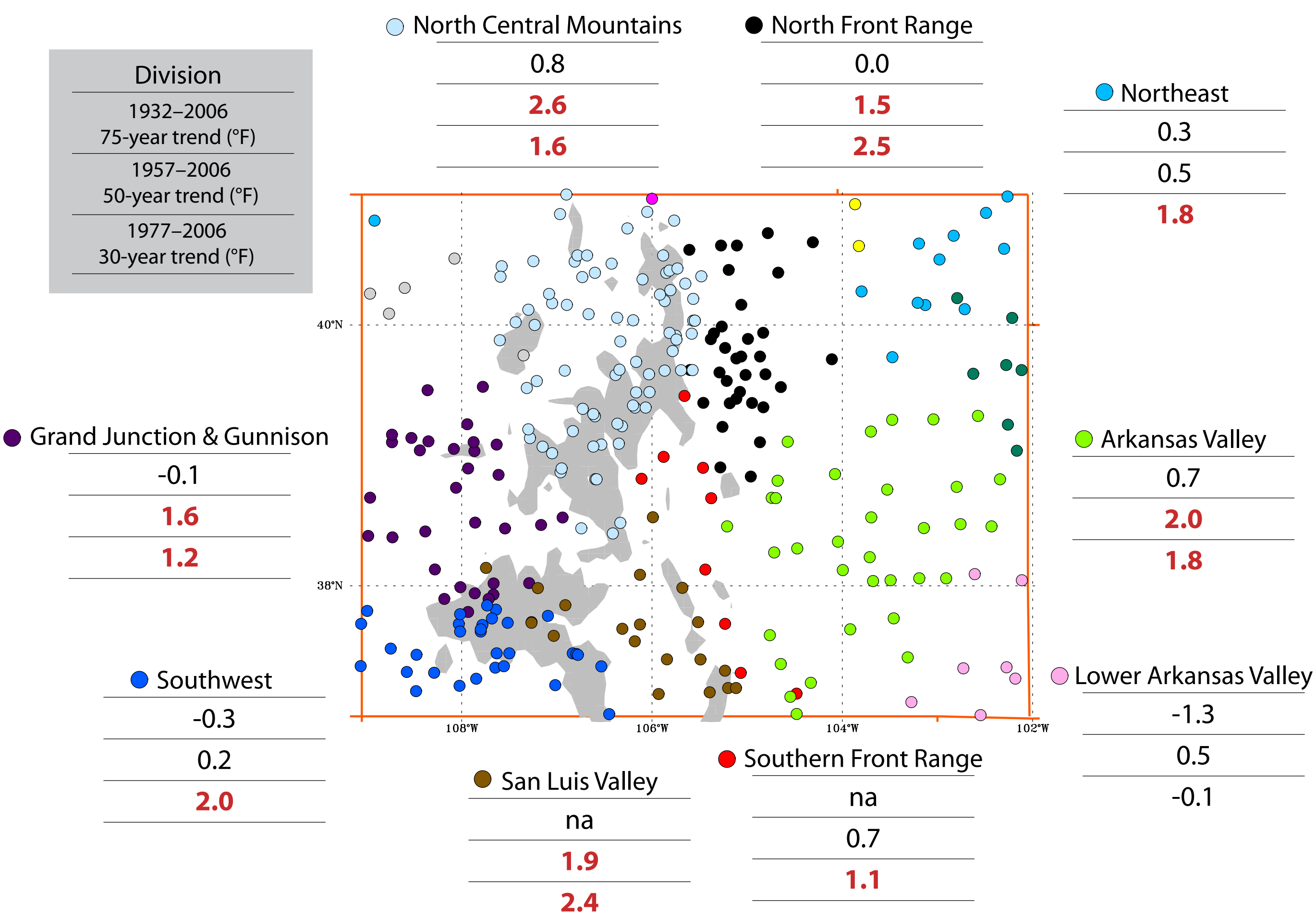


Fig. 2-4. Regional trends in annual average temperature (°F) for experimental climate divisions in Colorado. Groups of stations with similar climates comprise the divisions indicated by colored circles; there are no delineated geographic boundaries. Gray shading indicates terrain at an elevation higher than 9850 feet (3000 m). The tables show temperature changes for the 30-, 50-, and 75-year periods ending in 2006, as determined from linear trend analysis. Statistically significant trends (>95%; see the online Methods Supplement) are shown in red (warming) and blue (cooling). Trends were computed by averaging observations from a subset of locations within each division (between three and seven stations, depending on the division) that met quality control requirements. Although some divisions extend beyond the state's borders, only stations within Colorado were used to determine trends. Insufficient data were available to calculate 75-year trends for the San Luis Valley and the Southern Front Range divisions. Significant warming is evident in most divisions in the past 30 and 50 years.

50 years), while the southwestern corner has warmed the slowest over the same time period (+0.2°F). The most striking trends are for the most recent 30-year period (1977–2006), about a +2°F change during this period for most of the state, except the Lower Arkansas Valley (pink circles, FIGURE 2-4) climate division in the southeast corner of the state. This division also shows a regional cooling trend for the 75-year period. This period begins during the 1930s Dust Bowl years in Colorado, which were some of the warmest years on record for many stations. This division extends well beyond the state's borders; only two stations, Holly and Lamar were used to compute the regional average. Pielke et al. (2002, 2007) discuss problems with the observational record at these stations, including changes in observation time that may have introduced a cold bias. Using a larger selection of COOP stations in this division in Colorado and in neighboring states yields the following linear trends: 1932–2006 (-1.4°F), 1957–2006 (+0.1°F), 1977–2006 (+0.7°F).

Minimum temperatures show greater overall warming than maximum temperatures in the last 50 years. Analysis of seasonal trends for minimum and maximum temperatures for Northern Colorado Mountains and the Arkansas Valley (green circles, FIGURE 2-4) show upward trends in minimum temperatures in all seasons, with the largest trends in spring (TABLE 2-1). This finding is consistent with Knowles et al. (2006) who also found large and widespread warming trends in the intermountain west in March over a similar period. Across the state, winters also warmed during this 50-year period, but this trend is less pronounced than for spring.

TABLE 2-1: Seasonal Temperature Trends (1957–2006) in the Northern Colorado Mountains and the Arkansas Valley

		winter	*spring*	*summer*	*autumn*	*annual*
Arkansas Valley	Tmax	+2.1	**+3.8**	+0.4	+1.0	**+1.8**
	Tmin	**+3.2**	**+3.0**	**+1.4**	**+1.4**	**+2.2**
North Central Mountains	Tmax	+1.3	**+4.6**	**+1.8**	- 0.1	**+1.9**
	Tmin	**+2.7**	**+4.7**	**+3.0**	**+2.7**	**+3.2**

The observed trend in average maximum (Tmin) and minimum temperatures (Tmax) from 1957 to 2006 for the Arkansas Valley and the North Central Mountains experimental climate divisions. Locations of the divisions are shown in FIGURE 2-4. The 50-year trends for individual seasons and the annual mean are shown. Statistically significant *(red)* warming trends are evident in all seasons for Tmin. Springtime trends for Tmin and Tmax are particularly large.

2-4. Statewide Average Temperature, 1930s to present

Colorado's climate since 1930 shows a warm period in the 1930s and the 1950s, a cool period though the 1960s and 1970s, and a consistent upward trend in the 10-year average since about 1970 (FIGURE 2-5). The temperature has increased by +2.0°F from 1957 to 2006 (50 years), and by +2.1°F from 1977 to 2006 (30 years). These trends are based on the NCDC traditional climate division data.

This estimate can be compared with an alternate calculation using spatial averages of the experimental climate divisions (see FIGURE 2-4) that are based on unadjusted COOP station data. This calculation results in statewide linear trends of +1.6°F from 1957 to 2006 and +1.7°F from 1977 to 2006. Although the analysis methods and choice of dataset lead to the differing estimates of statewide trends, these methods converge on a statewide temperature increase of about 2°F. The above trends were calculated by fitting a straight line through the data. Temperatures changes between the beginning and the end of these periods show similar results.

FIGURE 2-5. Colorado Annual Mean Temperatures (°F) for 1930–2007

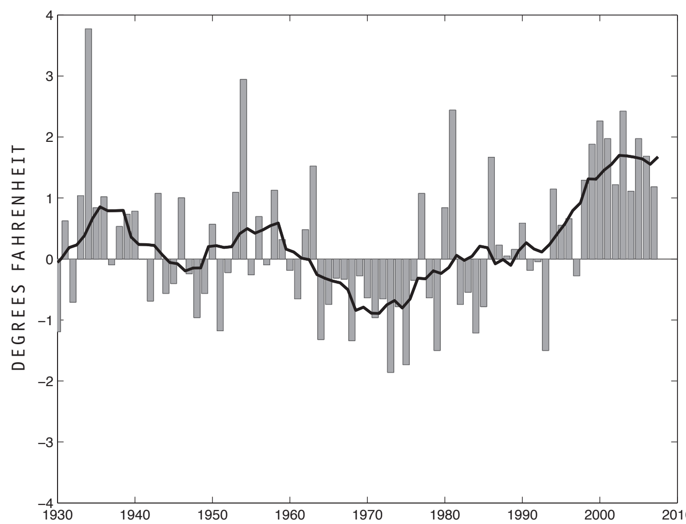


Fig. 2-5. Colorado annual mean temperatures (°F) from 1930 to 2007. Annual departures are shown as gray bars relative to a 1950–1999 reference period. The 10-year moving average of available data (black curve) highlights low frequency variations in the record. Warm periods occurred in Colorado in the 1930s and the 1950s, followed by a cool period through the 1960s and 1970s. Since about 1970, there has been a consistent upward trend in the 10-year average. (Data source: NCDC Climate Divisions, see http://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp)

FIGURE 2-6. Temperature Trend and Elevation (1979–2006)

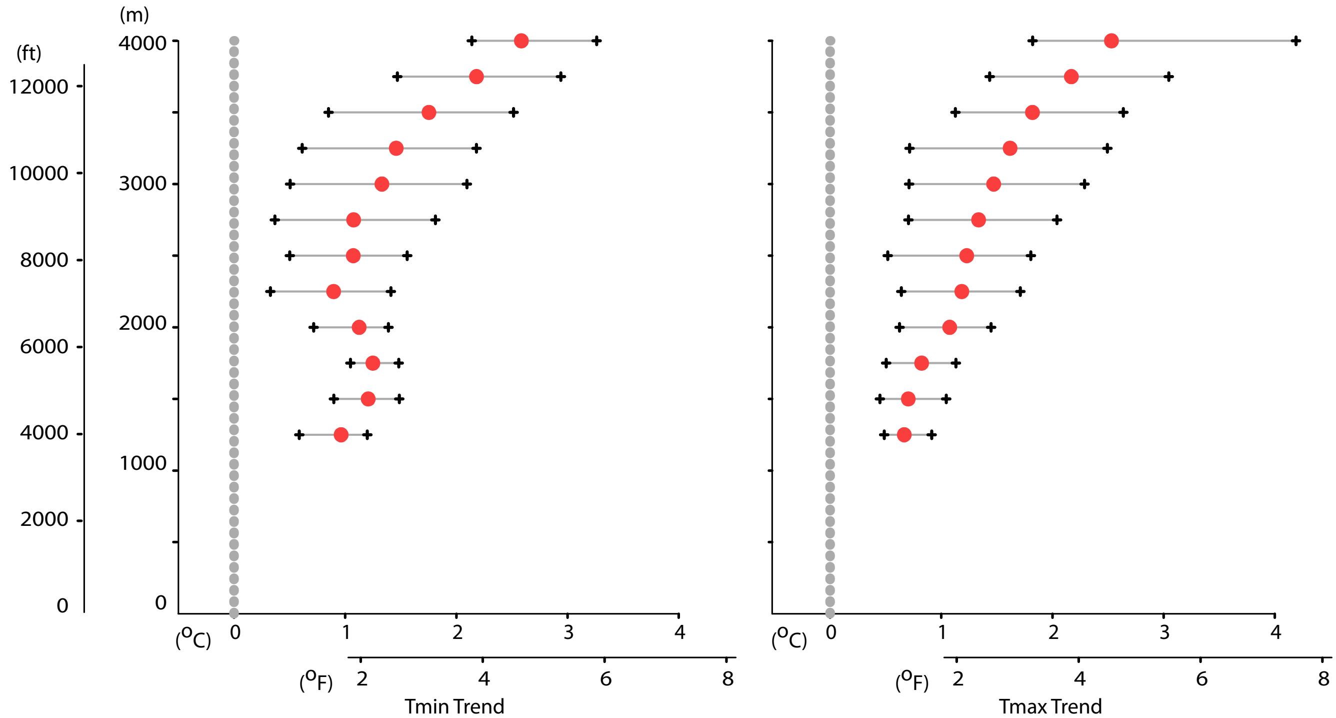


Fig. 2-6. Dependence of temperature trends on elevation. Annual mean daily minimum *(left panel)* and maximum *(right panel)* temperature trend (1979–2006) plotted in successive 250-meter elevation bands. The red dot is the median trend over the period of analysis at all locations within its elevation band; the crosses are the approximate 5th and 95th percentile values, and represent the range of trends throughout the state in the elevation band. The dotted line is zero trend or no change. (Diaz and Eischeid 2007)

2-5. Elevation

Another regional view of temperature is its relationship with elevation. Temperature typically decreases as elevation increases, and temperature is a significant factor in defining the ecosystems and habitats at different elevations. Diaz and Eischeid (2007) analyzed the temperature record using the Parameter-elevation Regressions on Independent Slopes Model dataset (PRISM; **http://www.prism.oregonstate.edu/**). They find larger warming trends at high elevations (Figure 2-6). Few reliable long-term surface air temperature records are available above 9850 feet (3000 m). PRISM temperatures at these elevations are estimated from in situ observations at lower elevation and from free-atmosphere (above the land surface) temperatures. The magnitude of estimated temperature trends from Diaz and Eischeid (2007) may not be consistent with in situ observational data from alpine locations, such as Niwot Ridge in Boulder County (>11,000 ft) and Loch Vale in Rocky Mountain National Park (>10,000 ft) (J. Baron pers. comm., M. Williams pers. comm.).

2-6. Trends in Hydroclimatic Variables: Temperature, Precipitation, Snow, and Streamflow

Colorado's temperature trends are consistent with multiple independent analyses showing widespread warming in the West (CCSP SAP 4.3 2008; Udall and Bates 2007; Mote et al. 2005; Stewart et al. 2005; Diaz and Eischeid 2007). However, a few sites in the southern San Juan Mountains show cooling (Mote et al. 2005). Regonda et al. (2005) observed that the onset of spring warm spells (defined as seven days greater than 53°F/12°C) shifted to an earlier date over the period 1950–99. Knowles et al. (2006) found positive temperature trends at the vast majority of stations across the West. The greatest warming was generally observed at the higher elevations in the Interior West, with the most warming observed in March (Figure 2-7; for other months see Knowles et al. 2006).

FIGURE 2-7. Trend in March Average Minimum Temperature on Days with Precipitation (1949–2004)

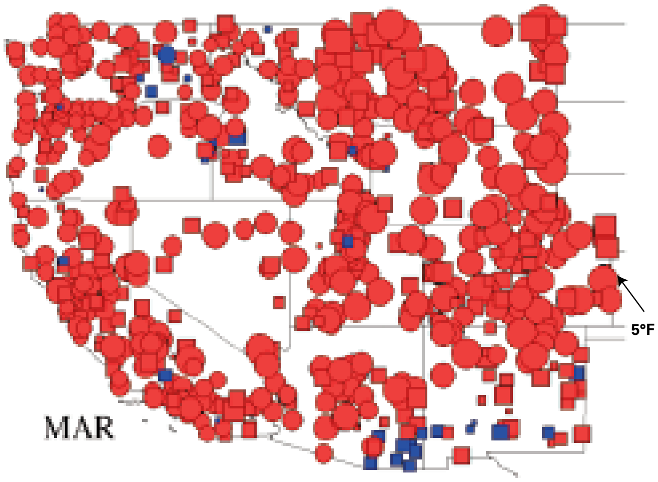


Fig. 2-7. Trend in March average minimum temperature on days with precipitation (1949–2004, the latest data available at the time of analysis). Red indicates an increase in temperature and blue indicates a decrease. The size of the circle is proportional to the temperature change. For scale, the arrow indicates a 5°F change. The circles represent statistically significant findings and the squares are not significant. (from Knowles et. al. 2006, FIGURE 9)

Water year precipitation ranges from roughly half the long-term average in a dry year to double the average in a wet year and varies across the state (see FIGURE 2-3). The El Niño Southern Oscillation (ENSO) has correlations with precipitation that vary regionally across Colorado (**http://www.cdc.noaa.gov/Climaterisks/**), but do not dominate the variability on annual and longer time scales (Wolter 2008). Eastern Colorado is dominated by warm season precipitation, largely a result of localized convective storms. The lower elevations of southern and central Colorado receive significant precipitation from late summer storms, while statewide, the mountains are dominated by winter and spring precipitation.

A widespread increase in the proportion of precipitation falling as rain rather than snow has been found in the winter months throughout the Western United States from 1949 to 2004; however, the data are highly variable for Colorado (Knowles et al. 2006; FIGURE 2-8).

At gauges throughout the West, there has been either no detected trend or a slightly increasing trend in mean annual streamflow over the period 1948–2002 (Stewart et al. 2005). In contrast, Walter et al. (2004) find a decrease in Colorado River Basin flow (1950–2000), although the trend is not statistically significant. For Colorado, Clow (2007) found that snowmelt and runoff timing shifted about two weeks earlier from 1978 to 2004, with the strongest trends in the western and southern regions of Colorado, and weak trends in the Northern Front Range. Stewart et al. (2005) also find a consistent one-to-four-week earlier shift in the spring pulse onset. Both studies (Clow 2007; Stewart et al. 2005) attribute changes in snowmelt timing to springtime warming. Hamlet et al. (2005) uses modeled runoff based on observed meteorological data and drew the same conclusion. Regonda et al. (2005) observed that between 1950 and 1999, the onset of runoff in Colorado trended toward later dates, but these data do not include the recent Colorado drought years.

Looking beyond mean streamflows, Pagano and Garen (2005) found increases in April–September streamflow variability in Colorado (the USGS gauge on the White River near Meeker, 1943–2002) which they attribute to increasing variability in spring precipitation. They also find an increase in year-to-year persistence of high or low flows.

Snow water equivalent (SWE) is a measure of the amount of water in the snowpack. SWE is measured at SNOTEL and snow course sites across the West by the Natural Resource Conservation Service (NRCS). Mote et al. (2005) and Regonda et al. (2005) have both studied trends in April 1 SWE in the West. While declining SWE is detected in other parts of the West, no spatially coherent trends were found in Colorado and some stations in Colorado recorded increases. Hamlet et al. (2005) concluded that those stations reporting increased SWE were associated with modest upward precipitation trends, and that widespread warming caused many of the downward trends in SWE.

Elevation and temperature are factors in the evolution of snowpack. Regonda et al. (2005) found that stations in the western United States below 2500 m (8200 ft) exhibited the largest decreases in SWE at March 1, April 1, and May 1. Much of Colorado's snowpack is above this elevation where winter temperatures remain well below freezing; note that

FIGURE 2-8. Trend in Snow vs. Rain in Winter (1949–2004)

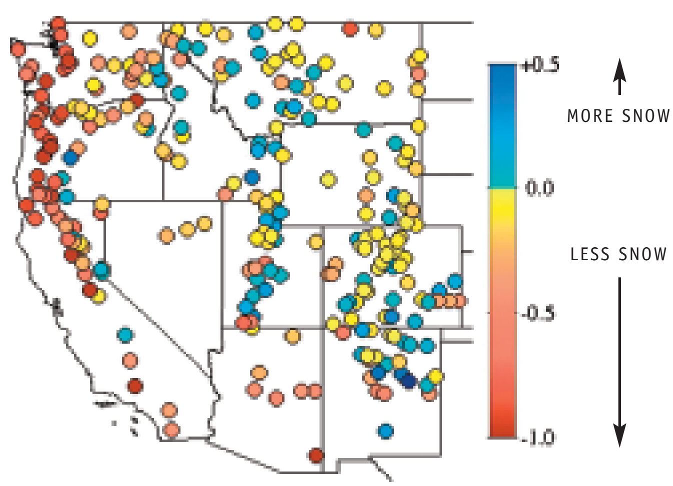


Fig. 2-8. Changes in the fraction of winter precipitation falling as snow vs. rain (1949–2004), after correcting for trends in precipitation amount. Blues indicates increasing fraction of snow; yellow decreasing fraction. Data are from NWS COOP stations. (from Knowles et. al. 2006, FIGURE 7)

SIDEBAR 2-1. Paleoclimate

Paleoclimate refers to climate during the period prior to the beginning of instrumental records—in Colorado, before the late 1800s. Various environmental indicators or "proxies" can be used to reconstruct paleoclimatic variability extending back hundreds or thousands of years.

In particular, the growth of trees in many parts of Colorado and the West closely reflects annual moisture variability, so tree-ring records can be used to reconstruct, or extend, gaged records of annual streamflow. These streamflow reconstructions can provide water managers and stakeholders with a much longer window—500 years and more—into the past hydrologic variability of a river system, and thus have the potential to inform sustainable management of water resources. The reconstructions indicate that more severe and sustained droughts occurred in the centuries prior to 1900 than those seen in the gaged records, including the most recent drought (FIGURE 2.9).

For more information on streamflow reconstructions, including access to data for Colorado and the upper Colorado River basin, see the WWA TreeFlow pages: http://wwa.colorado.edu/treeflow/. Woodhouse and Lukas (2006) provide streamflow reconstructions at 14 gauges in the Upper Colorado and South Platte River basins.

FIGURE 2-9. Reconstruction of Streamflow for the Colorado River at Lees Ferry

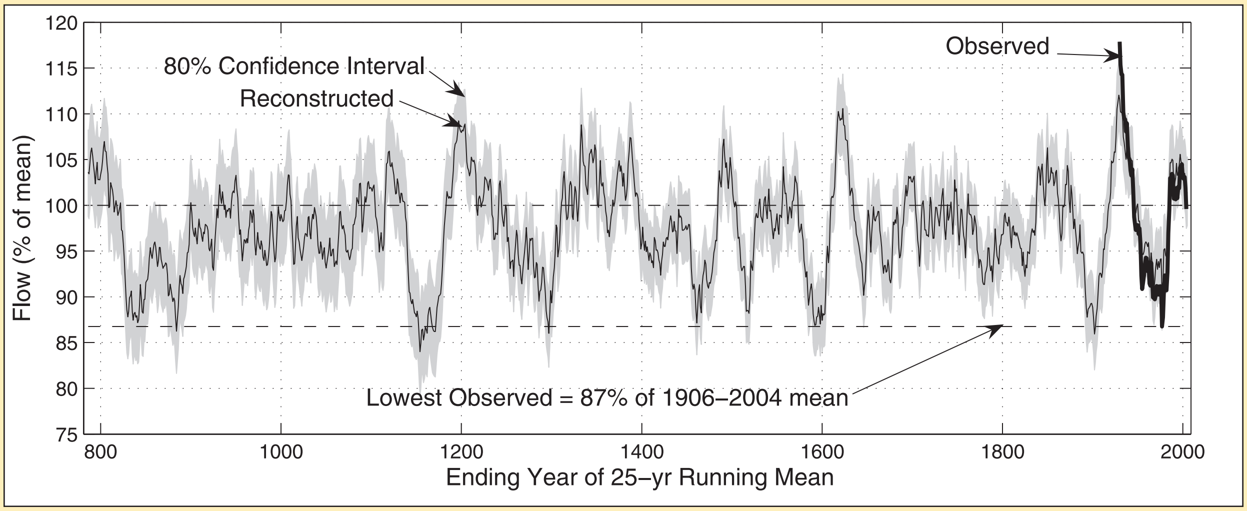


Fig. 2-9. A reconstruction of streamflow for the Colorado River at Lees Ferry (five-year moving average, with 80% confidence interval shown as gray band) is compared with the observed natural flow record (five-year moving average in black). The severity of the 2000–04 drought was probably exceeded at least once in the previous 500 years. (from Meko et al. 2007)

about 70% of the Colorado River Basin annual runoff is contributed by this higher-elevation snowpack. Therefore the statewide average snowpack in Colorado does not show the declines that have been observed at lower elevation mountains elsewhere in the West (Udall and Bates 2007).

These studies also illustrate how analysis of trends may be influenced by the period studied and by anomalies occurring during and after the period studied. For example, all but the most recent studies were completed before data was available from parts of the continuing 2000s drought, and all published analyses were completed before data on the record-setting snows of 2007–08 were available. Furthermore, analysis of year-to-year variations using SWE observations from any single month without seasonal context (e.g., March 1, April 1, and May 1) may not reflect changes in the seasonal evolution of snowpack.

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2-7. Extremes

A recent CCSP synthesis report presents a comprehensive assessment of the scientific literature for extremes in all of North America (CCSP SAP 3.3). For temperature trends, the report notes "a shift towards a warmer climate with an increase in extreme high temperatures and a reduction in extreme low temperatures. These changes have been especially apparent in the western half of North America" (CCSP SAP 3.3, P. 3). An increase in the number of heat waves nationwide has been detected over the past 50 years, but the report notes "the heat waves of the 1930s remain the most severe in the U.S. historical record" (CCSP SAP 3.3, p. 3). While there are no published recent studies on trends in heat waves in Colorado, the observed warming over Colorado is consistent with these findings. Even so, at many locations in Colorado, the extreme temperatures of the 1930s have yet to be surpassed. The number of frost days has been decreasing and the frost-free season has been lengthening, "particularly in the western part of North America" (CCSP SAP 3.3, p. 35). However, Kunkel et al. (2004) reports small (<3 days) observed changes in frost-free season length over much of Colorado; the much larger trends are located in regions to the west of Colorado. Increases in the frequency and intensity of extreme precipitation events (heavy downpours) were noted in most of the United States, however there were no significant trends detected for Colorado (Groisman et al. 2005).

A multi-year drought has occurred throughout the western United States since the late 1990s. This type of extreme event is covered in detail in Section 4.

SIDEBAR 2-2: IPCC Technical Paper on Water

Besides producing overarching assessments on global climate (e.g., IPCC AR4 2007) at the request of member nations, the IPCC will assess more detailed topics related to climate change. In July 2008, the IPCC publicly released the Technical Paper on Water (2008), which assesses the relationship between climate change and water resources. From the report, it is clear that "observational records and climate projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems" (IPCC 2008, p. 3). The report provides a case study on the Colorado River as an illustration of the importance of water–climate interactions in decision-making. Below is an excerpt from that section:

"As is widely documented, the allocation of Colorado River water to basin states occurred during the wettest period in over 400 years (i.e., 1905–25). The recent western drought has affected 30–40% of the region under severe drought since 1999, and the lowest 5-year period of Colorado River flow on record occurring from 2000 to 2004. At the same time, the states of the south-west USA are experiencing some of the most rapid growth in the country, with attendant social, economic and environmental demands on water resources, accompanied by associated legal conflicts (Pulwarty et al. 2005).

"Only a small portion of the full Colorado Basin area (about 15%) supplies most (85%) of its flow. Estimates show that, with increased climatic warming and evaporation, concurrent runoff decreases would reach 30% during the 21st century (Milly et al. 2005). Under such conditions, together with projected withdrawals, the requirements of the Colorado River Compact may only be met 60–75% of the time by 2025 (Christensen et al. 2004). Some studies estimate that, by 2050, the average moisture conditions in the south-western USA could equal the conditions observed in the 1950s. These changes could occur as a consequence of increased temperatures (through increased sublimation, evaporation and soil moisture reduction), even if precipitation levels remain fairly constant. Some researchers argue that these assessments, because of model choice, may actually underestimate future declines.

"Most scenarios of Colorado River flow at Lees Ferry (which separates the upper from the lower basin) indicate that, within 20 years, discharge may be insufficient to meet current consumptive water resource demands. The recent experience illustrates that 'critical' conditions already exist in the basin (Pulwarty et al. 2005). Climate variability and change, together with increasing development pressures, will result in drought impacts that are beyond the institutional experience in the region and will exacerbate conflicts among water users." (IPCC 2008, p. 105)

3
A Primer on Climate Models, Emissions Scenarios, and Downscaling

KEY POINTS

- **Climate models have improved in their ability to simulate the climate, even as the modeling community has set more demanding goals (Reichler and Kim 2008).**
- **A number of climate models are available from different research groups and countries, each with strengths and weaknesses in simulating different processes. For a set of model simulations, the average of all the models is consistently more accurate than any individual result. In projecting Colorado's water future, it is very important to compare a range of results from different models, and to consider multi-model averages.**
- **For planning horizons up to about mid-century, emissions scenarios result in a quantitatively similar range of projections of global and regional climate change. Consequently, the implications of the three scenarios (SRES B1, A1B, A2) are similar to one another for 25- to 50-year planning and adaptation horizons. These scenarios diverge in the latter half of the 21st century.**
- **The global climate models do not represent the complexity of Colorado's topography. However, they do simulate the large-scale climate processes that affect mountainous regions, including winter storm tracks.**
- **Downscaling techniques are being used to study processes that matter to Colorado water resource managers, since these methods can adjust for the effects of elevation and the mountains on snowfall and temperature.**
- **Projects are underway to improve understanding of the local processes that affect Colorado. These include developing better statistical downscaling methods, and enhanced climate modeling efforts to include finer spatial resolution that better represents Colorado's mountainous terrain.**

3-1. Anatomy of a Climate Model

Precipitation, wind, cloudiness, the ocean currents, air, and water temperatures—these and other variables evolve in time and space governed by physical, chemical, and biological processes. The processes included in the global climate models are quite varied. From the climate modeler's standpoint, these myriad processes have one thing in common—they can be expressed in terms of mathematical equations derived from scientific laws, empirical data, and observations. These equations are converted into computer code, and along with information about the Earth's geography (e.g., topography, vegetation), form the basis of a climate model.

In order to understand how a climate model is constructed, it helps to think of the Earth's climate as a complex system of many interacting parts: the atmosphere, the oceans, the cryosphere (sea-ice, land ice), the land surface, etc. "Component models" for each of these parts have been developed and are continually refined at more than a dozen scientific centers worldwide. Atmosphere models have been around the longest, having evolved during the 1960s from the first weather prediction computer models developed a decade earlier. Both weather models and the atmospheric component of climate models have at their cores the equations for fluid (air) motion and the first law of thermodynamics, and they represent similar processes; but the similarities end here. Relative to climate models, weather models cover a limited geographical area at greater spatial resolution for a shorter forecast period. Because climate is a global phenomenon, climate models cover the entire Earth, at a relatively lower spatial resolution, and simulate tens to hundreds of years of time.

The original climate models were referred to as General Circulation Models (GCMs) because of their ability to simulate the time evolution of the winds ("circulation"), temperatures, and atmospheric pressures simultaneously over the whole globe (GCM is also used as an abbreviation for Global Climate Model). Initially the models were crude representations of the Earth's climate with a very coarse model grid. As computer power and scientific understanding increased, the climate models became more refined in their ability to depict spatial detail and included more detailed process models. Oceanic "OGCMs" built to simulate ocean

FIGURE 3-1. Hydrologic Component of GCMs

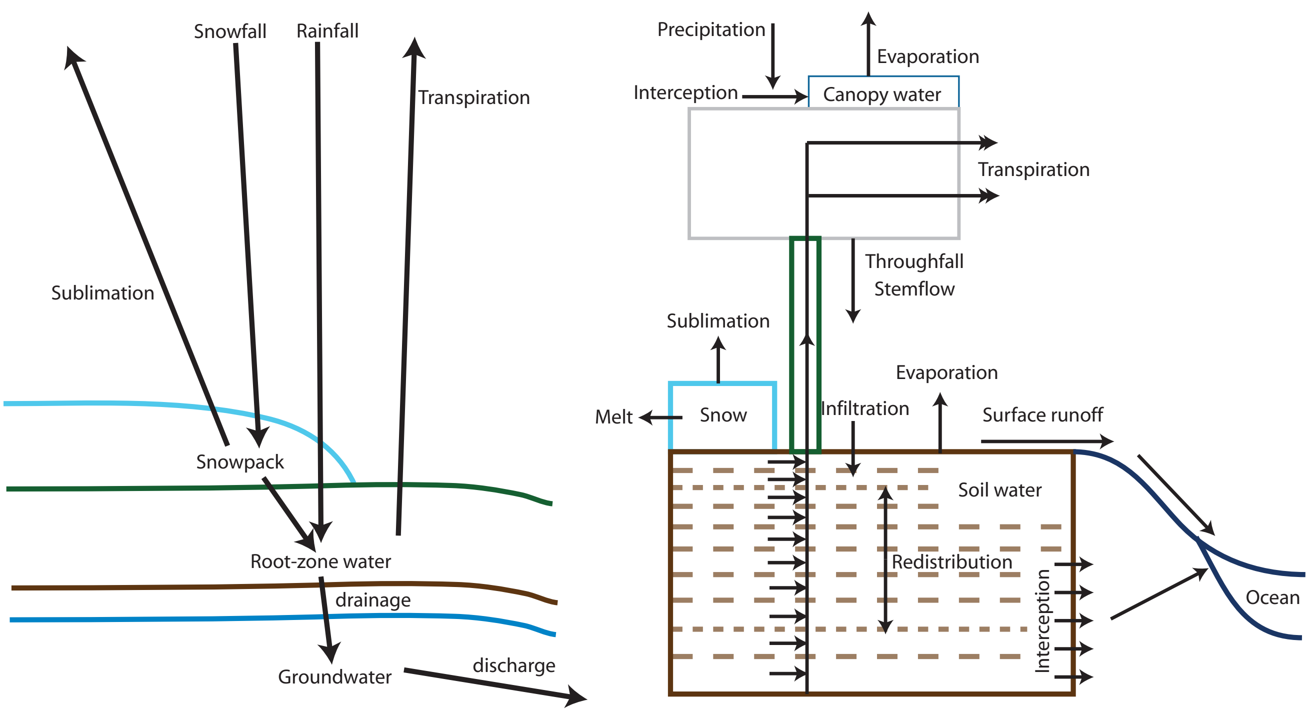


Fig. 3-1. The hydrologic component of GCMs differs in their formulation and detail. The National Center for Atmospheric Research (NCAR) Community Climate System Model (CCSM3, *right*) contains a surface hydrology model with 6 soil layers and a sophisticated biophysical model that tracks 11 categories of surface vegetation and soil type within each gridbox. The NOAA Geophysical Fluid Dynamics Laboratory (GFDL) model *(left)* represents a different philosophy, with three lumped reservoirs of water in each gridbox (snowpack, root zone, and groundwater). Only a handful of climate models still use a simple "bucket" model of hydrology; almost all models contain a river-routing model. See Chapter 8 in IPCC AR4 WGI (2007) and http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php for more information on hydrology components of GCMs. (Source: GFDL model adapted from Milly and Shmakin 2002, NCAR model adapted from Oleson et al. 2008)

currents, salinities, and temperatures soon followed. By 1970, the first coupled atmosphere–ocean GCM (AOGCM) was produced at NOAA Geophysical Fluid Dynamics Laboratory in Princeton, NJ. The terms "coupled model" and "Earth System Model" are sometimes used to describe the current generation of climate models. Other model development groups soon followed suit, and work using AOGCMs continues today. Simulations from 24 AOGCMs were included in the IPCC AR4 as part of the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset.

Surface hydrologic processes such as evapotranspiration, snowpack evolution, infiltration of water into the soil, and river routing are typically found in the "land surface" component of climate models. The hydrologic components in different climate models differ in their formulation and detail—just as do stand-alone hydrologic models. They can be quite sophisticated in the processes included, but operate on inputs from the coarse grid of the global model. Schematic illustrations of the surface hydrologic component from two GCMs are shown in FIGURE 3-1.

3-2. Emissions Scenarios—in the Driver's Seat

Emissions scenarios represent how greenhouse gas (carbon dioxide, methane, nitrous oxide) emissions, and thus the accumulation of greenhouse gases in the atmosphere, might unfold over the next century. The IPCC has developed a suite

FIGURE 3-3. Global Mean Surface Temperature and Model Projections

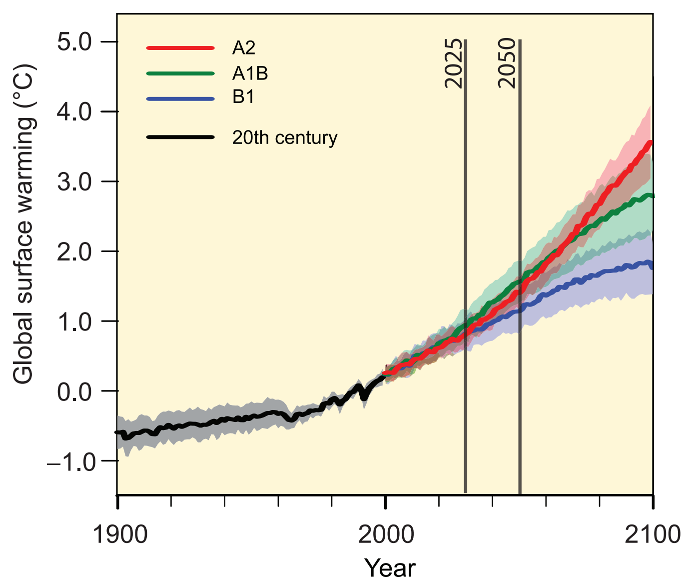


Fig. 3-3. Global mean surface temperature and model projections (relative to a baseline of 1980–99) for various emissions scenarios. Shaded regions depict the range of modeled historical simulations and projections. Temperatures for scenario B1 starts to diverge appreciably from A1B and A2 by the middle of the 21st century. A2 and A1B diverge in the latter quarter of the century. Continental and regional patterns of temperature and precipitation in these models also evolve in a similar manner. (IPCC AR4 WGI, 2007)

SIDEBAR 3-1: Time and Space in Models

Climate models are marched forward at discrete time intervals, called "timesteps." Timesteps can range from a few minutes to an hour, depending on the spatial resolution of the model. The models generate enormous amounts of data output that could easily amount to hundreds of terabytes for a single run. To put this in perspective, a single terabyte is equivalent to the storage capacity of about four typical desktop computers. Often, only a subset of the output, such as daily or monthly mean values, is archived. For the comprehensive archive of model simulations analyzed in the IPCC AR4, monthly averaged values for dozens of model variables are available from 22 climate models, while daily averaged values are available for certain time periods and for selected variables from a smaller subset of these models. (http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php)

Because of the complexity of the mathematical equations in climate models, these equations can only be solved approximately, even on the most powerful super computers. In order to determine the most precise result within this limitation, climate models typically divide the globe—the atmosphere and the oceans—into a grid in the horizontal and vertical, creating so-called "gridboxes" (FIGURE 3-2). The finer the grid, the higher the spatial resolution, and the more computer power required to run the simulations. Many climate processes take place at spatial scales much smaller than a model gridbox. The term-of-art for the expression of the "sub-grid" processes in terms of parameters that are resolved at the spatial scale of the gridbox is "parameterization." Choice of the methods used in parameterization can have a sizable impact on a model's climate simulations.

FIGURE 3-2. Model Grid for the Atmosphere Component

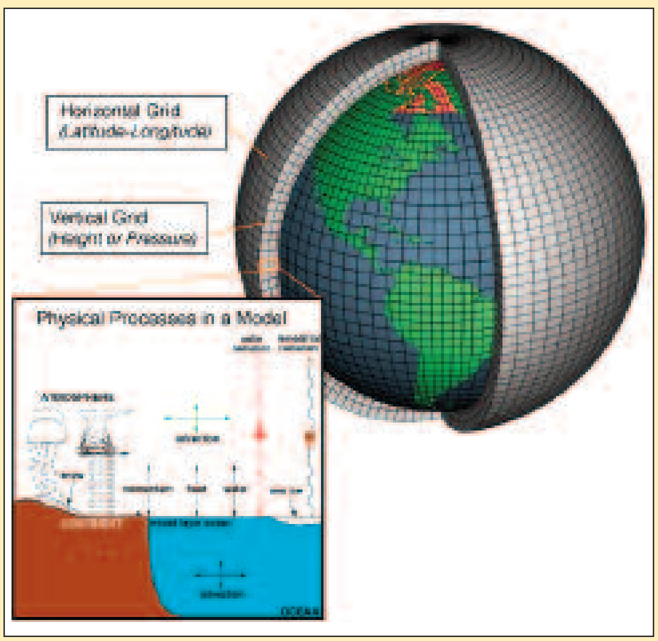


Fig. 3-2. Illustration of the model grid for the atmosphere component. Typical grid for global climate models analyzed in the IPCC AR4 WGI (2007) is about 180 mi (300 km) in the horizontal with ~25 layers of varying thickness in the vertical. The small-scale processes within a vertical column of gridboxes (shown in the inset) are represented through a process known as "parameterization." (Source: http://celebrating200years.noaa.gov/breakthroughs/climate_model/welcome.html)

of emissions scenarios that are widely used to generate climate projections from GCMs. These are reported in the IPCC Special Report on Emissions Scenarios (SRES). The SRES scenarios are based, in part, on assumptions about "demographic development, socio-economic development, and technological change." Probabilities are not assigned to the future occurrence of these scenarios; the scenarios "are alternative images of how the future might unfold" (IPCC SRES 2000, p. 3).

Of the many possible futures described in the IPCC SRES document, only three scenarios, labeled B1, A1B, and A2, were intensively studied by climate modeling centers (Figure 3-3). These three scenarios have become de facto *low*, *medium*, and *high* emissions scenarios based on the resulting greenhouse gas concentrations and global climate changes in year 2100. For planning horizons up to about mid-century, these three emissions scenarios result in very similar projections of global and regional climate change. Consequently, the implications of these three scenarios are similar to one another for 25- to 50-year planning and adaptation horizons. The scenarios diverge in the latter half of the century reflecting the climate response to different assumptions, including those about mitigation (greenhouse gas reduction) strategies.

A new set of emissions scenarios are being developed for use in the Fifth Assessment Report planned for 2013 (see **http://ipcc-wg1.ucar.edu/** for more information). These new scenarios will reflect the fact that greenhouse gas emissions over the past decade have been at or above the upper range of the SRES scenarios.

3-3. Climate Model Evaluation

The scenarios of future greenhouse gas emissions drive the current generation of climate model projections. These models are also used to simulate the climate of the 20th century. These historic simulations include known forcing factors such as variations in solar output, volcanic and industrial aerosols (fine particles suspended in the air), and historic greenhouse gas changes. The models also simulate

SIDEBAR 3-2. Boulder Study

A study of the impacts of climate change on Boulder, Colorado's water supply is the first in the United States to combine the potential impacts of climate change with long-term climate variability. Outputs from general circulation models (GCMs) for grid boxes, including Boulder, were examined and the wettest, driest, and a middle model were selected. Climate change was estimated for 20-year periods for 2030 and 2070, and a 437-year (1566–2002) reconstruction of streamflow in Boulder Creek, South Boulder Creek, and the Colorado River (conducted by Connie Woodhouse and Jeff Lukas) were used. A "nearest neighbor" approach was also used to select years in the observed climate record that resemble the paleoclimate reconstructions. Average monthly GCM changes in temperature and precipitation for 2030 and 2070 were combined with multiple recreations of the paleoclimate record to simulate the combined effects of changes in climate and paleoclimate variability.

An increase in temperature alone was estimated to have little effect on the total annual volume of runoff, but by 2070 the effect would shift peak runoff one month earlier, which results in increased late winter and spring runoff and decreased summer runoff levels. These seasonal changes in runoff levels were estimated even with increased or decreased precipitation. Total runoff is quite sensitive to changes in precipitation.

Using Boulder's management model, and accounting for population growth in Boulder and the changes in demand for crop irrigation, the study found that wet and "middle" scenarios had little effect on the reliability of Boulder's supply. But reduced precipitation scenarios resulted in violation of some of Boulder's water supply reliability criteria. By 2070, higher greenhouse gas emissions scenarios increase the risk of supply disruptions more than the lowest emissions scenario (see TABLE 3-1). While an earlier study found that Boulder's water supplies would be reliable with a repeat of climate conditions from hundreds of years ago, this study found that the *combination* of climate change imposed on a reconstruction of events from the 16th and 17th centuries would cause violations in the city's water supply criteria. Demand for irrigation was projected to increase substantially; and very little of this increased demand would be met under the middle or dry scenarios.

In general, Boulder is in a relatively good position to adapt to climate because it has relatively senior water rights and can draw water during later winter and spring months when runoff is projected to increase. Other municipalities and users with more junior rights or with rights to withdrawal only in the summer months would possibly be at greater risk to climate change. Nonetheless, Boulder will examine contingency plans for reducing the city's demands and enhancing supplies.

This study is a collaboration of Stratus Consulting, the City of Boulder, the University of Colorado, and AMEC Consulting (formerly Hydrosphere). This work was funded by a grant from the National Oceanographic and Atmospheric Administration to Stratus Consulting.

TABLE 3-1. Effect of Climate Change on Reliability of Boulder's Water Supply

Emission Scenario	*Model Type*	*Year*	*1-in-20 year criterion met?*	*1-in-100 year criterion met?*	*1-in-1000 year criterion met?*
Drought Plan (300 years)			Yes	Yes	Yes
BASE CASE			Yes	Yes	Yes
B1	Wet	2030	Yes	Yes	Yes
B1	Mid	2030	Yes	Yes	Yes
B1	Dry	2030	No	Yes	Yes
A1B	Wet	2030	Yes	Yes	Yes
A1B	Mid	2030	Yes	Yes	Yes
A1B	Dry	2030	No	Yes	Yes
A1B	Dry3	2030	No	No	No
A2	Mid	2030	Yes	Yes	Yes
A2	Dry	2030	No	Yes	Yes
B1	Wet	2070	Yes	Yes	Yes
B1	Mid	2070	Yes	Yes	Yes
B1	Dry	2070	Yes	Yes	Yes
A1B	Wet	2070	Yes	Yes	Yes
A1B	Mid	2070	Yes	Yes	Yes
A1B	Dry	2070	No	Yes	No
A1B	Dry3	2070	No	Yes	Yes
A2	Mid	2070	No	Yes	Yes
A2	Dry	2070	No	No	No

This table is representative of the typical output of a product that can be generated using climate models to aid decision-makers.

FIGURE 3-4. Elevation (feet above sea level) on Global and Regional Climate Model Grids

NCAR COMMUNITY CLIMATE SYSTEM MODEL

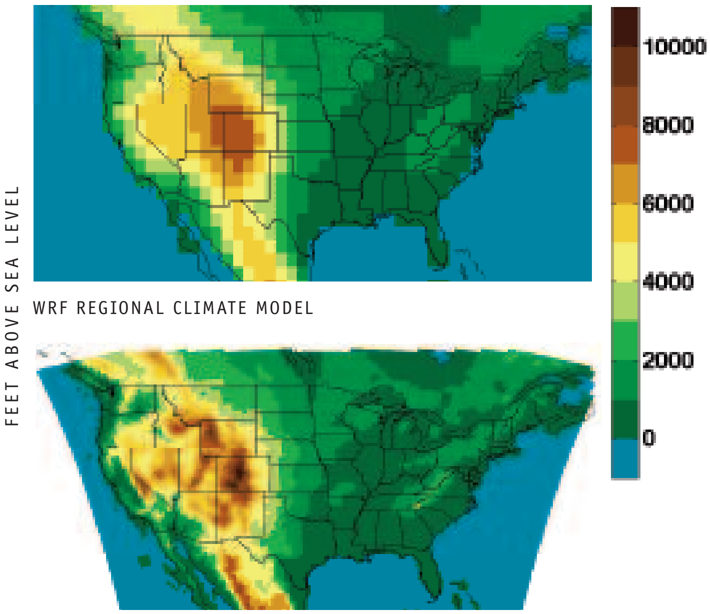


Fig. 3-4. The NCAR Community Climate System Model 3.0 (CCSM3.0)*(top panel)* has gridboxes that are about 100 miles on a side. The WRF regional climate model *(bottom panel)* has gridboxes that are about 30 miles on a side, typical of the RCMs used for dynamical downscaling in the North American Regional Climate Change Assessment Project (NARCCAP) project. The relatively smooth representation of the Colorado Rockies in global climate models reduces the elevations of the mountain peaks. Downscaling methods relate the large-scale climate features that are simulated by GCMs to the small-scale climatic and topographic features of Colorado.

natural "internal" variability of the climate from year to year and decade to decade.

Climate model simulations are evaluated by how well they reproduce climate statistics rather than individual events. This need arises because model projections are not periodically reset to observed conditions (as are weather forecasts), but rather run freely through time. Consequently, simulations cannot reproduce the weather on any specific day; but they should reproduce climatological averages and other statistics of the weather. Likewise, the projections cannot reproduce a specific event such as the 1997–98 El Niño event, but they should show El Niño and La Niña events that resemble those in nature in terms of magnitude, duration, and recurrence. These models do simulate a response to the known natural and anthropogenic forcing factors, resulting in periods of global warming in the early and late 20th century and slight cooling in the mid-20th century.

Spatial resolution poses another problem for model evaluation, particularly in mountainous regions like Colorado. Because the global models do not represent local and regional processes, they cannot exactly simulate the climate at a single observing station; but they should be able to simulate sub-continental climate averages—provided the region is relatively homogeneous. For example, in the central United States where the topography is relatively gentle, model temperature and precipitation data better represent the climate processes at individual stations.

In order to accommodate their coarse spatial grid, climate models use a smoothed representation of mountains, including the Rockies (see Figure 3-4). Individual stations in complex mountainous regions such as Colorado are influenced by topography and elevation that are not present in the climate models. Furthermore, snowpack is poorly represented in climate models due to the smoothed topography that reduces the elevation of mountain peaks. However, the climate models do simulate the large-scale climate trends affecting mountainous regions. Current climate models produce a winter storm track that impacts Colorado, and they broadly show the differences in annual precipitation as one traverses from the Great Plains across the Rockies to the Intermountain West. For this reason, it is possible that advanced techniques (e.g., downscaling, discussed later) can relate these large-scale phenomena in climate models to the detailed topography of the state, including an improved representation of snowpack.

The main reason for the differences among climate model results is an incomplete scientific understanding of many climate-related processes, particularly at smaller spatial scales. Even for processes that are comparatively well understood, there can be legitimate scientific differences about the best way to represent these processes in the models through parameterization. Developing a climate model means balancing the competing desires for higher resolution and for more complex and varied processes with the available computational resources. Different model development centers make different choices to achieve this balance. The result is that each model, while staying as close as possible to known scientific principles, has a "personality of its own" when it comes to future projections.

Each climate model has known systematic errors (model bias) in simulating climate. These biases can be assessed by comparing the temperature and precipitation (and other variables) at the model grid with a gridded observational dataset (PRISM monthly climatology, 1950–99). The Colorado temperature bias, averaged over the 22 CMIP3 models, varies throughout the year (Table 3-2). The models, on average, are too warm by about 2°F in winter, and too cold by about 3°F in summer, on par with the magnitude of the bias in neighboring regions. The models have too much precipitation in all seasons over Colorado, consistent with the biases for the western North America. Note that the model precipitation biases averaged over Central North America, a region of gentler topography, are considerably lower than for Colorado.

Year-to-year climate variability in Colorado arises from both climate oscillations and storm track dynamics. The simulation of the El Niño Southern Oscillation (ENSO),

TABLE 3-2. Seasonally Averaged Climate Biases of the IPCC AR4 WGI Climate Models in Temperature and Precipitation for Colorado

	TEMPERATURE BIAS (°F)			PRECIPITATION BIAS (%)		
	WNA	*Colorado*	*CNA*	*WNA*	*Colorado*	*CNA*
Winter	-1.62	1.94	-1.44	93	81	7
Spring	-3.60	-1.11	-1.98	71	65	8
Summer	-0.72	-3.32	-0.72	28	69	-12
Autumn	-2.16	-0.08	-1.08	61	63	-16
Annual	-2.34	-0.64	-0.90	65	65	2

Climate model biases are shown for Western North America (WNA), Colorado, and Central North America (CNA). Temperature biases are shown in °F, precipitation biases in percent above or below normal. The models are too warm over Colorado in winter, and too cold in summer, and the biases are on par with those in neighboring regions. The models produce too much precipitation over Colorado in all seasons, similar to the biases in Western North America. The values for the WNA and CNA regions are from IPCC AR4 WGI, Ch. 11 Supp. Material, Table S11.1. The area average for model gridboxes over Colorado was calculated from the same CMIP3 model output as used in the IPCC AR4.

and its effects on the atmospheric circulation patterns over North America, has improved from past generations of climate models (AchutaRao and Sperberg 2006). But while most models produce variability that resembles the observed ENSO in some respects, they still have problems accurately reproducing the amplitude, seasonal timing, and recurrence times seen in nature (see Capotondi et al. 2006). There has been comparatively little work in evaluating Pacific decadal variability that may have an influence on Colorado's climate (IPCC AR4 WGI 2007). Overall, climate models have too little Pacific Ocean variability on decadal time scales, particularly in the tropics (Newman 2007), though Barnett et al. (2008) claims that at least one model successfully simulates the Pacific Decadal Oscillation (PDO). However, climate models successfully simulate storm track dynamics in North America (CCSP SAP 3.1 2008), which are a major feature of climate in Colorado.

A combination of metrics should be used to judge the utility of a model's output. For example, a model that has a small temperature bias over Colorado may not have a good simulation of El Niño, or vice versa. A study of California precipitation projections showed that "while some models seem more capable at recreating limited aspects [of] twentieth century climate, the overall tendency is for comparable model performance when several credibility measures are combined" (Brekke et al. 2008, p. 371). It also found that culling models or applying weighting factors to models based on their overall credibility had little effect on the probabilistic distribution of outcomes in their study. Other studies may choose a smaller subset of models based on what the authors perceive as relevant selection criteria.

Climate models as a whole have improved in their ability to simulate the climate, even as the modeling community has set more demanding goals. Although they are imperfect descriptions of the Earth's climate, each generation of models has improved on the last, and the average of all the models is better than a single model (Reichler and Kim 2008). Many climate projections are available, reflecting the level of scientific understanding of the subject. Consequently, it is very important for planners to consider a range of model projections to assess the robustness of alternative planning scenarios.

3-4. Downscaling Methods

In order to use the coarse-grid global climate model output to study climate change impacts in Colorado, the model output has to be related to the detailed topography and climate of the state through a process called "downscaling." In addition a "bias correction" or "calibration" step is needed that removes known model biases in the average climate. Fowler et al. (2007) presents an overview of several downscaling methods.

TABLE 3-3. Strengths and Weaknesses of Statistical Versus Dynamical Downscaling (after Fowler et al. 2007)

	Statistical	*Dynamical*
Advantages	• Comparatively cheap and computationally efficient. • Can provide point-scale climatic variables from GCM-scale output. • Able to directly incorporate observations into method.	• Produces responses based on physically consistent processes. • Can resolve atmospheric processes on a smaller scale (e.g., orographic and rain-shadow effects in mountainous areas).
Disadvantages	• Dependent upon choice of predictors. • Does not account for non-stationarity in the predictor-predict and relationship. • Regional climate system feedbacks not included. • Affected by biases in underlying GCM.	• Computationally intensive. • Limited number of scenario ensembles available. • Dependent on GCM boundary forcing; affected by biases in underlying GCM. • Dependent on RCM parameterizations. • Different RCMs will give different results.

FIGURE 3-5. The Progression of Data and Models from Climate Models to Streamflow

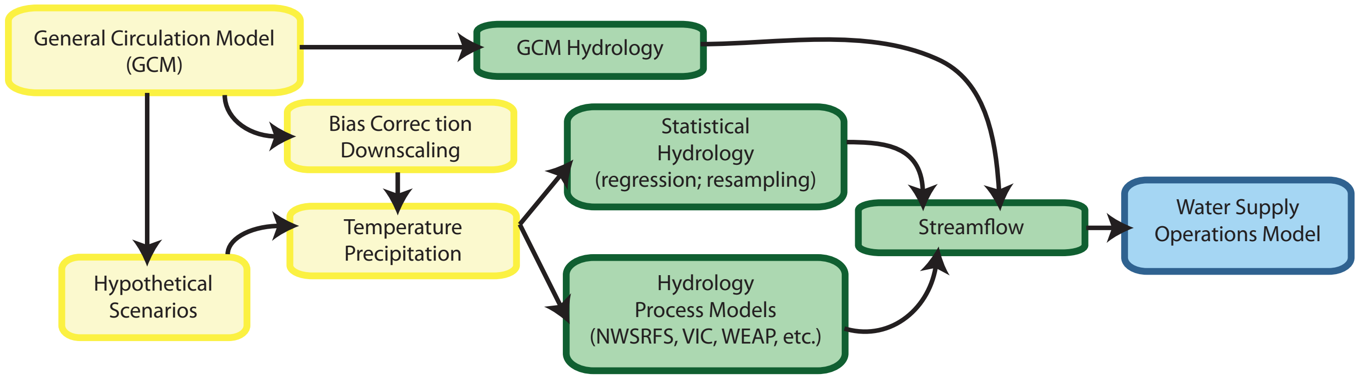


Fig. 3-5. Illustration of the progression of data and models from climate models to streamflow, which can be used in water supply operations models. While the output from the GCM hydrology component has been used in some studies (Milly et al. 2005), water supply studies typically use bias-corrected and downscaled projections. Hypothetical scenarios of climate change, such as adding or subtracting a fixed increment in temperature or precipitation to or from the historical sequences, may be used to investigate the sensitivity of water supply. The choice of these increments may be informed by climate model projections.

Simply, statistical downscaling methods use the temperature and precipitation at a model grid and relate each parameter to the smaller-scale variations within that grid. This spatial process is sometimes called disaggregation—the opposite of the spatial aggregation process that creates a gridbox (see Sidebar 3-1). The statistical downscaling procedure may be as simple as adding a model's projected changes in a gridbox to the high-resolution temperature climatology for the area within that gridbox. For precipitation, the percent change is typically applied to the high-resolution climatology (Salathe 2004; Smith et al. 2007). More sophisticated statistical methods can be used but at this time, these have found less application in Colorado.

Dynamical downscaling uses high-resolution regional climate models (RCMs)—many of which are derived from numerical weather prediction models—to simulate small-scale processes. These RCMs typically input the global model grids surrounding their geographical domain and then simulate wind, temperature, clouds, evapotranspiration, and variables on a much finer grid (see Wigley 2004; Wilby and Wigley 1997). RCM downscaling is computationally intensive.

The salient strengths and weaknesses of statistical versus dynamical downscaling are summarized in Table 3-3. In practice, the simpler statistical methods are primarily used to generate downscaled datasets on many of the global model simulations used in the AR4 report. RCM downscaling has typically involved using one or two global models downscaled with a single RCM. While this is very useful in studying how climate processes might change, it gives a very limited picture of the range and distribution of possibilities. It is worth noting that the ongoing North American Regional Climate Change Assessment Project (NARCCAP) will soon release a large dynamically downscaled dataset that uses six RCMs to downscale the projections from four of the IPCC AR4 models. This will enable a more comprehensive analysis of the full range of projections (See Resources). Even at the 30-mile (50-km) resolution of these RCMs, further downscaling may be needed depending on the application. On a finer spatial scale, the Colorado Headwaters Project plans a smaller set of model simulations using a 1.2 mile (2 km) grid (**http://www.times.ucar/ws**).

In many cases, only monthly-averaged model output is available. Since many hydrological and operational models require daily or even sub-daily inputs, the need for downscaling in time arises. So-called "weather generators" (see Gangopadhyay et al. 2005) use historical weather data that are re-sampled according to the conditions projected by the climate model. The same resampling technique can be applied to historical streamflow data to provide future hydrologic sequences that are consistent with both the historical variability (Prairie et al. 2006) and the climate model average projections.

For water resources planning, statistically downscaled climate model projections have been used as input to hydrology models (Maurer 2007; Reclamation 2008; Christensen et al. 2004; Christensen and Lettenmaier 2006). By using a single hydrology model that has been tuned to a specific river basin, a hydrologically consistent set of projections can be created based on a range of climate drivers (see the Joint Front Range Climate Change Vulnerability Study, Sidebar 3-3, Figure 3-5).

3-5. The Future of Global Models

The need for more advanced climate model projections for the anticipated IPCC Fifth Assessment Report is providing the impetus for the next stage of development in global climate models. These models will include more detailed process models—particularly those involved in the models of how sources and sinks of greenhouse gases will respond to climate change. The native resolution of these models, though increased, will still not be adequate for regional climate studies; downscaled output will be required.

Some climate modeling centers are now incorporating the observed ocean conditions into their simulations in order to make actual predictions of the climate a few decades into the future. Using this framework, Keenlyside et al. (2008) and Smith et al. (2007) predict a period of relatively unchanged global temperatures due to a natural cooling trend that is superposed on the GHG-forced warming trend. They both project this hiatus to end in the next several years and the warming to continue. These climate predictions, however, are in the early stages of development and evaluation.

SIDEBAR 3-3. Joint Front Range Climate Change Vulnerability Study (JFRCCVS)

With the increasing recognition of global and regional climate changes, metropolitan water providers along Colorado's Front Range are concerned about the possible impacts these changes may have on their future available water supply. This is of particular concern given that recent studies indicate global warming may lead to unprecedented drought conditions in the southwest United States (IPCC AR4 WGI 2007). Several Front Range providers including the City of Aurora, City of Boulder, Colorado Springs Utilities, Denver Water, City of Fort Collins, and Northern Colorado Water Conservancy District have come together to participate in a study intended to provide the education, tools, and methodology necessary to examine the possible effects of climate change on several common watersheds.

Through a collaboration with the Water Research Foundation, this JFRCCVS project will enable group members, which obtain their water supplies from the upper Colorado, South Platte, Arkansas, Cache la Poudre, St. Vrain, Boulder Creek, Big Thompson, and other similar river basins, to examine potential effects climate change may have on those supplies. This regional unified approach is intended to help Colorado water providers communicate with their customers and the media cohesively by working with the same historic and projected hydrometeorological data, historic natural streamflow, and methodology. Lessons learned from this collaborative approach can be used to encourage and establish other regional efforts in Colorado and throughout the country.

The project will assess changes in the timing and volume of hydrologic runoff that might be expected from selected climate change scenarios for the years 2040 and 2070. Since many water providers evaluate vulnerability using water allocation models that simulate system operations based on historic sequences of natural streamflow, the project will focus on investigations at these locations:

Basin	*Station*
Upper Colorado	Fraser River at Granby
	Williams Fork near Leal
	Blue River below Green Mountain Res
	Blue River below Dillon
	Colorado River near Granby
	Colorado River near Dotsero
	Colorado River near Cameo
	Homestake Creek at Gold Park
	Roaring Fork River near Aspen
Upper Arkansas	Arkansas River at Salida
Upper South Platte	South Platte River above Spinney Mountain Res
	South Platte River below Cheesman Res
	South Platte River at South Platte
	South Platte River at Henderson
Cache la Poudre	Cache la Poudre River at Mouth of Canyon
St. Vrain	St. Vrain Creek at Canyon Mouth near Lyons
Big Thompson	Big Thompson River near Drake
Boulder Creek	Boulder Creek at Orodell

4
Climate Attribution

KEY POINTS

- In North America, temperatures have increased by ~2°F in the last 30 years, "human-induced warming has likely caused much of the average temperature increase in North America over the past fifty years" (CCSP SAP 3.3, p. 3).
- In Colorado, temperatures have warmed by ~2°F in the past 30 years (Section 2). Climate models estimate that anthropogenic greenhouse gas emissions have contributed 1°F of warming over the same period. However no studies have specifically investigated whether the detected trends in Colorado can be attributed to anthropogenic greenhouse gases.
- The precipitation variations that are the main driver of drought in Colorado and low Lake Powell inflows, including the recent drought of 2000–07, are consistent with the natural variability observed in long-term and paleoclimate records (Barnett et al. 2008).
- Observed warming may have increased the severity of droughts (Andreadis and Lettenmeier 2006) and exacerbated drought impacts (Breshears et al. 2005).

PROACTIVE PLANNING AND DECISIONS to manage risks can benefit from an understanding of the full range of natural climate variability and the magnitude of climate trends that have happened, why they happened, and the likelihood of these trends continuing into the future. The process of establishing the principal causes for observed climate phenomena is known as climate attribution. Attribution of anthropogenic climate change, part of the focus of the Intergovernmental Panel on Climate Change (IPCC) assessment reports, has the specific objective of explaining a detected climate change that is significantly different from that which could be expected from natural variations of the climate system. According to the IPCC Third Assessment Report (IPCC TAR WGI 2001), the requirements for determining an attribution for detected change are that first, scientists can demonstrate that the change is consistent with a combination of anthropogenic and natural causes, and second, that these changes are inconsistent with alternative, physically plausible explanations of recent climate change that exclude anthropogenic causes. When attribution is established, the IPCC may assign a likelihood statement (see SIDEBAR ES-1) for the probability that that cause resulted in the observed conditions or trends.

Attribution studies use both empirical analyses of past climate relationships and simulations with climate models in which cause-and-effect relations are evaluated. Statistical analysis is used to analyze and compare the model simulations with the observed record, including estimates of natural variability and trends from climate models, historical observations, and paleoclimate reconstructions of past temperatures. "Fingerprint" methods seek the unique signature of climate change by simultaneously looking at changes in many variables. Attribution studies are also used to assess the natural and anthropogenic causes of drought and other extreme climate events.

4-1. The Global Consensus

Evidence that Earth's climate has changed during the last century is clear. According to the IPCC Fourth Assessment Report (IPCC AR4 WGI 2007, p. 5) "warming of the climate system is unequivocal." This statement is based on observed trends of melting snow and ice; rising sea level; and increasing surface, ocean, and atmospheric temperatures. The dominant forcing mechanisms to which recent climate change has been attributed all result from human activity. They are: increasing atmospheric concentrations of greenhouse gases; global changes to land surface, such as deforestation; and increasing atmospheric concentrations of aerosols.

The consensus attribution statements of the IPCC AR4 WGI (2007) link these observed trends, as well as changes in global wind patterns, to greenhouse gas emissions introduced to the atmosphere by human activities. For example, the IPCC reports that most of the observed increase in global average temperatures since the mid-20th century is ***very likely*** due to increased concentrations of anthropogenic greenhouse gases. Other important attribution statements made by the IPCC in 2007 include:

- It is ***very likely*** the observed warming of land and oceans, together with the loss in ice mass, is not due to natural causes alone.
- It is ***likely*** that there has been significant anthropogenic warming over the past 50 years averaged over each continent except Antarctica.
- It is ***likely*** that the increases in greenhouse gas concentrations alone would have produced even greater warming than what has actually been observed because volcanic and human-induced aerosols have offset some warming that would otherwise have occurred.

However, these statements are based on global attribution studies, and are not necessarily applicable to the trends observed in Colorado. Attribution studies are difficult on regional scales for several reasons. Natural variability grows larger as the observational scale decreases, making it more difficult to detect trends (as discussed in Section 2). Even if a signal is detected, uncertainties in regional and local processes (for example, the influence of the Rocky Mountains on precipitation patterns) complicate estimations of the contribution of anthropogenic greenhouse gases on discernable trends. Consequently, there is less confidence in the causes of observed trends as scale decreases. Thus, it is not surprising that there are no formal climate change attribution studies that focus on the spatial scale of Colorado. However, the CCSP is undertaking studies on the scale of North America, and studies are underway to understand the causes of the 2000s western U.S. drought and low Colorado River flows, and whether these are the result of natural variability or if they are related to climate change.

4-2. A Telescoping View

North America has warmed by almost 2°F in the past 30 years and it is ***likely*** that greenhouse gases produced from human activities alone caused much of this increase (CCSP SAP 3.3). Further analysis of these data will be presented in the CCSP SAP 1.3 (planned release, fall 2008). In North America, the largest annual mean temperature increases since the middle of the 20th century have occurred over the

FIGURE 4-1. Observed Annual Average North American Surface Temperature (1950–2007)

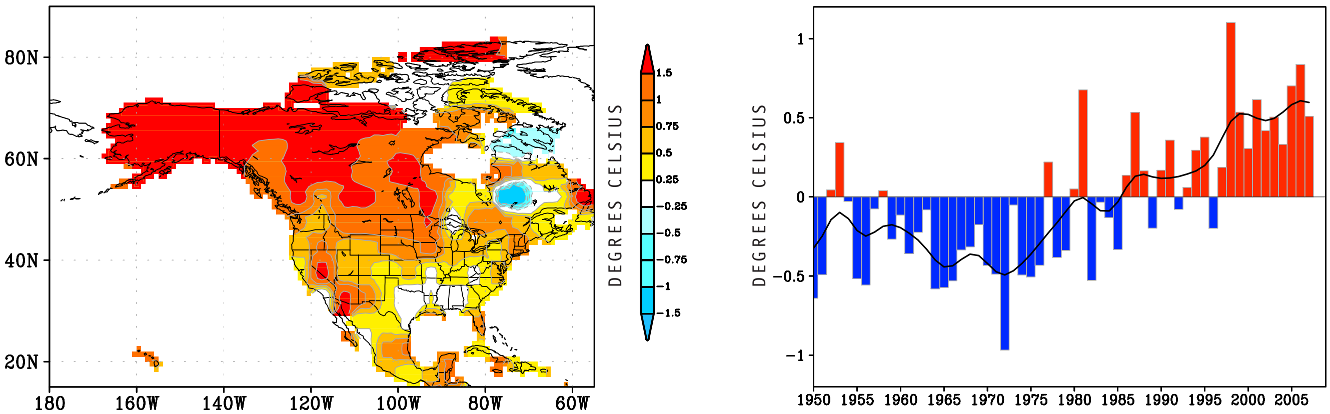


Fig. 4-1. The 1950–2007 trend in observed annual average North American surface temperature (°C, *left*) and the time series of the annual values of surface temperature averaged over the whole of North America *(right)*. Annual anomalies are with respect to a 1971–2000 reference. The smoothed curve *(black line)* highlights low frequency variations. A change of 1°C equals 1.8°F. (Data source: UK Hadley Center's CRUv3 global monthly gridded temperatures)

FIGURE 4-2. Modeled Annual Averaged North American Surface Temperature (1950–2007)

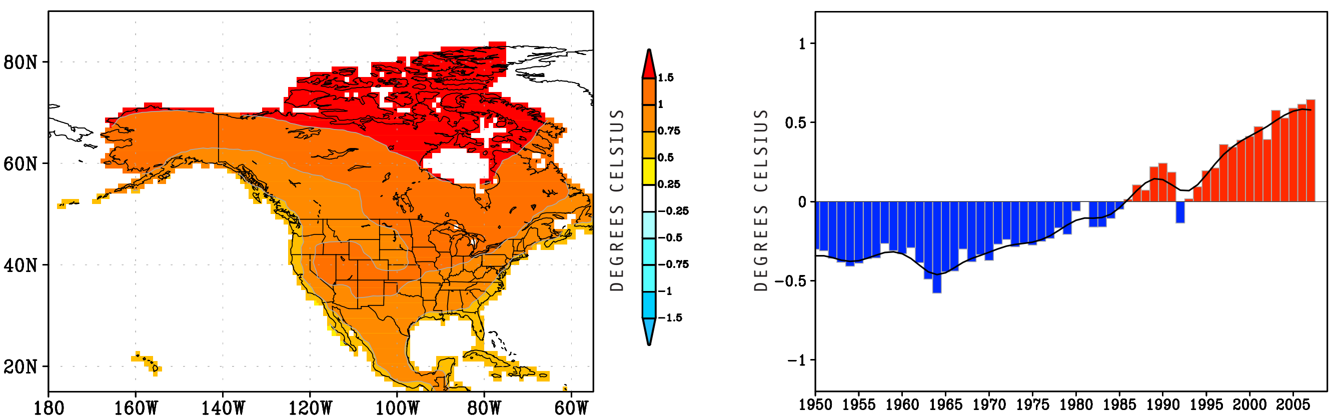


Fig. 4-2. The 1950–2007 trend in annual average North American surface temperature (°C) from 22 IPCC (CMIP3) model simulations forced with the greenhouse gas, aerosol, solar, and volcanic forcing from 1950 to 1999, and the A1B emissions scenario from 2000 to 2007 *(left)*. Annual values of surface temperature averaged over the whole of North America (anomalies compared to 1971–2000 average) *(right)*. The smoothed curve highlights low frequency variations. Comparison of these climate models with the data in FIGURE 4-1 suggests that anthropogenic greenhouse gas emissions have contributed about 1°F of the observed warming in the last 30 years.

northern and western portions of the continent. The warming trend between 1950 and 2007 in the Western United States is clear (Figure 4-1). The time series of annual North American-averaged temperatures (Figure 4-1, *right panel*) shows that every year since 1997 has been warmer than the 30-year climatological reference of 1971–2000. However, the rise in temperature has not been constant, as large year-to-year fluctuations are superimposed on an increasing trend.

To determine a cause, or attribution, of this signal, annually averaged North American surface temperatures from 1950–2007 were computed from the IPCC (CMIP3) model simulations. The models were forced with the observed record of greenhouse gases, volcanic aerosols, and solar forcing during 1950–99, and subsequently with the A1B scenario (see Section 3) of greenhouse gas emissions (Figure 4-2). Similarities between these results and the observed trends provide the best available evidence for external climate forcing of surface temperature change by anthropogenic greenhouse gases. First, the bulk of the warming occurs after about 1970 in both time series. Second, the externally forced warming of about 1.8°F (1°C) since 1950 is close to the observed warming rate.

Some inconsistencies between the two datasets (Figures 4-1 and 4-2) are also apparent. For instance, there is greater year-to-year variability in observed North American averaged temperatures, which cannot be explained by fluctuations in external forcing. Also, the IPCC simulated pattern of warming is more spatially uniform across the continent compared with spatial observations.

A simple comparison of the observed surface temperature trends across the continent and simulated changes suggests that half of the warming is attributable to greenhouse gas emissions related to human activities. This is consistent with CCSP SAP 3.3 (p. 3), which states "human-induced warming has ***likely*** caused much of the average temperature increase in North America over the past fifty years." A further analysis of these data will be presented in CCSP SAP 1.3 when it is released in late 2008.

4-3. Drought in Colorado and the West

Drought has many definitions. Meteorological drought is a deficit in precipitation, typically over an extended period of time. Hydrologic drought may be defined in terms of reduced runoff over a period of time, and agricultural drought may be defined in terms of soil moisture deficit. Both hydrologic and agricultural droughts can be related to a precipitation deficit or to increased evapotranspiration over the watershed associated with elevated temperatures. The assessment of drought severity may take into account water storage in the basin, including natural "reservoirs" such as snowpack and groundwater, as well as engineered water storage systems. (For further definitions see **www.drought.unl.edu**.)

Multiple indicators may be used to describe drought in Colorado. The Palmer Drought Severity Index (PDSI; Palmer 1965) is derived from the monthly records of precipitation and temperature and estimates the state of surface water balance (excluding reservoir storage). The percent area coverage where the PDSI is less than -3.0 is an indicator of the spatial extent of the drought. Another indicator is the annual Colorado River natural flow at Lees Ferry below Lake Powell. The flow is an indicator of annual water supply stored in the Upper Colorado River basin snowpack as it replenishes downstream storage in Lake Powell and Lake Mead.

Interpreting trends in these drought indicators is complicated by the many dimensions of drought—duration, extent, severity, impacts—and by the diversity of area averages and of periods of analysis used in studies published in the scientific literature. Consequently, each study must be considered in the context of recent events (e.g., the 2000s drought) and whether or not these events were in the period of record that was analyzed.

The history of Colorado droughts from 1895 to 2007 (Figure 4-3) is part of a bigger picture of droughts that occurred throughout the West. In Colorado, wet conditions prevailed at the turn of the 20th century, with the entire western United States virtually devoid of severe drought from 1905 to 1920. Dry periods emerged in Colorado during the 1930s and 1950s with severe social and economic consequences, but these conditions were eventually replaced by another wet epoch lasting from the 1960s to the end of the 20th century. The current dry period began in late 1998. One the most severe drought years of the 113-year instrumental record occurred in 2002, when severe drought occurred in all five traditional climate divisions in Colorado, an event that had not occurred since 1934.

FIGURE 4-3. Intensity and Extent of Drought in Colorado (1895–2007)

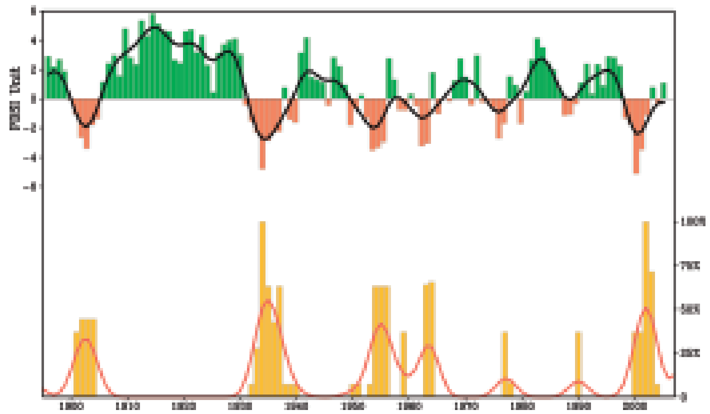


Fig. 4-3. Drought conditions in Colorado from 1895 to 2007. Top curve *(black)* is the area-averaged Palmer Drought Severity Index (PDSI), with negative anomalies *(orange bars)* indicating dry conditions compared to the region's normal moisture balance. Green bars represent wetter conditions. Yellow bars represent the % area of Colorado in severe drought (PDSI < -3). Black and red curves are smoothed similar to a 5-year moving average. (Data source: Climate division data from the National Climatic Data Center)

In the western United States from 1895 to 2007, no statistically significant trend in the PDSI drought record has been detected (M. Hoerling, pers. comm.) This finding is consistent with the paleo-hydroclimate evidence of droughts associated with natural variability that are more severe and longer in duration than those of recent history (Section 2, Figure 2-8). According to another study, however, there has been an increase in the severity of droughts over the period 1925 to 2003 in the southwestern United States, including the Western Slope of Colorado (Andreadis and Lettenmaier 2006). They qualitatively attribute the increased drought severity in the southwestern states (including Colorado) to the increase in observed temperatures and the resulting increase in evapotranspiration. Andreadis and Lettenmaier (2006) also show a decrease in drought severity over the eastern plains and south central Colorado (1925–2003). A different study compared the recent 2000s drought (defined in terms of vegetation impacts) to the 1950s drought and found that greater warmth has been a material factor in the recent drought's greater impacts (Breshears et al. 2005).

The Colorado River system storage is another indicator of drought. Lake Powell-Lake Mead storage was near full capacity in 1998. Storage levels have declined since; Lake Powell is 61% of capacity, and storage in Lake Mead is 46% of capacity as of August 2008. The principal reason for this rapid decline has been a reduction in Colorado River inflow (Figure 4-4, *bottom panel*). The 2000–04 period had

FIGURE 4-4. Precipitation and River Flow in the Upper Colorado Basin

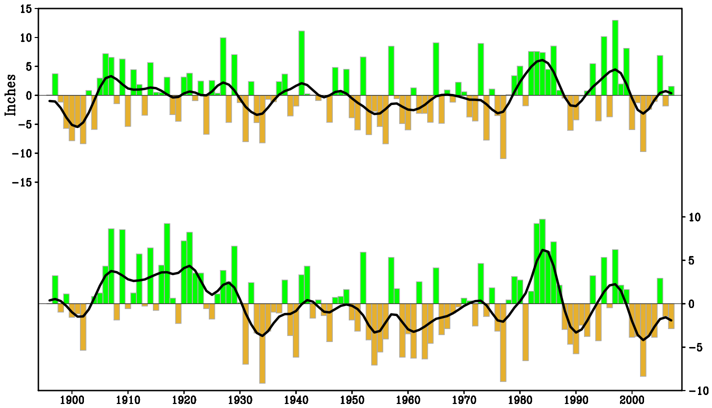


Fig. 4-4. Observed time series (1895–2007) of annually averaged precipitation departures area-averaged over the Upper Colorado drainage basin *(top panel)* and annual Colorado River natural flow departures at Lees Ferry in million acre-feet *(bottom panel)*. The precipitation data are based on 4km-gridded PRISM data. Colorado River natural flow data from the Bureau of Reclamation.

an average natural flow of 9.9 million acre feet (maf) per year, which was lower than the driest period during the Dust Bowl years of 1931–35 (11.4 maf), and the 1950s drought (1953–56; 10.2 maf) (Pulwarty et al. 2005).

Historically, reduction in Colorado River natural flow at Lees Ferry can be linked to the reduction in precipitation over the Upper Colorado River basin (Figure 4-4, top panel). Droughts in this area have been attributed in part to natural fluctuations of the El Niño and La Niña cycle of ocean surface temperature variations in the tropical Pacific (CCSP SAP 3.3 2008; Schubert et al. 2004; Seager et al. 2005). The El Niño cycle affects the movement of moisture-bearing storms in winter and spring that supply water for the region's mountain snowpack and provide the eastern plains with soil moisture. Note that IPCC model simulations indicate that it is ***very unlikely*** that the increase in greenhouse gases played a role in the recent period of low precipitation (IPCC AR4 WGI 2007).

The observed temperature trends may be exacerbating low flows. For example during the winter of 2004–05, precipitation in the Basin was average, but flow was 75% of normal. The combination of "low antecedent low soil moisture (absorption into soil), depleted high mountain aquifers, and the warmest January–July period on record (driving evaporation)" has been suggested as the cause for this discrepancy (CCSP SAP 3.3 2008).

One formal attribution study deserves special focus because of its implications for the entire hydrologic cycle in the West. Barnett et al (2008) used a "fingerprint" that combined several hydroclimatic indicators including the ratio of snow water equivalent to precipitation (SWE/P), January–March minimum temperatures, and streamflow runoff timing throughout the West, including the Colorado Rockies, to detect and attribute trends over the period 1950 to 1999. They concluded that 60% of the observed trends in the hydrologic cycle in the West are due to anthropogenic causes. These trends included earlier runoff, warming temperatures, and a smaller fraction of precipitation that is present as snow. They were unable to show any anthropogenic cause for precipitation trends in the West. Interestingly, the model fingerprint of anthropogenic warming shows very small changes in runoff timing and in SWE/P over Colorado and over the southern Sierra Nevada Mountains—the two highest elevation regions in the study area. Relevant to the recent drought they note "[t]his period excludes the large-scale changes in runoff, precipitation, and water storage that have occurred in the southwest, especially the Colorado River drainage, since 2000. We do not claim that the large changes since 2000 are necessarily the result of human-induced warming."

In summary, the research suggests that precipitation—the main historic driver of drought in Colorado—has not exhibited trends that can be attributed to anthropogenic climate change, and that the observed record of drought is consistent with natural variability. The research also indicates that observed temperature trends may have created conditions more favorable to droughts, or have exacerbated the impacts of droughts, and that, at least at the scale of the western United States, may be attributed in part to anthropogenic climate change. The CCSP SAP 1.3 and 3.4, when they are issued later this year, are planning to have specific statements on the attribution of the recent drought in the West.

5
Climate Projections

KEY POINTS

- Climate models project Colorado will warm by 2.5°F [+1.5 to +3.5°F] by 2025, relative to the 1950–99 baseline, and 4°F [+2.5 to +5.5°F] by 2050. This baseline likely includes some anthropogenic warming for North America (Section 4). The projections show summers warming more (+5°F [+3 to +7°F]) than winters (+3°F [+2 to +5°F]), and suggest that typical summer temperatures in 2050 will be as warm as or warmer than the hottest 10% of summers that occurred between 1950 and 1999. By 2050, temperatures on the Eastern Plains of Colorado will shift westward and upslope, bringing into the Front Range temperature regimes that today occur near the Kansas border. Note that the range of climate model projections does not capture the entire range of uncertainty.
- Winter projections show fewer extreme cold months, more extreme warm months, and more strings of consecutive warm winters. By contrast with summer, typical projected winter temperatures do not lie within the top 10% warmest months in the historical record. Between today and 2050, the January climate of the Eastern Plains of Colorado is expected to shift northward by ~150 miles. In all seasons, the climate of the mountains migrates upward in elevation, and the climate of the Desert Southwest progresses up into the valleys of the Western Slope.
- Individual models projections do not agree whether annual mean precipitation will increase or decrease in Colorado by 2050. The multi-model average shows little change in annual mean precipitation by 2050, although a seasonal shift in precipitation does emerge. Combined effects of a northward shifting storm track, potentially wetter storms and a global drying of the sub-tropical regions may result in more mid-winter precipitation throughout the state, and in some areas, a decrease in late spring and summer precipitation.
- Projections show a precipitous decline in lower-elevation (below 8200 ft) snowpack across the West. Modest declines (10–20%) are projected for Colorado's high-elevation snowpack (above 8200 ft) within the same timeframe (Christensen and Lettenmaier 2006). The timing of runoff is projected to shift earlier in the spring, and late-summer flows may be reduced. These changes are probably going to occur regardless of changes in precipitation.
- Recent hydrologic studies on climate change in the Upper Colorado River Basin point to an expected decline in runoff by the mid-to-late 21st century (Table 5-1). Those studies that explicitly calculate runoff report multi-model average decreases ranging from 6% to 20% by 2050 compared to 20th century conditions; the one recent study that bases streamflow on a large-scale statistical relationship (Hoerling and Eischeid 2006) projects a 45% decrease by 2050.
- The range of individual model projections within a single study can include both increasing and decreasing runoff due to the range of climate model output used to drive the hydrology models, reflecting both model-simulated climate variability and differences in model formulation.
- Ongoing studies are attempting to resolve methodological differences in order to reduce the range of uncertainty in Upper Colorado River Basin runoff projections.
- The impact of climate change on runoff in the Rio Grande, Platte, and Arkansas Basins has not been studied as extensively as the Colorado River Basin.

This section provides temperature and precipitation projections for North America, then telescopes into Colorado. To illustrate how broad scale model projections may play out at a local scale, projections from a downscaled dataset for three areas in Colorado are highlighted. It then synthesizes projected changes in hydroclimatic variables in the state and its river basins. The focus here is on mid-21st century projections, although projections for other timeframes may be of use depending on the type of decision or planning horizon (Sidebar 1-1). Most temperature projections show continued warming beyond 2050.

5-1. Temperature and Precipitation Projections

Projected changes in North American temperature and precipitation from a recent baseline (1950–99 average) through mid-century (2040–60 average) are shown in Figure 5-1. Focusing on Colorado, the multi-model average projects an annual mean warming of about 4°F [+2.5 to +5.5°F] by 2050 in Colorado as part of a continent-wide pattern of warming. The projections show summers warming more (+5°F [+3 to +7°F]) than winters (+3°F [+2 to +5°F]) (Figure 5-1, *top row*). For total yearly precipitation, the dominant pattern in North America projects a wetter climate in regions north of Colorado and a drier climate southwest of the state (Figure 5-1, *middle row*). However, for Colorado, projections diverge and the models do not show substantial agreement (Figure 5-1, *bottom row*). While the multi-model average shows little change in annual mean precipitation in Colorado, a seasonal shift in precipitation emerges with a decrease in late spring and summer, and an increase in winter precipitation.

The range of climate model projections (shown in square brackets above) was estimated from the 10th and 90th percentiles of 112 model projections for the 20-year period centered on 2050, averaged over Colorado, rounded to the nearest half-degree Fahrenheit. These 112 CMIP3 model runs of 16 climate models include projections from the B1, A2B, and A2 emissions scenarios. The range of projections results from different model formulations, model-simulated natural variability, and differences in emissions scenarios used to drive the climate models.

Several processes triggered by greenhouse gas increases contribute to the warming over the Western United States, including increased water vapor in the atmosphere (Compo and Sardeshmukh 2008), changes in atmospheric circulation patterns (Tebaldi et al. 2006—particularly for increased heat waves), and drying of the soils in summer. Precipitation changes in the Colorado Mountains, which receive the bulk of their precipitation from winter and spring storms— are dominated by changes in the climatological storm track. The storm track is projected to move slightly to the north as the climate warms (Yin 2005), but with somewhat wetter storms. The net effect over Colorado is a seasonal shift towards more mid-winter precipitation, and in some areas a decrease in late spring precipitation. Summertime precipitation is projected to decrease over much of the conterminous United States, but there is more disagreement among the models than for winter. The thunderstorms that dominate Colorado's summer precipitation are difficult to simulate and must be parameterized in the climate models. Larger scale systems such as the North American Monsoon that influence Colorado's summertime precipitation are not well simulated by climate models (Lin et al. 2008). Despite these shortfalls, the magnitude of potential changes in the timing of precipitation is small compared to year-to-year or even decade-to-decade variations in precipitation. Consequently, interpretation of these projections suggests that the future out to 2050 will be dominated by natural variations in precipitation.

5-2. A Closer Look

Average daily temperature in Colorado for 1950–99 and projections for 2025 and 2050 are shown in Figures 5-2 (January) and 5-3 (July). It is clear that by 2050 the January climate of the Eastern plains has moved northward by a distance greater than half the state. The climate zones of the mountains have migrated upward in elevation, and the climate of the Desert Southwest has progressed into the valleys of the Western Slope. For July, the temperatures on the Eastern Plains have moved westward and upslope, such that the temperature regime near the western Kansas border has reached the Front Range by 2050.

FIGURE 5-1. Temperature and Precipitation Changes over North America Projected for 2050

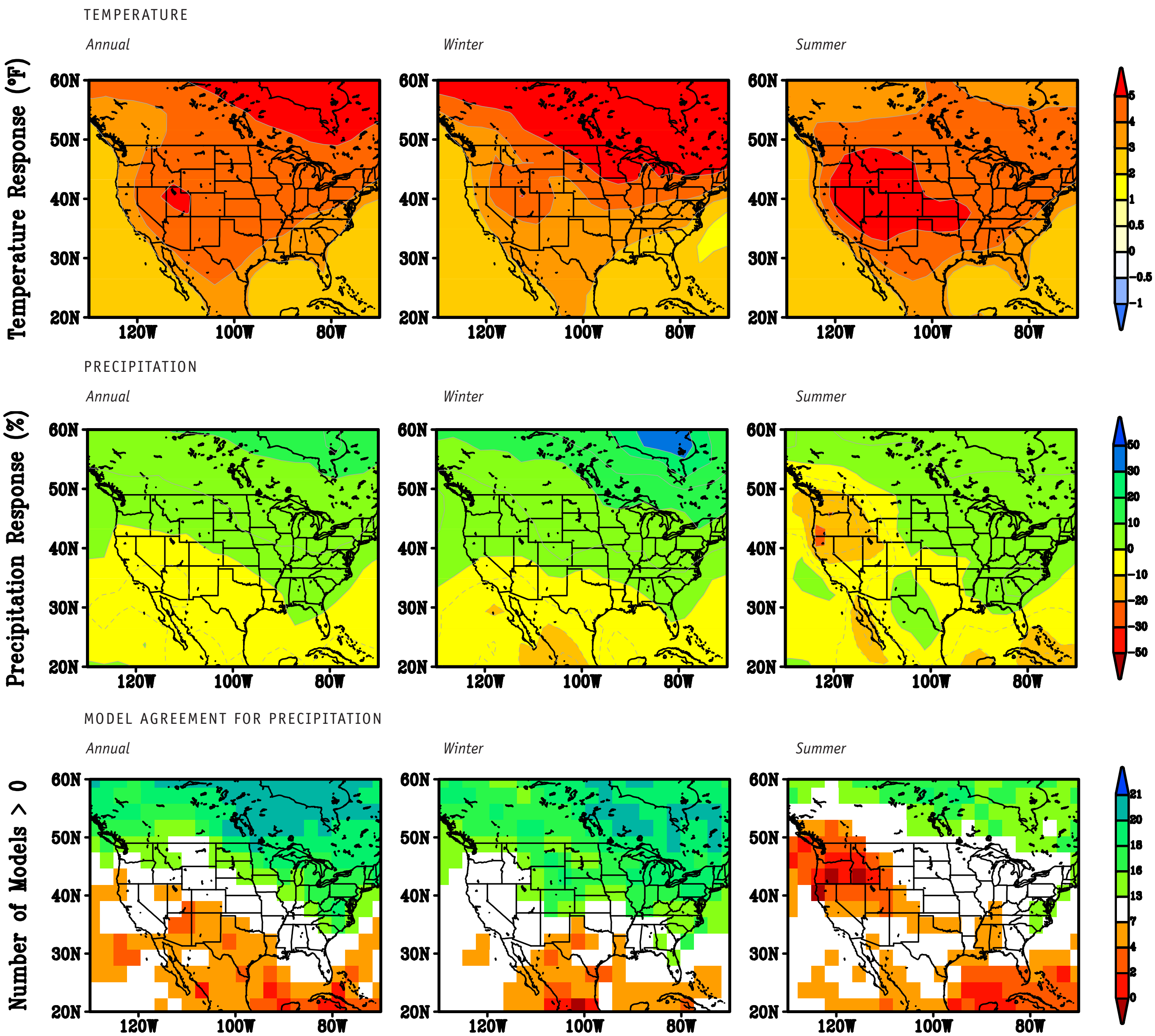


Fig. 5-1. Temperature and precipitation changes over North America projected for 2050 (2040–60 average) by an ensemble of 22 climate models used in the IPCC AR4. Changes are shown relative to the 1950–99 baseline average. The top row is the multi-model average temperature change for the annual mean *(left)*, winter *(center)*, and summer *(right)*. For Colorado, the average projected temperature changes are about 4°F (annual), 3°F (winter), and 5°F (summer). The second row shows the percentage change in total precipitation. The multi-model average shows small changes in precipitation in Colorado, although individual model projections *(not shown)* exhibit a range of projected changes. There is only weak agreement among the models whether annual precipitation will increase or decrease in Colorado *(third row)*, though there is an indication of an increase in winter and a decrease in summer. (Data source: CMIP3 multi-model dataset, PCMDI)

FIGURE 5-2. January Observed and Projected Temperatures

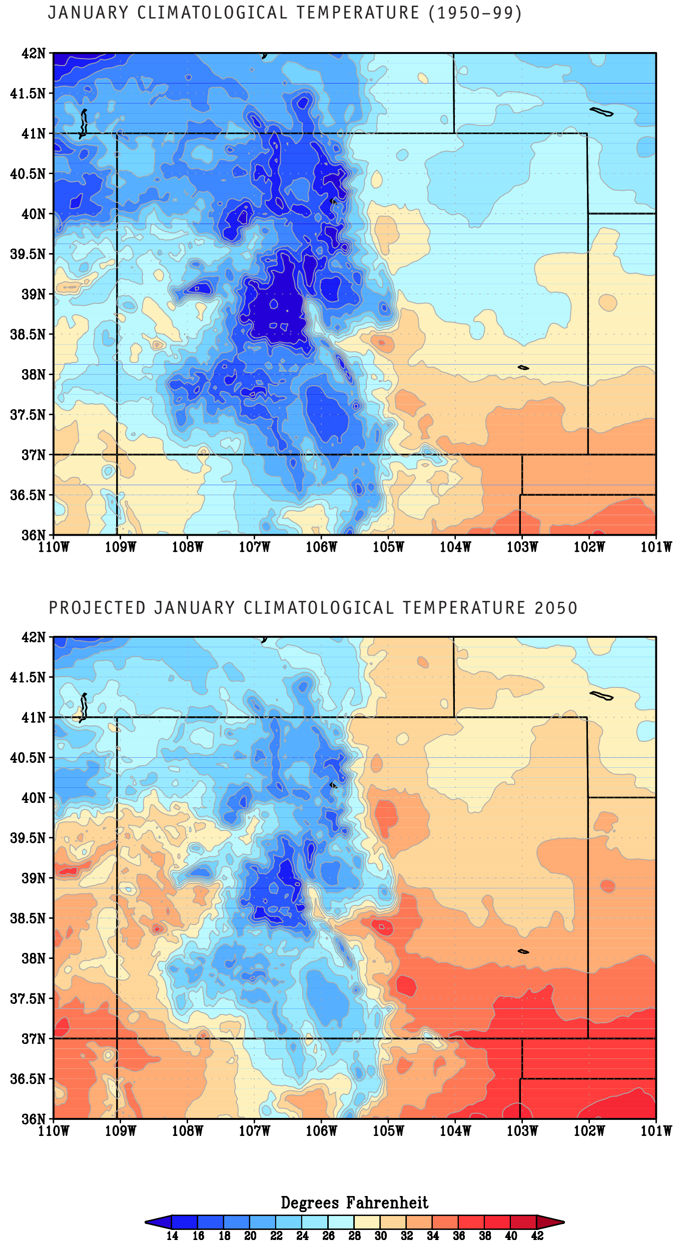


Fig. 5-2. January observed average daily temperature in Colorado for 1950–99 *(top panel)* and projections for 2050 *(bottom panel)*. By 2050 the January climate of the Eastern Plains has moved northward by a distance greater than half the state. The climate zones of the mountains have migrated upward in elevation, and the climate of the Desert Southwest has progressed into the valleys of the Western Slope. Projections were calculated by adding the multi-model average temperature changes to the observed climatology. Observed climatological averages are from PRISM (DiLuzio et al. 2008), and projected changes from the IPCC (CMIP3) 22-model average for the A1B emissions scenario.

FIGURE 5-3. July Observed and Projected Temperatures

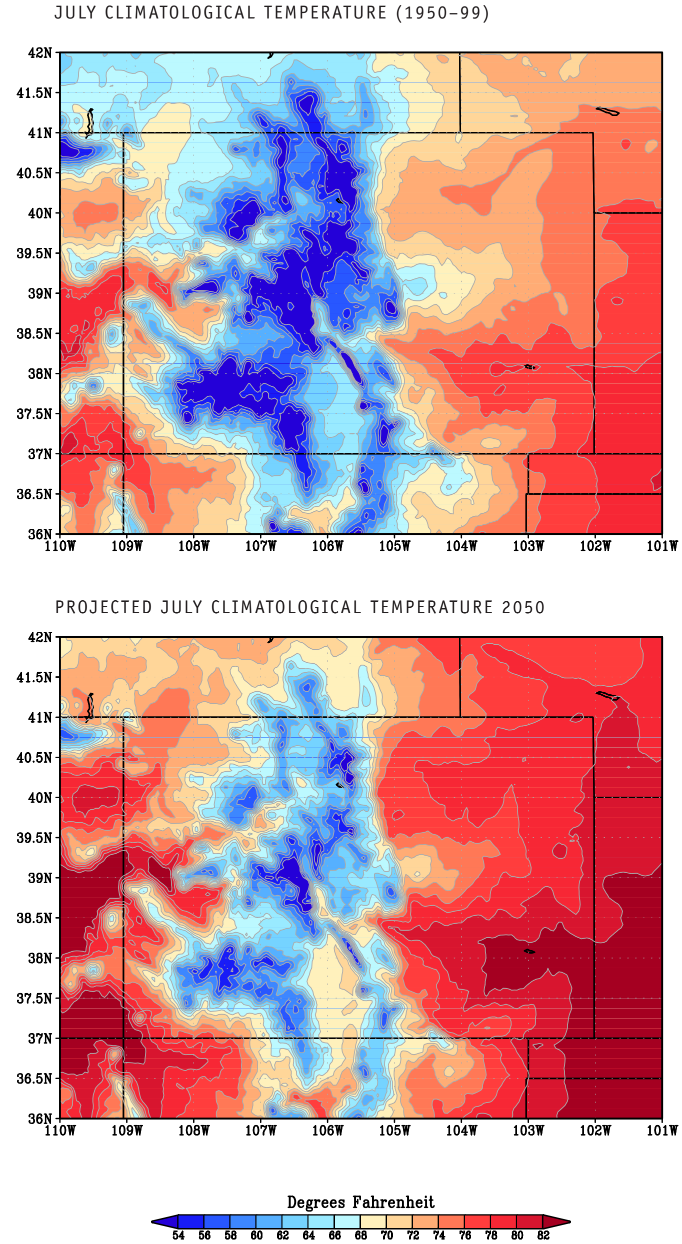


Fig. 5-3. July observed average daily temperature in Colorado for 1950–99 *(top panel)* and projections for 2050 *(bottom panel)*. For July, the temperatures on the Eastern Plains have moved westward and upslope, such that the temperature regime near the western Kansas border has reached the Front Range by 2050. Projections were calculated by adding the multi-model average temperature changes to the observed climatology. Observed climatological averages are from PRISM (DiLuzio et al. 2008), and projected changes from the IPCC (CMIP3) 22-model average for the A1B emissions scenario.

Just as the observed temperature climatology does not capture the year-to-year or day-to-day variations (Figures 5-2 and 5-3, *top*), neither do the climate projections (Figures 5-2 and 5-3, *bottom*). While Figures 5-2 and 5-3 are illustrative of climate change in Colorado, it is unclear how the details will play out at any given location. Due to local and regional climatic effects, some places may warm more than projected, some less (or even cool, particularly in the next couple of decades when average warming trends are comparable to observed variability). Until higher resolution dynamical downscaling is performed, and until projected local land use and potential ecosystem changes (e.g., forest cover changes resulting from pine beetle infestation) are considered, it will be difficult to determine these local variations. But the larger picture must be kept in mind. Comparable warming is projected for most of the western United States. The projected changes, especially in summer, are large compared to present-day climate variations—an indication that the warming signal may be clearly seen throughout Colorado by 2050.

The implications of the model-projected changes in 2050, including the seasonal cycle, are best illustrated by looking in more detail at three locations in Colorado (FIGURE 5-4): the Western Slope (FIGURE 5-5), the North Central Mountains (FIGURE 5-6), and the Eastern Plains (FIGURE 5-7). At all these sites, the monthly average temperatures from 1950 to 1999 are compared with those projected for 2050 using the statistically downscaled projections of Maurer (2007; **http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/**). The cluster of lines shows the seasonal cycle of all 112 available projections from the B1, A1B, and A2 scenarios, depicting the range of model projections (FIGURES 5-5, 5-6, and 5-7; *bottom panels*). To provide a reference for how unusual the projected temperatures *(red lines)* will seem, compared to today, the 10th and 90th percentiles of monthly average temperatures are also shown *(dashed black lines)*. These percentiles represent the top-five-warmest and top-five-coolest months in the period 1950–99. The present and range of projected precipitation climatologies are shown in the bottom panels of FIGURES 5-5, 5-6, and 5-7 for each location.

FIGURE 5-4. Locations of Precipitation and Temperature Projections in FIGURES 5-5, 5-6, and 5-7

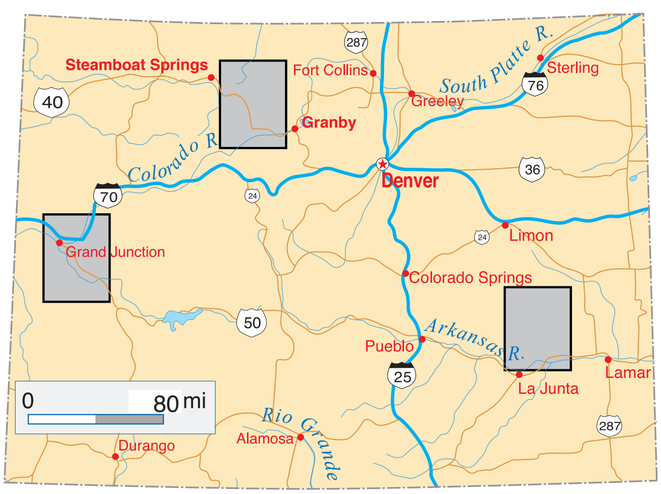


Fig. 5-4. The areas used to calculate monthly temperature and precipitation projections for FIGURES 5-5, 5-6, and 5-7.

FIGURE 5-5. Projected Monthly Temperature and Precipitation near Grand Junction, CO (2050)

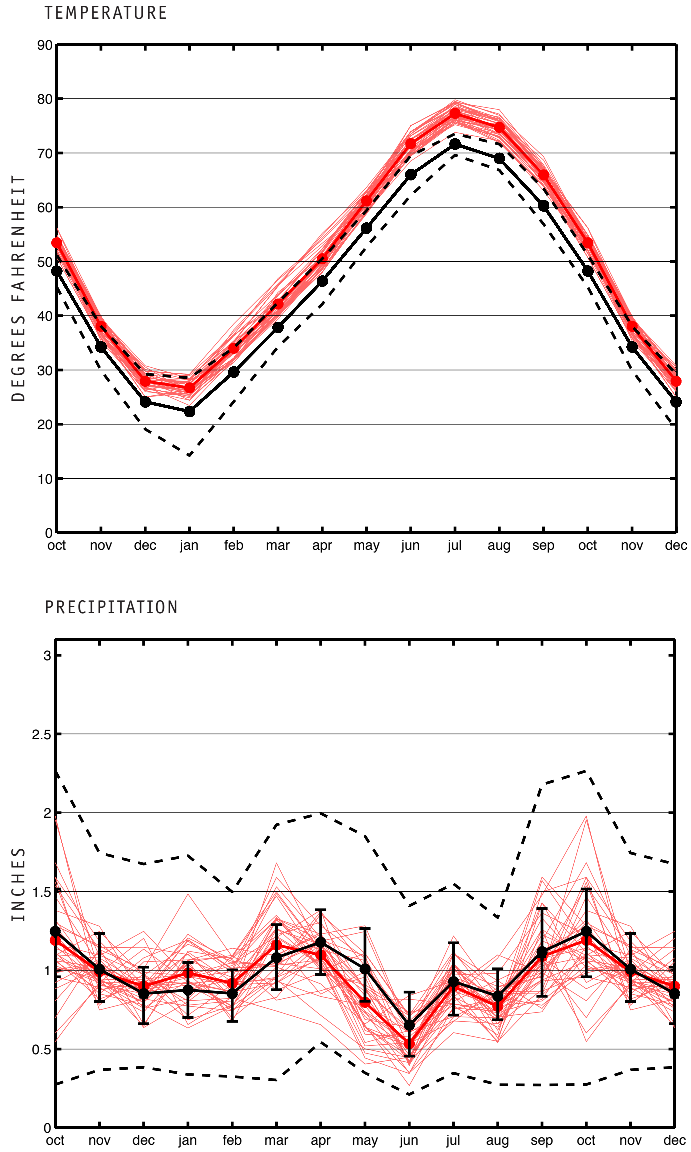


Fig. 5-5. Observed monthly average temperature (°F) *(top panel)* and precipitation (inches) *(bottom panel)* compared with projections for 2050 over a 30 x 40 mile region on the West Slope near Grand Junction *(see FIGURE 5-4)*. The monthly average *(solid black)* and 10th and 90th percentiles values (dashed black lines) are based on observations over the period 1950–99. Projected monthly climatologies *(thin red lines)* are from the multi-model ensemble for the 20-year period centered on 2050. Average of the projections is shown as a heavy red line. Data are derived from bias-corrected and downscaled climate model output and gridded observations (Maurer et al. 2007). For precipitation, the 10th and 90th percentile values of 20-year averages, estimated from nearby station data with ~100 year records, are also shown *(vertical bars)*. The magnitude of projected temperature change is comparable to or greater than the year-to-year variations throughout the historical record; however, this is not the case for precipitation.

FIGURE 5-6. Projected Monthly Temperature and Precipitation near Steamboat Springs, CO (2050)

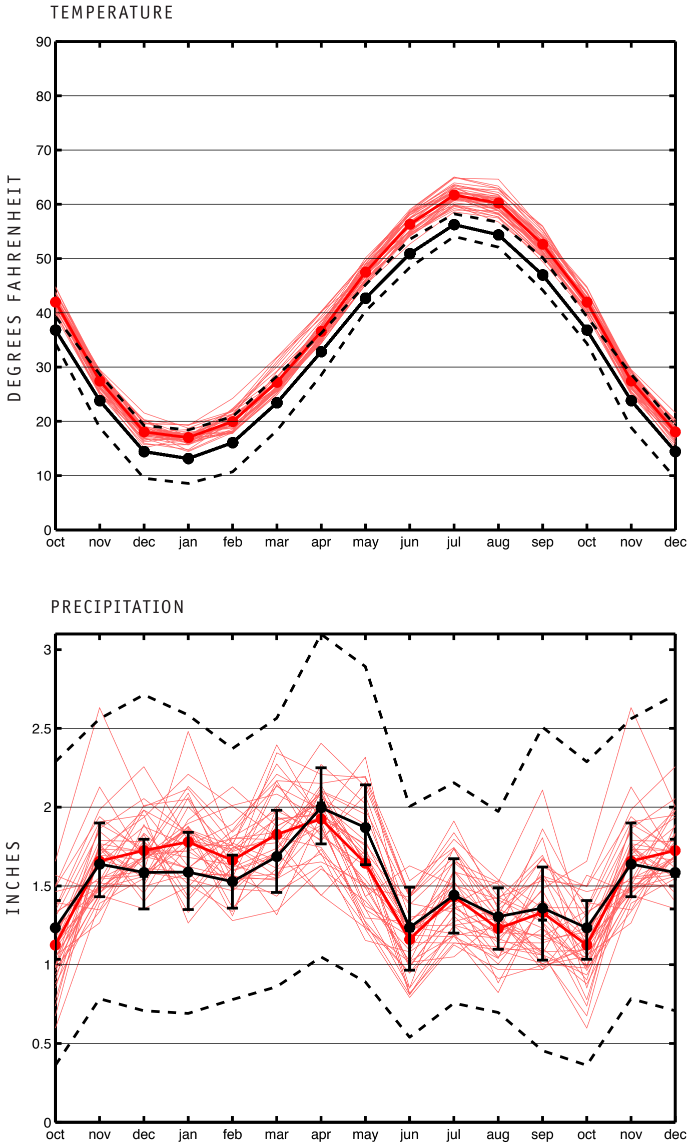


Fig. 5-6. Same as FIGURE 5-5, but for a region in the North Central Mountains between Granby and Steamboat Springs.

FIGURE 5-7. Projected Monthly Temperature and Precipitation near La Junta, CO (2050)

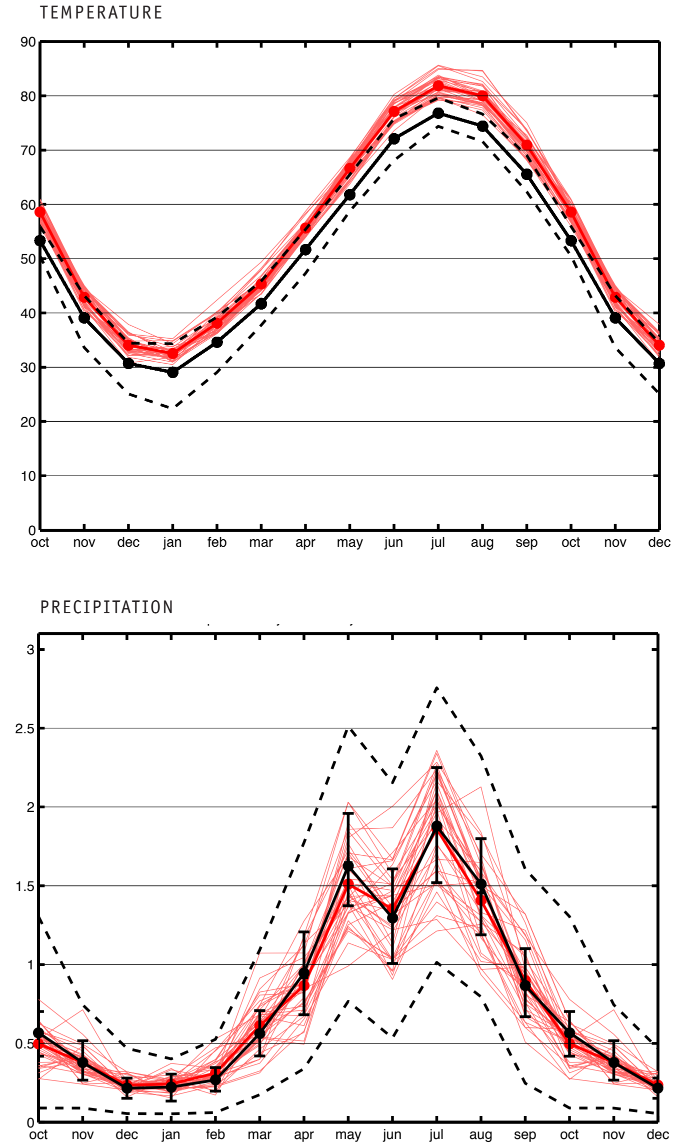


Fig. 5-7. Same as FIGURE 5-5, but for a region on the Eastern Plains near La Junta.

At all three sites, the temperature increases are largest in summer. The July temperatures from almost all the model projections at all three sites lie at or above the 90th percentile of the present climate. The bulk of the projections suggest that typical summer temperatures will equal or exceed the extreme warm summers of the last half of the 20th century. The projected temperature changes are somewhat smaller in winter and the year-to-year variations are larger. While extreme warm winter months would increase in these projections, most years, even in 2050, will not be extreme by present standards. Winter warming will be manifest in the relative absence of cold months and in the cumulative effects of consecutive warm winters.

Unlike temperature projections, potential future changes in precipitation are smaller than the year-to-year and decade-to-decade variations observed in the historical record. This is consistent with the IPCC: “Models suggest that changes in mean precipitation amount, even where robust, will rise above natural variability more slowly than the temperature signal” (IPCC AR4 WGI 2007, p. 74). The Western Slope site has considerable precipitation in most months, with maxima in the spring and autumn. The multi-model average projections for this locale show a shift to a wetter winter and drier spring, although the range of projections is large. In the central mountains, where most precipitation falls in the cold season, the projections show an increase in winter precipitation and smaller changes in other times of the year. There is a strong summertime maximum in precipitation in the present climate near La Junta in the eastern plains. The downscaled multi-model projections indicate little change. However, model uncertainties are largest in summer, so less confidence can be put in the projected precipitation at this location. These three locations are indicative of what may happen throughout Colorado, as they reflect the large-scale climate model projections.

5-3. Hydrologic Changes

The state of Colorado is the headwaters of the Arkansas, Platte, Rio Grande, and Colorado Rivers. While climate change is projected to impact all these basins (Figure 5-8), the impact on the Colorado River has received by far the most study. A decrease in runoff in the Upper Basin of the Colorado River—and the resulting decrease in the natural flow at Lee Ferry on the Colorado River—could increase the chance of the Upper Basin failing to meet its delivery requirements under the Colorado Compact (e.g., Christensen et al. 2004; McCabe and Wolock 2008). Other interstate water compacts could also be affected.

Recent hydrologic studies on climate change in the Upper Colorado River Basin point to an expected decline in runoff by the mid-to-late 21st century (Table 5-1). Those studies that explicitly calculate runoff report multi-model average decreases ranging from 6% to 20% by 2050 compared to 20th century conditions; the one recent study that bases streamflow on a large-scale statistical relationship (Hoerling and Eischeid 2006) projects a 45% decrease by 2050 (Table 5-1). The range of individual model projections within a single study can include both increasing and decreasing runoff due to the range of climate model output used to drive the hydrology models (Figure 5-9). Table 5-1 also identifies the studies that analyze the risk that climate change poses to water supply and storage (details are beyond the scope of this document, see references in Table 5-1).Extensive discussions of hydrologic studies can be found in National Research Council (2007), the USBR Climate Technical Working Group (Appendix U of USBR EIS 2008), and in chapter four of the CCSP SAP 4.3 (2008).

FIGURE 5-8. Projected Changes in Annual Runoff (2041–2060)

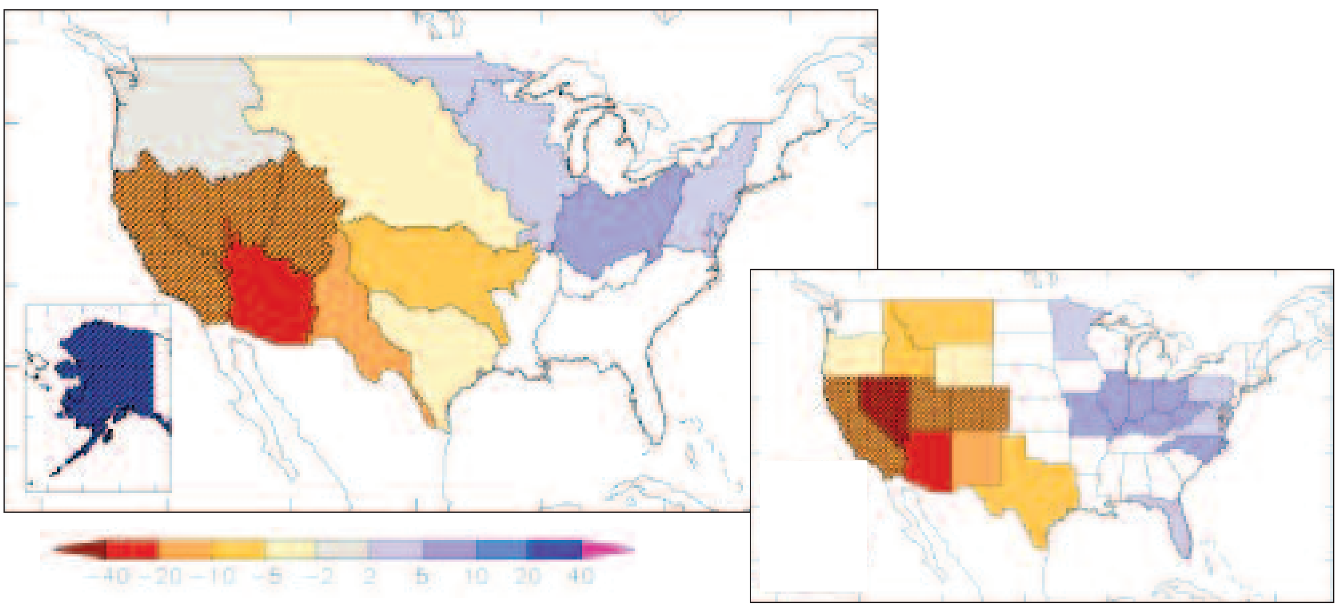


Fig. 5-8. Model-projected changes in annual runoff (2041–60 average) for different river basins in the United States. The scale represents the percentage change relative to a 1900–70 baseline. Colors indicate that >66% of models agree on whether the change is positive or negative; diagonal hatching indicates >90% agreement. (data from Milly 2005, replotted by P.C.D. Milly)

TABLE 5-1. Projected Changes in Colorado River Basin Runoff or Streamflow in the Mid-21st Century from Recent Studies

Study	*GCMs (runs)*	*Spatial Scale*	*Temperature*	*Precipitation*	*Year*	*Runoff (Flow)*	*Risk Estimate*
Christensen et al. 2004	1 (3)	VIC model grid (~8 mi)	+3.1°F	-6%	2040–69	-18%	Yes
Milly 2005, replotted by P.C.D. Milly	12 (24) (~100–300 mi)	GCM grids —	—		2041–60	-10 to -20% 96% model agreement	No
Hoerling and Eischeid 2006	18 (42)	NCDC Climate Division	+5.0°F	~0%	2035–60	-45%	No
Christensen and Lettenmaier 2007	11 (22)	VIC model grid (~8 mi)	+4.5°F (+1.8 to +5.0)	-1% (-21% to +13%)	2040–69	-6% (-40% to +18%)	Yes
Seager et al. 2007*	19 (49)	GCM grids (~100–300 mi)	—	—	2050	-16% (-8% to -25%)	No
McCabe and Wolock 2008	—	USGS HUC8 units (~25–65 mi)	Assumed +3.6°F	0%	—	-17 %	Yes
Barnett and Pierce 2008*	—	—	—	—	2057	Assumed -10% to -30%	Yes

Values and ranges (where available) were extracted from the text and figures of the references shown. Columns provide the number of climate models and individual model runs used to drive the hydrology models, the spatial scale of the hydrology, the temperature and precipitation changes that drive the runoff projections, and whether or not the study quantified the risk these changes pose to water supply (e.g., the risk of a compact call or of significantly depleting reservoir storage).

* Two studies do not specifically make projections of Upper Basin runoff or streamflow. Seager et al. (2007) average over a large area (95°W–125°W, 25°N–40°N) that only partially overlaps with the Upper Basin. Barnett and Pierce (2008) assume Lees Ferry streamflow changes to drive their water balance model of reservoir storage.

FIGURE 5-9. Range in Temperature and Precipitation Projections for the Upper Colorado River Basin

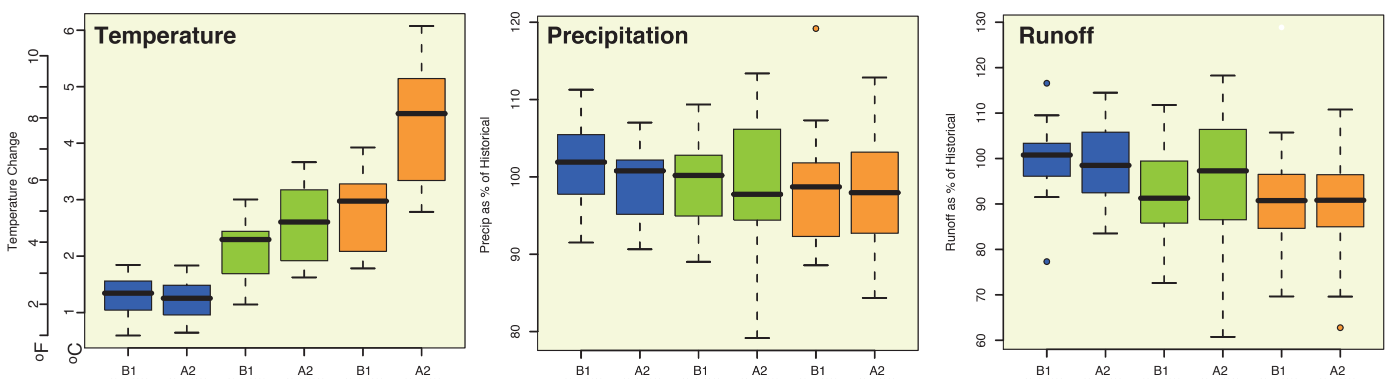


Fig. 5-9. Range in temperature and precipitation projections for the Upper Colorado River Basin from 11 GCMs, and the resulting range in runoff projections from Christensen and Lettenmaier (2007). Box-and-whiskers symbols represent the 5th, 25th, 50th, 75th, and 95th percentiles of the data; outliers are shown by circles. Projections are shown for the SRES B1 and A2 emissions scenarios for 30-year averages centered on the years 2025, 2055, and 2085. Changes are relative to 1950–2000 averages. The range results from different climate model formulations and from model-simulated climate variability. For comparison, 30-year averages of the historical and reconstructed flows at Lees Ferry (Meko 2006) range from 92% (5th percentile) to 108% (95th percentile) of the long-term average. Note that when the downscaled precipitation data that is used as input for this study is adjusted to show the same percentage change as the GCM gridboxes, the runoff shows a greater decline, ~14% on average, by 2070–2100. (D. Lettenmaier, pers. comm.)

The range in model projections both within and among the various studies is influenced by modeling methodologies and natural variability. First, a number of differently formulated climate models, each with different projected temperature and precipitation changes over the Upper Basin, are used to drive the hydrology models that generate runoff projections. These different climate drivers lead to different runoff projections (FIGURE 5-9). A second, related factor is that runoff in the Upper Basin varies due to natural climate variability, some of which is captured by the climate models. Therefore the range of individual model simulations (e.g., the range reported by Christensen and Lettenmaier 2007) results from differences in climate model formulation and from different realizations of model-simulated climate variability. It would be ideal to analyze a large number of realizations (runs) from each climate model to isolate these two factors, but multi-run ensembles are not available for most GCMs. For this reason, most researchers emphasize the multi-model average over the range of individual model projections.

A third factor is that different downscaling and bias-correction techniques are used to relate GCM grids to hydrology model grids (see Section 3-4). For example, the percentage change in GCM precipitation projections is modified by the downscaling technique used by Maurer (2007) (Dennis Lettenmaier, pers. comm.). Fourth, different hydrologic models are used to make runoff projections. These include GCM hydrology component models (Milly 2005), simple statistical regressions (Hoerling and Eischeid 2006), and distributed hydrologic process models (Christensen and Lettenmaier 2007).

The spatial scale at which the hydrology is resolved is a particularly important factor in determining the simulated hydrologic response to climate change. In particular, there is the need to resolve small-scale topographic effects including cooler average temperatures at higher elevations that have a strong effect on evapotranspiration and snow hydrology. For the studies listed in TABLE 5-1, the spatial scale ranges from a few hundred miles (the typical GCM grid) to eight miles (the Variable Infiltration Capacity hydrology model grid).

Feedback from water managers has motivated an ongoing research project, the NOAA-funded *Reconciling Projections of Future Colorado River Stream Flow* study, to understand the differences among these projections in order to provide water managers with more useful information. The goal of this project is to quantify the effects of methodological differences on the range of streamflow projections and, if possible, to reduce the range of uncertainty in these projections.

The impact of climate change on runoff in the Rio Grande, Platte, and Arkansas basins has not been studied as extensively. A multi-model study of GCM-simulated runoff projects a decrease of 5–10% in the Arkansas (62% model agreement on the sign of the change) and Rio Grande (75% model agreement) basins by 2050, and no appreciable change in the Platte/Missouri Basin (FIGURE 5-8). This is compared with the 10–25% reduction (95% model agreement) for the Upper Colorado River Basin. These numbers should be interpreted with caution because they are based on GCM-scale hydrology and they reflect the runoff in the entire river basins, not just the part in Colorado. Hurd and Conrood (2007) project a decline in streamflow of -3% to -14% by 2030 and -8 to -29% by 2080 for the Rio Grande Basin.

Regarding hydroclimatology of the western United States, the IPCC (2008, p. 102) states, "[w]arming and changes in the form, timing and amount of precipitation will be ***very likely*** to lead to earlier melting and significant reductions in snowpack in the western mountains by the middle of the 21st century." The high-elevation snowpack in the Colorado River Basin is projected to have a moderate decline (FIGURE 5-10), whereas lower-elevation snowpack (primarily outside Colorado) experiences a precipitous decline. At high elevations mid-winter temperatures would remain below freezing even with relatively large warming, and the main effects of rising temperatures on snowpack would be seen in the spring. The high-elevation headwaters also lie in a region where small, or even positive, changes in wintertime precipitation are projected.

FIGURE 5-10. Projected Change in Colorado River Basin Snowpack

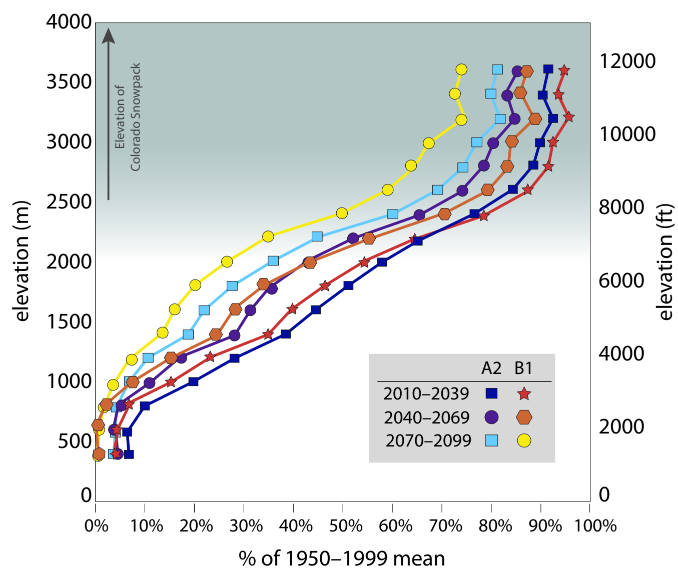
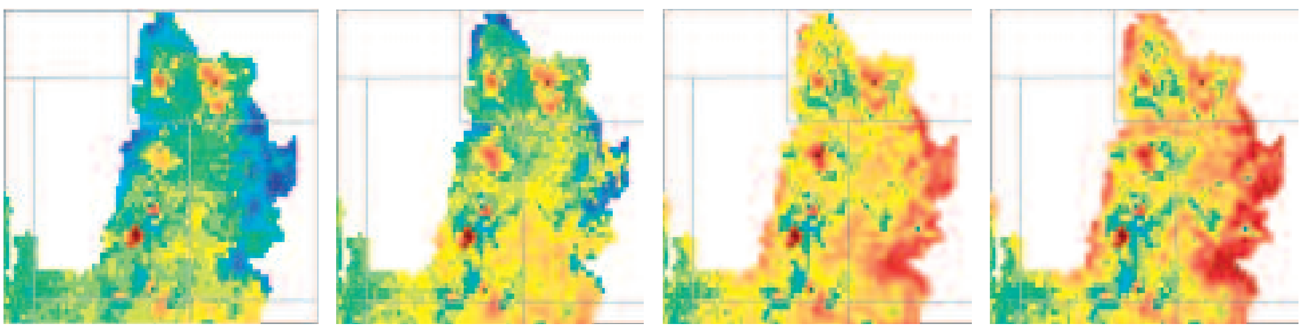


Fig. 5-10. Projections of snowpack changes as a function of elevation for the Colorado River Basin. The data show average snowpack declines throughout the cold season, and are a function of both the snow water equivalent and the amount of time snow is on the ground. The downscaled projections from 11 climate models for the 30-year average centered on 2025, 2055, and 2085 are shown for the B1 and A2 emissions scenarios. Most of the snowpack in the state of Colorado that feeds the Colorado River lies above 2500 m (8200 ft) in elevation. Modest declines in snowpack are projected at these high elevations, and larger declines (80–90%) may occur at lower elevations. The basinwide average April 1 snow water equivalent (SWE) is projected to decline by 13% (2025), 21% (2055), and 38% (2085) in scenario A2, and by 15% (2025), 25% (2055), and 29% (2085) in scenario B1. (Christensen and Lettenmeier 2007)

FIGURE 5-11. Projected Soil Moisture Changes in the Upper Colorado River Basin for 2050 for April, May, June, and July



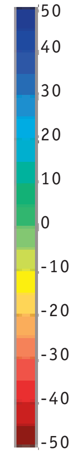


Fig. 5-11. Projected soil moisture changes for 2050 in the Upper Colorado River Basin for April, May, June, and July. The shift in the median (50th percentile) soil moisture is shown in terms of the percentiles of the 1950–2000 soil moisture simulation. Zero shift represents no change in the median soil moisture. Warm colors represent drying in the future; cool colors represent wetter conditions in the future. Earlier snowmelt leads to wetter soil moisture conditions in April and drier conditions by summer.

The resulting earlier snowmelt is evident in the maps of projected changes in soil moisture in the Colorado River Basin (Figure 5-11). April soil moisture *(left)* increases in most of the mountainous regions due to the earlier snowmelt. In May *(center left)*, only the highest elevations show increased soil moisture, while by June *(center right)* and July *(right)*, the soil moisture is greatly reduced compared to the present values. This is consistent with the IPCC Technical Paper on Water (2008), in which projections for mountain snowmelt-dominated watersheds indicate an increase in winter and early spring flows (raising flooding potential), and a substantial decrease summer flows. "Hence, over-allocated water systems of the western USA and Canada that rely on capturing snowmelt runoff could be especially vulnerable. . . ." (IPCC 2008, p. 102).

5-4. Extremes

An extreme weather event is defined by the IPCC as an "event that is rare at a particular place and time of year," where rare is below the 10th or above the 90th percentile of observations. Using analyses of the IPCC AR4 climate model monthly and daily output, the CCSP SAP 3.3 (2008) addresses projections of climate extremes, including heat waves, drought, flooding, and storms that are most relevant to Colorado.

For the western United States, projected changes in precipitation extremes are larger than changes in mean precipitation (IPCC 2008). Model simulations suggest that in the West, cold air outbreaks will continue to occur even in a warmer climate, though the frequency will be somewhat reduced.

Damaging flood events have been associated with intense summer precipitation on the Eastern Plains and the Front Range. Based on physical principles, thunderstorms could be more intense in a warmer climate because warmer air can potentially "hold" more moisture and transport it into the storms (Trenberth 1999). Multi model analyses (Tebaldi et al. 2006) discussed in the CCSP SAP 3.3 suggest an increase in strong precipitation events over most of the conterminous United States. However, the vicinity of Colorado shows an unchanged or decreased chance of strong events. The reason for this result is not understood. Given the small spatial scales involved, and given the often dominant importance of topographic effects precipitation, an analysis such as Tebaldi et al. (2006) that is based on the global climate models has to be interpreted with great caution. Regional climate model simulations may help to shed some light on this difficult problem in the future.

The CCSP projects that in the southwestern United States (boundaries not specified), the combination of increasing temperature and decreasing wintertime precipitation means that it is "***likely*** that droughts will become more severe" (CCSP SAP 3.3, p. 5). Of relevance for Colorado is that "in other places where the increase in precipitation cannot keep pace with increased evaporation, droughts are also ***likely*** to become more severe. It is ***likely*** that droughts will continue to be exacerbated by earlier and possibly lower spring snowmelt run-off in the mountainous West, which results in less water available in late summer" (CCSP SAP 3.3, p. 5).

SIDEBAR 5-1. Aspen Snow: Consideration of Climate Change Information in Planning

A case study evaluated how the quantity and quality of snow at Aspen Mountain ski area in 2030 and 2100 may be affected by changes in regional climate resulting from increased greenhouse gas emissions. This study estimated changes in regional climate using MAGICC/SCENGEN, software for downscaling models, and ran combinations of five general circulation models (GCMs) that best simulate current conditions. The climate change estimates were run using the relatively low, mid-range, and high GHG emissions scenarios: B1, A1B, and A1FI. Output from a regional climate model statistical downscaling model was used to generate higher resolution estimates of changes in climate using output from the Hadley model (HADCM3). Snow quantity was evaluated using the Snowmelt Runoff Model and a module developed to estimate snow quantity during the accumulation season, before snowmelt initiation. Snow quality was also evaluated.

By 2030, the estimated temperatures increase is 1.8 to 2.5°C at Aspen Mountain from circa 1990, and the length of the ski season is estimated to decrease by approximately 1 to 1.5 weeks. By 2030, the snowline is estimated at 2250 m above sea level; an increase of approximately 200 m from current (2006) conditions. By 2100, average annual temperatures are projected to increase 2.9 to 9.4°C. The snowline is estimated at 2800 to 2900 m for the A1B and B1 scenarios in 2100, and 3100 to 3200 m for the A1FI scenario. The date when snow starts to accumulate at the base area is delayed by six to seven days by 2030, and anywhere from 1.5 to 4.5 weeks by 2100 relative to circa 1990. For mid-winter snows, a 15% increase in snowfall compensates for a 1.5°C increase in air temperature such that there would be little change in snow depth. Snow depth is reduced to almost zero for the base area in 2100 under the medium greenhouse gas emissions A1B scenario. In the high greenhouse gas emissions A1FI scenario, snow depth is reduced to near zero for the entire lower two-thirds of the mountain. The effect is substantially reduced under the low greenhouse gas emissions B1 scenario (FIGURE 5-12). In spite of earlier snowmelt initiation and the reduction in snowpack, snow density in the top 10 centimeters increases by less than 20% by 2030.

The study was led by the Aspen Global Change Institute and funded by the City of Aspen. Stratus Consulting analyzed snowpack and ecological changes; the Rural Planning Institute analyzed economic implications of climate change impacts on tourism; and the University of Colorado examined stakeholder responses and adaptation; Tom Wigley at the National Center for Atmospheric Research provided advice on modeling simulations.

FIGURE 5-12. Projected Change in Snow Covered Area, Aspen

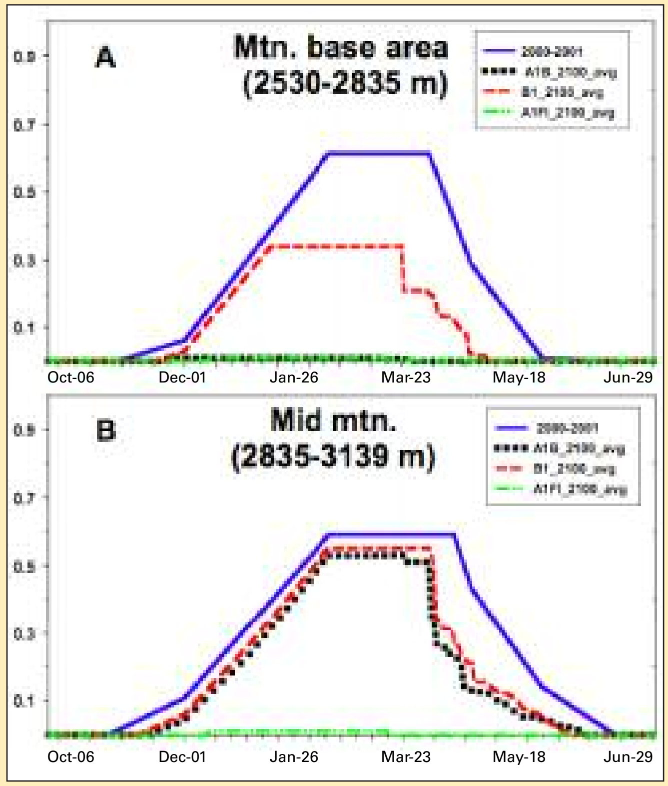
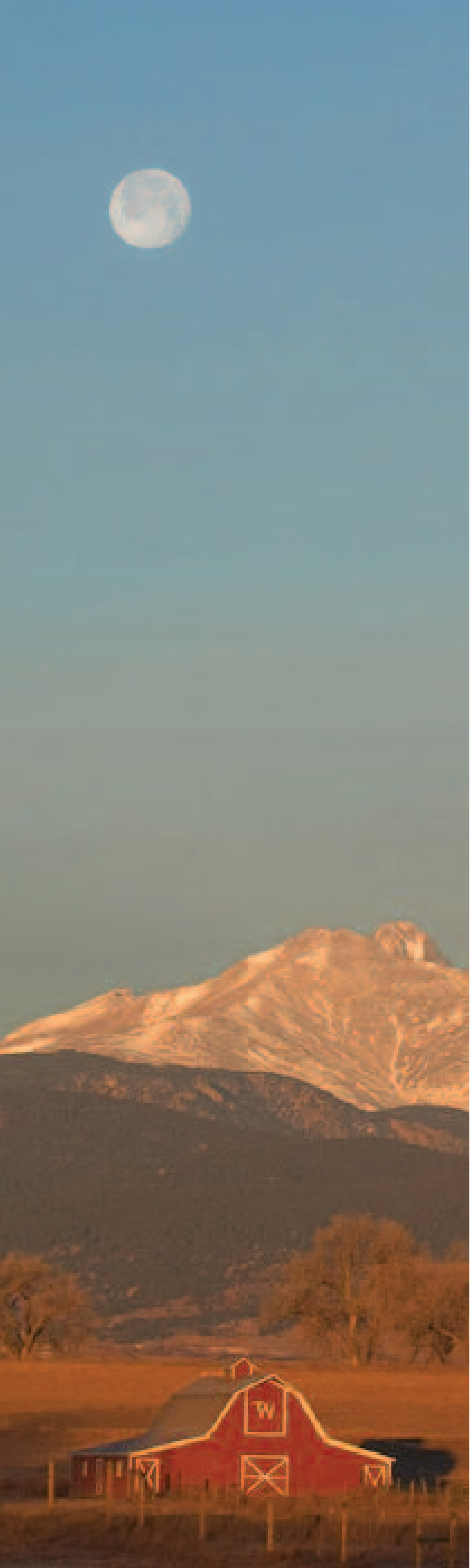


Fig. 5-12. Change in snow covered area. Percentage of the mountain zone covered in snow in 2100 from October through June based on scenarios A1B, B1, and A1FI.



6
Implications of Changing Climate for Colorado's Water Resources

Colorado's water resources are sensitive to the changing climate on a range of time scales. As a buffer against natural seasonal and interannual variability, Colorado pioneers and their descendants developed infrastructure for water storage and conveyance, and adopted institutional arrangements capable of allocating shortages when necessary, including the prior appropriations system and interstate compacts. These actions helped in managing water during drought and other climate variations in the 20th century. But the 21st century climate may pose new challenges to water managers that are unlike those experienced in the 20th century.

Paleoclimate studies reveal that previous centuries were unlike the past century. Lengthy droughts and wet periods were more common from about 800 to 1900 in the West (FIGURE 2-8). Even in the absence of climate change this new understanding of past hydrology would warrant a renewed focus on drought planning. Second, water supply systems are facing complex stresses, including increasing demands from a growing population and potential energy development. Third, these challenges are magnified by the need to consider climate change. Therefore, there is an emerging need for vulnerability assessments, for adaptation planning, and for bringing climate change information into ongoing integrated resource planning.

This report provides a synthesis of the physical aspects of changing climate and a scientific basis to support further studies of water resources impacts. The assessment and quantification of specific climate change impacts on water resources is beyond the scope of this document. Few published studies address potential water resources impacts in Colorado. Two of these—Aspen and Boulder (SIDEBARS 5.1 and 3.2)—are examples of how climate change information has been considered in water-related resource planning. However, much further work is needed to assess the multi-dimensional impacts and cascading effects on water resources affecting humans and the environment. A number of projects are in progress, such as the Joint Front Range Climate Change Vulnerability Study (JFRCCVS, SIDEBAR 3.3) and the Colorado River Water Availability Study (**http://ibcc.state.co.us/Process/Needs/WaterSupplyAvailability/**), in which climate projections are being used to explore possible water supply scenarios to which managers may need to adapt.

Section 6 identifies some implications of climate change for Colorado water management. It also briefly discusses the potential uses of the information within this report in water resources management, including assessing vulnerabilities and creating adaptive strategies, such as those called for in the Governor's Colorado Climate Action Plan.

Key Implications

Climate change will affect Colorado's use and distribution of water. Changes in economies and land use, environmental concerns, and population growth are already affecting water management decisions. Water managers and planners currently face specific challenges that may be further exacerbated by projected climate changes (Table 6-1). The implications of climate change in this report are consistent with the broader conclusions in the CCSP SAP 4.3 and the report, *Colorado River Basin Water Management* (NRC 2007).

The consistent projections for a substantial temperature increase over Colorado (IPCC 2008) have important implications for water management. Increases in temperature imply more evaporation and evapotranspiration leading to higher water demands for agriculture and outdoor watering. Temperature-related changes in the seasonality of streamflows (e.g., earlier runoff) may complicate prior appropriation systems and interstate compact regimes; and modify the interplay among forests, hydrology, wildfires, and pests (e.g., pine beetles).

The wide range of precipitation projections makes it difficult to assess likely changes in annual mean precipitation by mid-21st century. However, a synthesis of findings in this report suggests a reduction in total water supply by then. Furthermore, there is potential for increased drought severity in the region due to higher temperatures alone. When combined with temperature increases and related changes in evaporation and soil moisture, recent hydrologic studies on climate change in the Upper Basin of the Colorado River point to an expected decline in runoff by the mid-to-late 21st century. These studies report multi-model average decreases ranging from 6% to 20% by 2050 (Section 5-3). This synthesis is consistent with the conclusion of the IPCC that globally the negative impacts of climate change on water resources outweigh the positive (IPCC 2008).

Strategies for Incorporating Climate Information into Water Planning and Adaptation

Two pathways for integrating climate information into water resources planning and management are vulnerability analysis and integrated resource planning (see Cromwell et al. 2007; Miller and Yates 2006). Vulnerability analysis includes *top-down* or *bottom-up* perspectives. In the top-down perspective, projections of global or spatially downscaled models are used to drive resource models and project resource impacts. The top-down strategy is illustrated in Figure 3-5, which depicts how climate projections may be used in water operations models. Some approaches include the use of sensitivity studies based on changing temperature and/or precipitation by a fixed amount guided by the range of model projections, the direct use of climate model output with existing downscaling methods (e.g., the Aspen Study, Sidebar 5-1), and the use of conditionally re-sampled historical record that shifts the average climate according to the model projections, while preserving the character of day-to-day and year-to-year historical sequences.

TABLE 6-1. Challenges Faced by Water Managers, and Projected Changes

Issues	*Observed and/or Projected Change*
Water demands for agriculture and outdoor watering	Increasing temperatures raise evapotranspiration by plants, lower soil moisture, alter growing seasons, and thus increase water demand.
Water supply infrastructure	Changes in snowpack, streamflow timing, and hydrograph evolution may affect reservoir operations including flood control and storage. Changes in the timing and magnitude of runoff may affect functioning of diversion, storage, and conveyance structures.
Legal water systems	Earlier runoff may complicate prior appropriation systems and interstate water compacts, affecting which rights holders receive water and operations plans for reservoirs.
Water quality	Although other factors have a large impact, "water quality is sensitive both to increased water temperatures and changes in patterns of precipitation" (CCSP SAP 4.3, p. 149). For example, changes in the timing and hydrograph may affect sediment load and pollution, impacting human health.
Energy demand and operating costs	Warmer air temperatures may place higher demands on hydropower reservoirs for peaking power. Warmer lake and stream temperatures may affect water use by cooling power plants and in other industries.
Mountain habitats	Increasing temperature and soil moisture changes may shift mountain habitats toward higher elevation.
Interplay among forests, hydrology, wildfires, and pests	Changes in air, water, and soil temperatures may affect the relationships between forests, surface and ground water, wildfire, and insect pests. Water-stressed trees, for example, may be more vulnerable to pests.
Riparian habitats and fisheries	Stream temperatures are expected to increase as the climate warms, which could have direct and indirect effects on aquatic ecosystems (CCSP SAP 4.3), including the spread of in-stream non-native species and diseases to higher elevations, and the potential for non-native plant species to invade riparian areas. Changes in streamflow intensity and timing may also affect riparian ecosystems.
Water- and snow-based recreation	Changes in reservoir storage affect lake and river recreation activities; changes in streamflow intensity and timing will continue to affect rafting directly and trout fishing indirectly. Changes in the character and timing of snowpack and the ratio of snowfall to rainfall will continue to influence winter recreational activities and tourism.
Groundwater resources	Changes in long-term precipitation and soil moisture can affect groundwater recharge rates; coupled with demand issues, this may mean greater pressures on groundwater resources.

FIGURE 6-1. Approaches to Climate Change Assessment

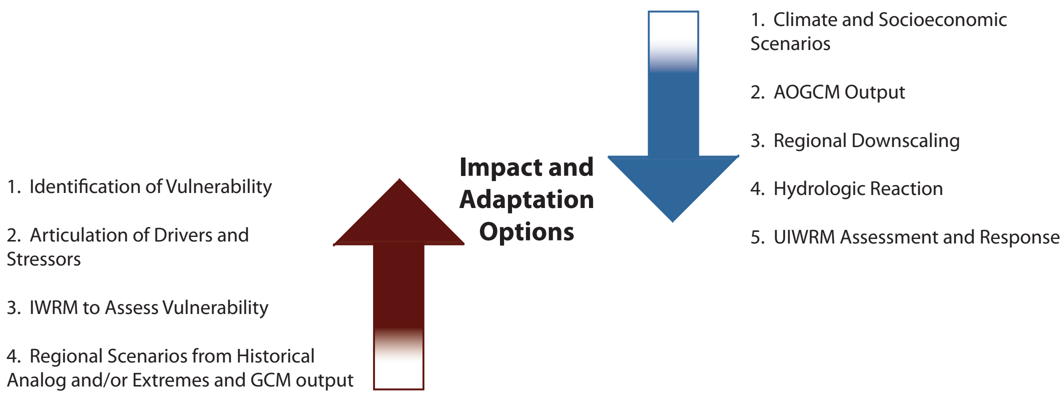


Fig. 6-1. Bottom-up and top-down approaches to climate change assessment. These approaches are not necessarily exclusive. (Yates and Miller 2006)

Information from global climate model simulations is beginning to be used in water resource related planning studies, such as the Environmental Impact Study supporting the recent Record of Decision on Colorado River Interim Guidelines (DOI 2007, see **http://www.usbr.gov/lc/**). This report assessed the state of knowledge with regard to climate change and modeling to support planning for operations under long-term drought conditions (Bureau of Reclamation 2007). Miller and Yates (2006) find that most efforts to incorporate climate change information into their planning process have used the top-down perspective. These top-down perspectives, however, are limited by the current state of the art of climate models, downscaling techniques, and observations.

Another approach is often referred to as bottom-up, illustrated in Figure 6-1. Bottom-up approaches are place-based and deal with specific resources of interest, as described for agriculture by Pielke et al (2007). In this approach water managers start with their knowledge of their system and utilize their water supply planning tools to identify what changes in climate would be most threatening to their long-range plans or operations. These are the system's critical vulnerabilities, such as the types of changes in climate that would cause these critical problems e.g., a 10% increase in flow from the 100-year flood. This is known as the threshold approach. The next step is to assess what adaptations can be made to cope and roughly at what cost. By examining the outputs of climate models or studies, water managers can then assess the likelihood of such system critical vulnerabilities.

Climate change information can be incorporated into either top-down scenario-driven or bottom-up vulnerability assessments. In the case of water resources, these assessments might include the risks of compact calls in Colorado's river basins or the risks of large-scale drought. Integrated planning processes based on these might include mitigation planning to assess and prepare for drought and developing for each major river basin a mechanism to deal with potential interstate compact calls.

The information in this report can be used to generate climate vulnerability assessments for Colorado water management that are consistent with the IPCC and CCSP reports. There remain uncertainties in projections of temperature, precipitation, and runoff; model formulation; emissions scenarios; and the role of natural variability.

Therefore, water managers will have to make plans based on a range of possible futures. This uncertainty suggests incorporating climate information in Integrated Resource Planning (IRP) (Cromwell et al. 2007; Yates and Miller 2006). IRP is a widely used long-term planning approach that integrates multiple facets of water management challenges, and is a strategy for keeping a wide range of options open and maintaining flexibility in the face of uncertain futures. This strategy is important given the uncertainties about climate futures. While the science continues to advance, the information will always have uncertainties, a range of possible futures, and there will still be natural variability across time scales. Lempert and Collins (2007) recommend decision pathways that are robust for a range of conditions.

Key Unresolved Issues

The current state of the science is unable to provide sufficient information to decision makers and stakeholders on a number of crucial scientific issues regarding Colorado's water resources. Often, there are insufficient data, in time or space, to assess long-term observational trends. In other cases, research is in progress, but the results may not be as robust as needed. Four overlapping areas with unresolved issues are climate models, research specific to Colorado, drought, and reconciling hydrologic projections.

- **Modeling issues.** To produce model projections at the scale desired by decisionmakers, regional and local processes and their role in Colorado's climate must be better modeled. Precipitation projections and related phenomena are key uncertainties. Enhanced climate modeling efforts to include finer spatial resolution are needed that better represent Colorado's mountainous terrain and precipitation processes.
- **Colorado-specific research.** Further research is needed focused on the state of Colorado and its river basins, and specifically on regions where there is little or no work, such as the basins of the Arkansas, Rio Grande, and the North and South Platte Rivers.
- **Understanding the causes of drought.** Issues include runoff efficiency, effects of increased temperatures, and uncertainty in precipitation projections. The attribution of the 2000s drought is an area of ongoing research.
- **Hydrologic projections for the Colorado River.** There is a large range among projections of river flows (Section 5). A key uncertainty is how efficient future runoff will be in the Colorado as well as other basins. A study is underway to reconcile the differences among these projections, and to better resolve projections for future flows. These uncertainties arise both from climate models and hydrologic models.

A View Toward the Future

This is a challenging time for both climate science and water management in Colorado. A warming climate will amplify Colorado's water related challenges, with potential reductions and seasonal shifts in water availability. While most water resource planning has been based on past hydrology, water users can no longer assume that future conditions will reflect the past. Although there are uncertainties regarding aspects of the science, enough information is available to support adaptation planning for risks associated with climate variability and change. Understanding of climate change in Colorado is evolving and many projects are underway to reduce these uncertainties. A continuing dialogue among climate scientists, water resources managers, planners, and policymakers will ensure that the robust scientific findings benefit society.

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Glossary

Most of the definitions included in this glossary are quoted directly from other sources, including IPCC products and Colorado State documents. The source for each definition is noted after each definition.

A1B

The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies).

IPCC AR4 WGI SPM

A2

The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

IPCC AR4 WGI SPM

Adaptation

An adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory, autonomous, and planned adaptation.

IPCC AR4 WGII

Aerosols

A collection of airborne solid or liquid particles, with a typical size between 0.01 and 10 micrometer (a millionth of a meter) that reside in the atmosphere for at least several hours. Aerosols may be of either natural or anthropogenic origin. Aerosols may influence climate in several ways: directly through scattering and absorbing radiation, and indirectly through acting as cloud condensation nuclei or modifying the optical properties and lifetime of clouds.

IPCC Technical Paper—Climate Change and Water

Annual mean temperature

The average of all daily high and low temperatures.

Anthropogenic

Resulting from or produced by human beings.

IPCC AR4 WGI

Attribution

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

IPCC AR4 WGI

B1

The B1 storyline and scenario family describes a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

IPCC AR4 WGI SPM

Climate

Climate in a narrow sense is usually 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 classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation and wind. Climate in a wider sense is the state, including a statistical description, of the climate system. For further discussion of the difference between weather and climate, see the IPCC AR4 WGI, FAQ 1.2.

IPCC AR4 WGI

Climate Divisions

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

Climate variability

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

Cryosphere

The component of the climate system consisting of all snow, ice and frozen ground (including permafrost) on and beneath the surface of the Earth and ocean.

IPCC AR4 WGI

Downscaling

Downscaling is a method that derives local- to regional-scale (10 to 100 km) information from larger-scale models or data analyses. Two main methods are distinguished: dynamical downscaling and empirical/statistical downscaling. The dynamical method uses the output of regional climate models, global models with variable spatial resolution or high-resolution global models. The empirical/statistical methods develop statistical relationships that link the large-scale atmospheric variables with local/regional climate variables. In all cases, the quality of the downscaled product depends on the quality of the driving model.

IPCC AR4 WGI

Drought

Drought can be defined in a number of ways. In general terms, drought is a 'prolonged absence or marked deficiency of precipitation', a 'deficiency that results in water shortage for some activity or for some group', or a 'period of abnormally dry weather sufficiently prolonged for the lack of precipitation to cause a serious hydrological imbalance'. Agricultural drought relates to moisture deficits in the topmost 1 meter or so of soil (the root zone) that affect crops, meteorological drought is mainly a prolonged deficit of precipitation, and hydrologic drought is related to below-normal streamflow, lake, and groundwater levels. A megadrought is a long-drawn out and pervasive drought, lasting much longer than normal, usually a decade or more.

IPCC AR4 WGI

El Niño Southern Oscillation (ENSO)

The term El Niño was initially used to describe a warm-water current that periodically flows along the coast of Ecuador and Perú, disrupting the local fishery. It has since become identified with a basin-wide warming of the tropical Pacific Ocean east of the dateline. This oceanic event is associated with a fluctuation of a global-scale tropical and subtropical surface pressure pattern called the Southern Oscillation. This coupled atmosphere-ocean phenomenon, with preferred time scales of two to about seven years, is collectively known as the El Niño-Southern Oscillation (ENSO). It is often measured by the surface pressure anomaly difference between Darwin and Tahiti and the sea surface temperatures in the central and eastern equatorial Pacific. During an ENSO event, the prevailing trade winds weaken, reducing upwelling and altering ocean currents such that the sea surface temperatures warm, further weakening the trade winds. This event has a great impact on the wind, sea surface temperature and precipitation patterns in the tropical Pacific. It has climatic effects throughout the Pacific region and in many other parts of the world, through global teleconnections. The cold phase of ENSO is called La Niña.

IPCC AR4 WGI

Emissions scenarios

A plausible representation of the future development of emissions of substances that are potentially radiatively active (e.g., greenhouse gases, aerosols), based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socioeconomic development, technological change) and their key relationships. Concentration scenarios, derived from emission scenarios, are used as input to a climate model to compute climate projections. In IPCC (1992) a set of emission scenarios was presented which were used as a basis for the climate projections in IPCC (1996). These emission scenarios are referred to as the IS92 scenarios. In the IPCC Special Report on Emission Scenarios new emission scenarios, the so-called SRES scenarios, were published, some of which were used, among others, as a basis for the climate projections presented in Chapters 9 to 11 of IPCC (2001) and Chapters 10 and 11 of this report. For the meaning of some terms related to these scenarios, see SRES scenarios.

IPCC AR4 WGI

Evapotranspiration

The combined process of evaporation from the Earth's surface and transpiration from vegetation.

IPCC AR4 WGI

Extreme

An extreme weather event is an event that is rare at a particular place and time of year. Definitions of rare vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of the observed probability density function. By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense. Single extreme events cannot be simply and directly attributed to anthropogenic climate change, as there is always a finite chance the event in question might have occurred naturally. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g., drought or heavy rainfall over a season).

IPCC AR4 WGI

Forcing

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

IPCC AR4 WGI

General Circulation Models

Climate model: (spectrum or hierarchy) A numerical representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes, and accounting for all or some of its known properties. The climate system can be represented by models of varying complexity, that is, for any one component or combination of components a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical or biological processes are explicitly represented, or the level at which empirical parameterizations are involved.

Coupled Atmosphere-Ocean General Circulation Models: (AOGCMs) provide a representation of the climate system that is near the most comprehensive end of the spectrum currently available. There is an evolution towards more complex models with interactive chemistry and biology (see Chapter 8). Climate models are applied as a research tool to study and simulate the climate, and for operational purposes, including monthly, seasonal and interannual climate predictions.

IPCC AR4 WGI

Greenhouse effect

Greenhouse gases effectively absorb thermal infrared radiation, emitted by the Earth's surface, by the atmosphere itself due to the same gases, and by clouds. Atmospheric radiation is emitted to all sides, including downward to the Earth's surface. Thus, greenhouse gases trap heat within the surface-troposphere system. This is called the greenhouse effect. Thermal infrared radiation in the troposphere is strongly coupled to the temperature of the atmosphere at the altitude at which it is emitted. In the troposphere, the temperature generally decreases with height. Effectively, infrared radiation emitted to space originates from an altitude with a temperature of, on average, –19°C, in balance with the net incoming solar radiation, whereas the Earth's surface is kept at a much higher temperature of, on average, +14°C. An increase in the concentration of greenhouse gases leads to an increased infrared opacity of the atmosphere, and therefore to an effective radiation into space from a higher altitude at a lower temperature. This causes a radiative forcing that leads to an enhancement of the greenhouse effect, the so-called enhanced greenhouse effect.

IPCC AR4 WGI

Greenhouse gas

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 thermal 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 and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. In addition to CO2, N2O and CH4, the Kyoto Protocol deals with the greenhouse gases sulphur hexafluoride (SF6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs).

IPCC AR4 WGI

Hydroclimatic variables

Physical parameters relevant to both hydrology and climate, including temperatures, precipitation, and snowpack.

Hydrologic drought

Hydrologic drought is related to below-normal streamflow, lake, and groundwater levels.

IPCC Technical Paper—Climate Change and Water

Interstate Compacts

Interstate waters are allocated under agreements between two or more states that govern specific interactions among those states, and require consent by the United States Congress. These compacts are intended to allow each state to exercise its own water law and to use its allocated water within its boundaries whenever it might choose.

IPCC

The Intergovernmental Panel on Climate Change (IPCC) established by World Meteorological Organization (WMO) and United Nations Environmental Programme (UNEP) provides an assessment of the state of knowledge on climate change based on peer-reviewed and published scientific/technical literature in regular time intervals.

Bureau of Reclamation
Climate Technical Work Group—Appendix U

IPCC Fourth Assessment Report

The Fourth Assessment Report "Climate Change 2007", also referred to as AR4 is a series of reports by the IPCC and provides an assessment of the current state of knowledge on climate change including the scientific aspects of climate change, impacts and vulnerabilities of human, natural, and managed systems, and adaptation and mitigation strategies.

Bureau of Reclamation
Climate Technical Work Group—Appendix U

Likelihood

The likelihood of an occurrence, an outcome or a result, where this can be estimated probabilistically.

IPCC Technical Paper—Climate Change and Water

Model bias

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

Model grid

Spatial scale represented in a climate model.

North American monsoon

The North American monsoon (NA monsoon), variously known as the southwest United States monsoon, the Mexican monsoon, or the Arizona monsoon, is experienced as a pronounced increase in rainfall from an extremely dry June to a rainy July over large areas of the southwestern United States and northwestern Mexico. These summer rains typically last until mid-September when a drier regime is re-established over the region. Geographically, the NA monsoon precipitation region is centered over the Sierra Madre Occidental in the Mexican states of Sinaloa, Durango, Sonora, and Chihuahua. The regime extends northward into the Arizona, New Mexico, and Colorado. Typically, the NA Monsoon region is defined by sites that receive at least 50% of its annual precipitation in July, August, and September.

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Pacific Decadal Oscillation

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

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Paleoclimate

Climate during periods prior to the development of measuring instruments, including historic and geologic time, for which only proxy climate records are available.

IPCC AR4 WGI

Palmer Drought Severity Index

An index formulated by Palmer (1965) that compares the actual amount of precipitation received in an area during a specified period with the normal or average amount expected during that same period. The PDSI is based on a procedure of hydrologic or water balance account by which excesses or deficiencies in moisture are determined in relation to average climatic values. Values taken into account in the calculation of the index include precipitation, potential and actual evapotranspiration, infiltration of water into a given soil zone, and runoff. This index builds on Thornthwaite's (1931; 1948) work; adding 1.) soil depth zones to better represent regional change in soil water-holding capacity; and 2.) movement between soil zones and, hence, plant moisture stress, that is, too wet or too dry.

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Prior Appropriations System

A simplified way to explain this system is often referred to as "first in time, first in right." An appropriation is made when an individual physically takes water from a stream (or underground aquifer) and places that water to some type of beneficial use. The first person to appropriate water and apply that water to use has the first right to use that water within a particular stream system. This person (after receiving a court decree verifying their priority status) then becomes the senior water right holder on the stream, and that water right must be satisfied before any other water rights can be fulfilled.

(http://water.state.co.us/wateradmin/prior.asp)
Colorado Division of Water Resources

PRISM

Parameter-elevation Regressions on Independent Slopes Model.

Projection

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

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Regional climate models

These models typically input the global model grids surrounding their geographical domain and then simulate wind, temperature, clouds, evapotranspiration, and other variables on a much finer grid.

SNOTEL

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

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Snow water equivalent (SWE)

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

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Streamflow

Water flow within a river channel, for example expressed in m3/s. Also a synonym for river discharge.

IPCC Technical Paper—Climate Change and Water

Time series analysis

Time series analysis, including trend analysis, uses statistical methods to analyze records from a period of time.

Urban heat island effect

Urban heat island (UHI) The relative warmth of a city compared with surrounding rural areas, associated with changes in runoff, the concrete jungle effects on heat retention, changes in surface albedo, changes in pollution and aerosols, and so on.

IPCC AR4 WGI

Variability

Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal 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 or external forcing (external variability).

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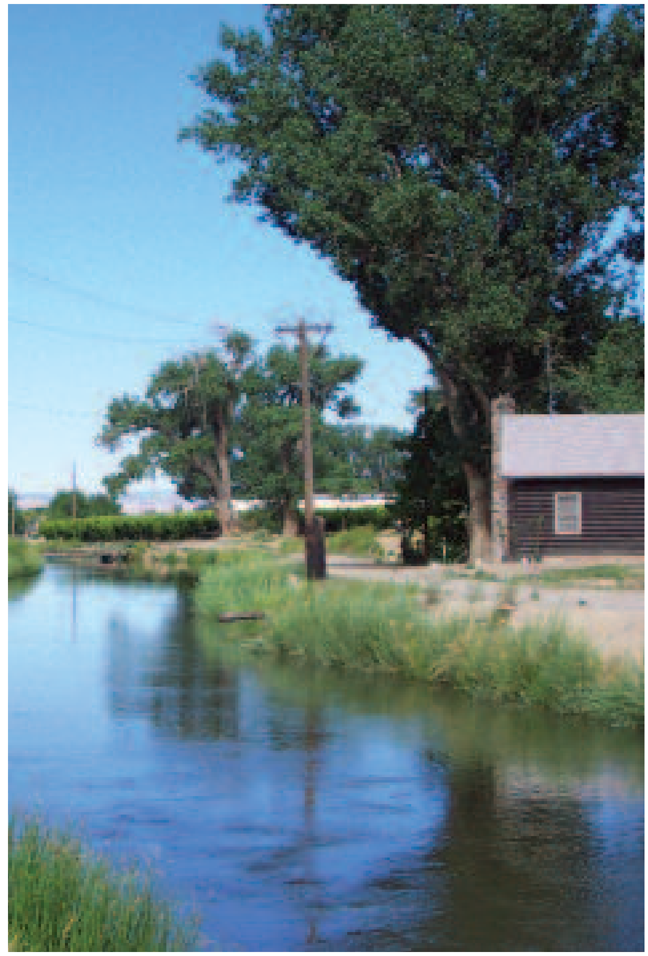
Water Year

The 12-month period, October 1 through September 30. The water year is designated by the calendar year in which it ends and which includes 9 of the 12 months. Thus, the year ending September 30, 1992, is called the “1992 water year.”

USGS, http://il.water.usgs.gov/glossary.html

Acronym List



AOGCM	Atmospheric-Oceanic General Circulation Models
AR4	Fourth Assessment Report of the IPCC
CCAP	Colorado Climate Action Plan
CCSM3	Community Climate System Model
CCSP	US Climate Chance Science Program
CMIP3	Coupled Model Intercomparison Program
COOP	National Weather Service Cooperative Observer Network
CT	Streamflow Central Tendency
ENSO	El Niño Southern Oscillation
FRCVG	Front Range Climate Vulnerability Group
GCM	General Circulation Models
GHG	Greenhouse Gas
HADCM3	Hadley Centre Coupled Model Version 3
IPCC	Intergovernmental Panel on Climate Change
MM5	Mesoscale Model
NARCCAP	North American Regional Climate Change Assessment Project
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resource Conservation Service
NWS	National Weather Service
OGCM	Oceanic General Circulation Models
PCM	Parallel Climate Model
PDSI	Palmer Drought Severity Index
PRISM	Parameter-elevation Regressions on Independent Slopes Model
RCM	Regional Climate Models
SAP	Synthesis and Assessment Product (of the CCSP)
SDSM	Statistical Downscaling Model
SNOTEL	Snowpack Telemetry
SNTHERM	Snow Thermal Model
SRES	Special Report on Emissions Scenarios
SWE	Snow Water Equivalent
SWE/P	Snow Water Equivalent Normalized by Precipitation
TAR	Third Assessment Report of the IPCC
WGI	Working Group I of the IPCC
WWA	Western Water Assessment

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