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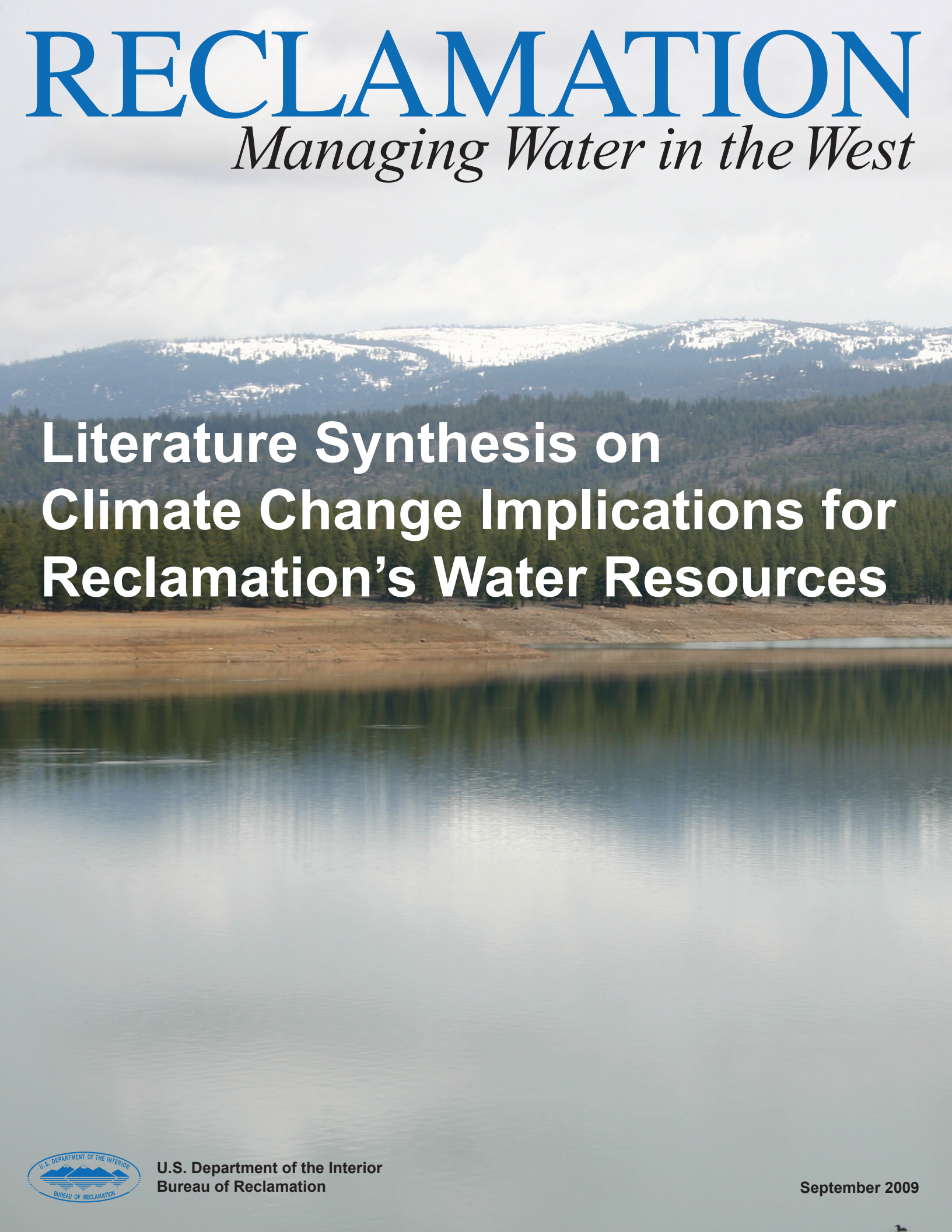
Managing Water in the West



Literature Synthesis on Climate Change Implications for Reclamation's Water Resources

U.S. Department of the Interior
Bureau of Reclamation

September 2009

Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Literature Synthesis on Climate Change Implications for Reclamation's Water Resources

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Acronyms

AR4 – the IPCC's Fourth Assessment Report

CA DWR – California Department of Water Resources

CAT – Climate Action Team

C-CAWWG – Climate Change and Western Water Group

CCSP – Climate Change Science Program

cm – centimeter

CMIP – Coupled Model Intercomparison Project

CMIP3 – Coupled Model Intercomparison Project phase 3(see Appendix C, Glossary of Terms)

CO_2 – carbon dioxide

CRRM – Clorado River Reservoir Model

CRSS – Colorado River Storage System

CVP – Central Valley Project

DHSVM – Distributed Hydrology Soil Vegetation Model

CT – center timing

EIS – environmental impact statement

ENSO – El Niño Southern Oscillation (see Appendix C, Glossary of Terms)

ESA – Endangered Species Act

ET – evapotranspiration

FAR – IPCC Fourth Assessment Report

FEIS – final environmental impact statement

GCM – global climate model or general circulation model (see Appendix C, Glossary of Terms, Climate Model)

GMT – global mean temperature

GHG – greenhouse gas (see Appendix C, Glossary of Terms)

GWSIM IV – Groundwater Simulation Model

HUMUS – Hydrologic Unit Model of the United States

IPCC – International Panel on Climate Change

ISB – Independent Science Board

LC – Lower Colorado

MAF – million acre-feet (see Appendix C, Glossary of Terms)

MP – Mid-Pacific

NEPA – National Environmental Policy Act (see Appendix C, Glossary of Terms)

PCM – Parallel Climate Model

PDO – Pacific decadal oscillation (see Appendix C, Glossary of Terms)

PDSI – Palmer Drought Severity Index
PN – Pacific Northwest
PPR – prairie pothole region
PRISM – Precipitation Regression on Independent Slopes Method
R&D – research and development
Reclamation – Bureau of Reclamation
SAP – Synthesis and Assessment Product
SFE –snowfall liquid water equivalent
SRES – Special Report on Emissions Scenarios
SWAT – Soil Water Assessment Tool
SWE – snow water equivalent (see Appendix C, Glossary of Terms)
SWP – State Water Project
UC – Upper Colorado
USHCN – United States Historical Climatology Network
VEMAP – Vegetation/Ecosystem Modeling and Analysis Project
VIC – Variable Infiltration Capacity Model (see Appendix C, Glossary of Terms)
WCRP – World Climate Research Programme
WETSIM 3.1 – Wetland Simulation Model
°C – degrees Celsius
°F – degrees Fahrenheit
% – percent
~ – approximately

1.0 Introduction

The Bureau of Reclamation's (Reclamation) mission involves managing water and power systems in an economically efficient and environmentally sensitive manner. Mission requirements often involve conducting planning studies for the longer term, potentially involving proposed system changes (e.g., changes in criteria that would govern operations for the long term, changes in physical system aspects). For these longer-term studies, questions arise on the how consideration of climate change might affect the assessment of benefits and costs for the various planning alternatives under evaluation. Such questions may lead to the analytical treatment of climate change implications for the study. However, such analysis would be predicated on a documented understanding that chosen analytical methods and usage of climate change information are consistent with the scientific understanding of climate change and the published scientific and assessment literature.

This report aims to support longer-term planning processes by providing region-specific literature syntheses on what already has been studied regarding climate change implications for Reclamation operations and activities in the 17 Western States. These narratives are meant for potential use in planning documents (e.g., National Environmental Policy Act [NEPA] environmental impact statements, biological assessments under Federal/State Endangered Species Act [ESA], general planning feasibility studies). It is envisioned that this report would be a living document, with literature review and synthesis narratives updated annually to take advantage of ongoing research developments.

1.1 Background

Development of this report was motivated by discussion at the February 2008 research scoping workshop convened by the Climate Change and Western Water Group (C-CAWWG)[1], involving Federal Western water managers and researchers. C-CAWWG was founded by research groups in three Federal agencies of C-CAWWG located in the Colorado Front Range region: Reclamation, the U.S. Geological Survey (USGS), and National Oceanic and Atmospheric Administration (NOAA). The primary purpose of C-CAWWG is to ensure efficient research and development (R&D) collaborations and sharing of information across Federal agencies toward understanding and addressing climate change impacts on Western United States water supplies and water use.

[1] See Notes for the C-CAWWG February 2008 Workshop "Research & Development Roadmap: Managing Western Water as Climate Changes – Knowledge Gaps and Initial Research Strategies and Projects," at http://www.esrl.noaa.gov/psd/workshops/mwwcc/docs/Workshop_Notes_080714.pdf.

At the February 2008 workshop, water operations and environmental compliance managers discussed Reclamation's water resources planning processes, their perceptions on required capabilities in incorporating climate change information into such planning processes, and their views on the status of capabilities at that time. Gaps between required and current capabilities were discussed. One such gap was having region-specific literature syntheses that could be used to provide common support to the multitude of longer-term planning processes that might be occurring in a given region at any given time. Motivations for addressing this gap included ensuring consistent discussion of climate change implications in a given region's planning documents and also efficient development of these narratives rather than reinventing the narrative uniquely for each planning process.

Development of this literature synthesis for use in long-term planning processes was given high priority during a February 2008 C-CAWWG workshop. Following the workshop, Reclamation's Research and Development Office commissioned the Technical Service Center Water Operations and Planning Support Group to conduct literature reviews and develop a collection of region-specific literature syntheses to address this capability gap. This document represents a first product of that effort, featuring both synthesis framework and a bibliography of reviewed literature.

1.2 About This Document

The scope of the report is to offer a summary of recent literature on the past and projected effects of climate change on hydrology and water resources (chapter 2) and to then summarize implications for key resource areas featured in Reclamation planning processes (chapter 3). In preparing the synthesis, the literature review considered documents pertaining to general climate change science, climate change as it relates to hydrology and water resources, and application of climate change science in Western United States and region-specific planning assessments. Most of the documents reviewed consist of anonymously peer-reviewed scientific literature. Certain other documents, such as national and regional assessments, were included because of their comprehensive nature and/or for management-related perspectives. The effort did not involve conducting any new analyses.

Appendix A provides capsule descriptions of many of the studies included in this synthesis narrative. Appendix B provides map resources which describe geographic climate change information evident in current climate projections. The report and appendices are organized with respect to each of Reclamation's five regions: Pacific Northwest, Mid-Pacific, Lower Colorado, Upper Colorado, and Great Plains.

The primary audience for this report is meant to be Reclamation staff involved in planning and environmental compliance activities. Other potential audiences

include staff from other Reclamation divisions, other government agencies, and nongovernment entities associated with Reclamation projects and activities.

This 2009 version of the report generally is informed by literature surveyed through summer 2008 (although there are several exceptions, as cited). The literature survey was not exhaustive but is offered as being representative of the state of the science.

2.0 Literature Summary on Hydrologic and Water Resources Impacts

This chapter presents a synthesis of climate change literature relevant to hydrology and water resources impacts in each of Reclamation's regions. Summaries generally are divided in terms of studies focused on historical or projected impacts and studies including projected climate change impacts to environmental resources and ecosystems. Summaries for the Mid-Pacific Region also include a section on sea level rise impacts. At present, there is a greater body of literature concerning historical and projected climate and hydrologic changes relative to literature on environmental resources and ecosystem impacts. Prioritization will be given to expanding sections on environmental resources and ecosystems impacts in future updates to the report.

2.1 Pacific Northwest Region

Numerous studies have been conducted on the potential consequences of climate change for water resources in Reclamation's Pacific Northwest (PN) Region. This section summarizes findings from recent studies (1994–2008) demonstrating evidence of regional climate change during the 20th century and exploring water resources impacts associated with various climate change scenarios.

2.1.1 Historical Climate and Hydrology

It appears that all areas of the PN Region became warmer, and some areas received more winter precipitation over the course of the 20th century. Cayan et al. (2001) reports that Western United States (U.S.) spring temperatures increased 1–3 degrees Celsius (ºC) (1.8–5.4 degrees Fahrenheit [ºF]) between 1970 and 1998. Regonda et al. (2005) reports increased winter precipitation trends during 1950–1999 at many Western U.S. sites, including several in the Pacific Northwest, but a consistent region-wide trend is not apparent over this period.

Coincident with these trends, the Western United States and PN Region also experienced a general decline in spring snowpack, reduced snowfall to winter precipitation ratios, and earlier snowmelt runoff between the mid- and late-20th century. Reduced snowpack and snowfall ratios are indicated by analyses of 1948–2001 snow water equivalent (SWE) measurements at 173 Western U.S. stations (Knowles et al., 2007). Regonda et al. (2005) evaluated 1950–1999 data from 89 stream gauges in the Western United States and reports peak runoff occurred earlier at most stations during the period and significant trends toward earlier runoff were found in the Pacific Northwest.

These findings are significant for regional water resources management and reservoir operations because snowpack has traditionally played a central role in determining the seasonality of natural runoff. In many PN Region headwater basins, the precipitation stored as snow during winter accounts for a significant portion of spring and summer inflow to lower elevation reservoirs. The mechanism for how this occurs is that (with precipitation being equal) warmer temperatures in these watersheds cause reduced snowpack development during winter, more runoff during the winter season, and earlier spring peak flows associated with an earlier snowmelt.

It is important to note that linear trends in hydrologically important variables (including springtime SWE, indices of runoff timing, and surface air temperature) are crucially dependent upon the time period considered in the analysis. Mote et al. (2008), for instance, show that SWE trends for the Washington and Oregon Cascades computed between start dates within a decade of 1955 and 2006 are robust, while those computed from later start dates differ dramatically, (and are statistically insignificant because the shorter-term variability is much larger than the longer-term linear trends). This sensitivity to start date is a direct result of the combined influences of natural interdecadal time scale climate variations and longer-term anthropogenic trends that are part of many climate records for the 20th century.

A recent collection of journal articles have targeted research at the question of *detection* and *attribution* of late 20th century trends in hydrologically important variables in the Western United States, aimed directly at better understanding the relative roles of anthropogenically forced versus natural origin climate variations in observed trends. Barnett et al.(2008) find that up to 60 percent (%) of the climate-related trends of Western U.S. river flow, winter air temperature, and snow pack from 1950 to 1999 are human-induced. Similar results are reported in related studies by Pierce et al. (2008) for springtime SWE, Bonfils et al.(2008) for temperature changes in the mountainous Western United States, and Hidalgo et al.(in press) for streamflow timing changes. An additional key finding of these studies is that the statistical significance of the anthropogenic signal is greatest at the scale of the entire Western United States and weak or absent at the scale of regional scale drainages with the exception of the Columbia River Basin (Hidalgo et al., in press).

2.1.2 Projected Future Climate and Hydrology

Given observed trends in regional warming and declining snowpack conditions, studies have been conducted to relate potential future climate scenarios to runoff and water resources management impacts. An early study by Hamlet and Lettenmaier (1999) evaluated potential future changes to Pacific Northwest climate relative to the ability of the Columbia River reservoir system to meet regional resource objectives. The authors report decreased summer streamflows up to 26% relative to the historic average would create significant increased

competition by water users. A subsequent study by Mote et al. (2003) included evaluations of impacts associated with climate change scenarios from numerous climate projections available at that time and reported findings suggesting that regional resources have a greater sensitivity to climate relative to what was previously understood.

Payne et al. (2004) evaluated hydrologic and reservoir operations impacts for the Columbia River Basin and explored mitigation options that might become necessary to balance the needs of the various water users. Their findings included that increased winter runoff may necessitate earlier dates of winter flood control drawdown relative to current dates. The most significant operational result was an increased competition for water supply between demands associated with instream flows and hydropower production. In order to maintain current levels of instream flows, a 10–20% reduction in firm hydropower production would be required.

2.1.3 Studies of Impacts on Environmental Resources

A study by Battin et al. (2007) focused on the impacts of climate change on the effectiveness of proposed habitat restoration efforts in the Snohomish River Basin of western Washington State. Based on climate model estimated mean air temperature increases of 0.7 to 1.0 ºC (1.1 to 1.8 ºF) by 2025 and 1.3 to 1.5 ºC (2.3 to 2.7 ºF) in 2050 relative to 2001 conditions, impacts on freshwater salmon habitat and productivity for Snohomish Basin Chinook salmon were found to be consistently negative. This study also found that scenarios for freshwater habitat restoration partially or completely could mitigate the projected negative impacts of anthropogenic climate change.

2.2 Mid-Pacific Region

Numerous studies have been conducted on the potential consequences of climate change for water resources in Reclamation’s Mid-Pacific (MP) Region. This section summarizes findings from recent studies (1994–2008) demonstrating evidence of regional climate change during the 20th century and exploring water resources impacts associated with various climate change scenarios. For the MP Region within California, Vicuna and Dracup (2007) offer an exhaustive literature review of past studies pertaining to climate change impacts on California hydrology and water resources.

2.2.1 Historical Climate and Hydrology

It appears that all areas of the MP Region became warmer, and some areas received more winter precipitation during the 20th century. Cayan et al. (2001) reports that Western U.S. spring temperatures increased 1–3 °C between the 1970s and late 1990s. Increasing winter temperature trends observed in central

California average about 0.5 °C per decade from the late 1940s to the early 1990s (Dettinger and Cayan, 1995). Regonda et al. (2005) reports increased winter precipitation trends during 1950–1999 at many Western U.S. sites, including several in California's Sierra Nevada, but a consistent region-wide trend is not apparent.

Coincident with these trends, the Western United States and MP Region also experienced a general decline in spring snowpack, reduced snowfall to winter precipitation ratios, and earlier snowmelt runoff from the late 1940s to early 2000s. Reduced snowpack and snowfall ratios are indicated by analyses of 1948–2001 SWE measurements at 173 Western U.S. stations (Knowles et al., 2007). Regonda et al. (2005) reports monthly SWE trends during 1950–1999 and suggests that there were statistically significant declines in monthly SWE over roughly half of the Western U.S. sites evaluated for the period 1970–1998. Peterson et al. (2008) also found earlier runoff trends in an analysis of 18 Sierra Nevada river basins with various periods beginning between 1947 and 1961 and ending between 1988 and 2002.

These findings are significant for regional water resources management and reservoir operations because snowpack traditionally has played a central role in determining the seasonality of natural runoff. In many MP Region headwater basins, the precipitation stored as snow during winter accounts for a significant portion of spring and summer inflow to lower elevation reservoirs. The mechanism for how this occurs is that (with precipitation being equal) warmer temperatures in these watersheds causes reduced snowpack development during winter, more runoff during the winter season, earlier spring peak flows associated with an earlier snowmelt.

The extent to which observed trends are due to climate change is a subject of ongoing research. Barnett et al. (2008) performed a multiple variable formal detection and attribution study and showed how the changes in minimum temperature (Tmin), SWE, precipitation and center timing (CT) for the period 1950–1999 co-vary. They concluded, with a high statistical significance, that up to 60% of the climatic trends in those variables are human-related. Similar results are reported in related studies by Pierce et al. (2008) for springtime SWE, Bonfils et al.(2008) for temperature changes in the mountainous Western United States, and Hidalgo et al.(in press) for streamflow timing changes. An additional key finding of these studies is that the statistical significance of the anthropogenic signal is greatest at the scale of the entire Western United States, and weak or absent at the scale of regional scale drainages with the exception of the Columbia River Basin (Hidalgo et al., in press). Bonfils et al. (2007) reports that 1914–1999 and 1950–1999 observed temperature increase trends at eight California sites are inconsistent with model-based estimates of natural internal climate variability, which implies that there were external agents forcing climate during the evaluation period. The authors suggest that the warming of California's winter over the second half of the 20th century is associated with human induced changes

in large-scale atmospheric circulation. Cayan et al. (2001) reports that warmer-than-normal spring temperatures observed in the Western United States were related to larger scale atmospheric conditions across North America and the North Pacific, but whether these anomalies are due to natural variability or are a symptom of global warming is not certain.

2.2.2 Projected Future Climate and Hydrology

Given observed trends in regional warming and declining snowpack conditions, studies have been conducted to relate potential future climate scenarios to runoff and water resources management impacts. Many of these studies have been summarized already in a literature synthesis focused on California hydrology and water resources impacts under past and projected climate change (Vicuna and Dracup, 2007), which summarized studies completed through 2005. Representative findings from these studies are illustrated by Van Rheenan et al. (2004). They identified potential impacts of climate change on Sacramento-San Joaquin River Basin hydrology and water resources and evaluated alternatives that could be explored to reduce these impacts. Five climate change scenarios were evaluated under various alternatives. Under the current operations alternative, releases to meet fish targets and historic hydropower levels would decrease during the 21st century. Under a conceptual "best case" comprehensive management alternative, average annual future system performance to meet fish targets would improve over current operations slightly, but in separate months and in individual systems, large impairments still would occur. Following studies by Anderson et al. (2008) and Brekke et al. (2009) suggest operations impacts generally consistent with those reported by Van Rheenan et al. (2004) but for more recently developed climate projection scenarios. Brekke et al. (2009) also explored impacts possibilities within a risk assessment framework, considering a greater number of climate projections, and considering how assessed risk is sensitive to choices in analytical design (e.g., whether to weight projection scenarios based on projection consensus, whether to adjust monthly flood control requirements based on simulated runoff changes). Results showed that assessed risk was more sensitive to future flood control assumptions than to consensus-based weighting of projections.

Switching from hydrologic to water demand impacts, Baldocchi and Wong (2006) evaluated how increasing air temperature and atmospheric carbon dioxide (CO_2) concentration may affect aspects of California agriculture, including crop production, water use, and crop phenology. They also offered a literature review and based their analysis on plant energy balance and physiological responses affected by increased temperatures and CO_2 levels, respectively. Their findings include that increasing air temperatures and CO_2 levels will extend growing seasons, stimulate weed growth, increase pests, and may impact pollination if synchronization of flowers/pollinators is disrupted.

2.2.3 Studies of Impacts on Environmental Resources

Chapter 5 of Synthesis and Assessment Product (SAP) 4.3 discusses how biodiversity may be affected by climate change (Janetos et al., 2008), and indicates that many studies have been published on the impacts of climate change for individual species and ecosystems. Cayan et al. (2001) document earlier blooming of lilacs and honeysuckles correlated to increasing spring temperatures.

2.2.4 Studies on Historical Sea Level Trends and Projected Sea Level Rise Under Climate Change

Sea level conditions at San Francisco Bay's Golden Gate determine water level and salinity conditions in the upstream Sacramento-San Joaquin Delta. Over the 20th century, sea levels near San Francisco Bay increased by more than 0.21 meters (Anderson et al., 2008). Some tidal gauge and satellite data indicate that rates of sea level rise are accelerating (Church et al., 2006; Beckley et al., 2007). Sea levels are expected to continue to rise due to increasing air temperatures which will cause thermal expansion of the ocean and melting of land-based ice, such as ice on Greenland and in southeastern Alaska (International Panel on Climate Change [IPCC], 2007).

On the matter of sea level rise under climate change, the IPCC AR4 from Working Group I (Chapter 10, "Sea Level Change in the 21st Century" (IPCC, 2007)) provides projections of global average sea level rise that primarily represent thermal expansion associated with global air temperature projections from current global climate models (GCMs). These GCMs do not fully represent the potential influence of ice melting on sea level rise (e.g., glaciers, polar ice caps). Given this context, inspection of figure 10.31 in IPCC, 2007 suggests a global average sea level rise of approximately 3 to 10 centimeters (cm)(or 1 to 4 inches) by roughly 2035 relative to 1980–1999 conditions. These projections are based on Coupled Model Intercomparison Project Phase 3 (CMIP3) models' simulation of ocean response to atmospheric warming under a collection of greenhouse gas (GHG) emissions paths. The report goes on to discuss local deviations from global average sea level rise due to effects of ocean density and circulation change. Inspection of figure 10.32 in IPCC, 2007 suggests that sea level rise near California's Golden Gate should be close to the global average rise, based on CMIP3 climate projections associated with the A1b emissions path.

As noted, the current GCMs do not fully account for potential ice melt in their sea level rise calculations and, therefore, miss a major source of sea level rise. Bindoff et al. (2007) note that further accelerations in ice flow of the kind recently observed in some Greenland outlet glaciers and West Antarctic ice streams could substantially increase the contribution from the ice sheets, a possibility not reflected in the CMIP3 projections. Further, the sea level data associated with direct CMIP3 output on sea level rise potentially are unreliable due to elevation datum issues.

A separate approach for estimating global sea level rise (Rahmstorf 2007) uses the observed linear relation between rates of change of global surface air temperature and sea level, along with projected changes in global surface air temperature. Following this approach, the CALFED Independent Science Board (ISB) estimated a range of sea level rise at Golden Gate of 1.6–4.6 feet (ft) (50–140 cm) by the end of the century (CALFED ISB, 2007). Likewise, the California Department of Water Resources (CA DWR) applied this approach using the 12 future climate projections selected by the Climate Action Team (CAT) (CA DWR, 2009) to estimate future sea levels. At mid-century, sea level rise estimates based on the 12 future climate projections ranged from 0.8 to 1.0 ft with an uncertainty range spanning 0.5 to 1.3 ft. By the end of the century, sea level rise projections ranged from 1.8 to 3.1 ft, with an uncertainty range spanning from 1.0 to 3.9 ft. These estimates are slightly lower than those from the Rahmstorf (2007) study because the maximum projected air temperature increase in that study was 5.8 °C (10.4 °F), and the maximum projected air temperature increase for the 12 future climate projections selected by the CAT was 4.5 °C (8.1 °F). It should be noted that projections using this air temperature-sea level rise relationship represent the average sea level rise trend and do not reflect water level fluctuations due to factors such as astronomical tides, atmospheric pressure changes, wind stress, floods, or the El Niño/Southern Oscillation.

2.3 Lower Colorado Region

Numerous studies have been conducted on observed climate change trends and potential impacts for water resources in Reclamation's Lower Colorado (LC) Region. Many of these studies have been summarized already in two available literature syntheses. The first focuses on California hydrology and water resources and summarized studies completed through 2005 (Vicuna and Dracup, 2007). Although the majority of the information in this document pertains to central and northern California, some studies have geographic focus that extends into the LC Region. The second literature synthesis (Reclamation, 2007) focuses on Colorado River Basin studies, addressing water resources in both the Upper Colorado (UC) and LC Regions. It was prepared as appendix U for the *Final Environmental Impact Statement, Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead* (i.e., Shortage Guidelines FEIS). It includes studies that had been published through early 2009.

The summaries of hydrologic and water resources trends and impacts provided in this section are consistent with the key themes offered in these preceding efforts.

2.3.1 Historical Climate and Hydrology

It appears that all areas of the LC Region have become warmer during the 20th century, but the causes of precipitation trends are more uncertain. Cayan

et al. (2001) reports that Western U.S. spring temperatures have increased 1–3 ^{o}C since the 1970s. Based on data available from the Western Climate Mapping Initiative,[2] the change in 11-year annual mean during the 20th century is roughly +1.2 °C for the Upper Colorado River Basin and +1.7 °C for the Lower Colorado River Basin.[3] Groisman et al. (2004; figure 4), using gridded U.S. Historical Climate Network (USHCN) stations data, note annual mean and minimum temperature increases of 1–2°C for most of the LC Region for the period 1900–2002, and 2–4°C spring minimum temperature increases throughout most of the LC Region (figure 5). Mote et al. (2005; Figure 6) document positive linear trends in winter temperature of up to 4°C at LC Region USHCN stations, for the periods 1930–1997 and 1950–1997. Hoerling et al. (2007) report a net summer season warming of 0.9 °C since 1951 in the Southwest, with very high confidence that the warming exceeds levels of natural climate variability. Weiss and Overpeck (2005) show significant positive temperature trends in Sonoran Desert weather stations (1960–2000), with widespread spatially coherent trends evident in January, February, March, and May. Moreover, Weiss and Overpeck (2005) note an increase in the length of the frost-free season in the heart of the Sonoran Desert, which corroborates similar findings in a study of U.S. trends in numbers of frost days and dates of first and last frosts (Easterling, 2002). For the LC Region, the number of winter and spring frost days in the second half of the 20th century decreased, the date of the last spring frost arrives earlier in the year, and the date of the first fall frost arrives later in the year (Easterling, 2002). Sheppard et al. (2002) report that the most prominent feature in low-frequency variability in a 400-year-long reconstruction of Southwest summer temperatures is the recent increase in regional temperature; the Southwest region cited in Sheppard et al. stretches from Texas to California. All of the aforementioned results demonstrate various nuances of the overall increase in temperatures across the LC region.

Over the periods 1930–1997 and 1950–1997, winter precipitation has increased in the LC Region, exhibiting increasing trends of over 60% at USHCN stations prior to onset of extended drought in the late 1990s; this result is corroborated by Regonda et al. (2005), who find statistically significant increases in winter precipitation (November–March total) for the majority of the LC region NOAA Coop Network stations during 1950–1999. For the period 1900–2002, Groisman et al. (2004; figure 6) show a mix of annual precipitation trends in gridded USHCN stations in the LC Region, with clear declines in the western part of the region but increases in the eastern part of the region. Investigations for the period 1916–2003, by Hamlet et al. (2005), show that precipitation variability is most strongly associated with multidecade variability, rather than long-term trends. Hamlet et al. (2005) conclude that "[although] the precipitation trends from 1916

[2] http://www.cefa.dri.edu/Westmap/.

[3] Computed as difference in 11-year mean annual T during period centered on 2001 (i.e., 1996–2006) minus that during period centered on 1901 (i.e., 1896–1906).

to 2003 are broadly consistent with many global warming scenarios, it is not clear whether the modestly increasing trends in precipitation that have been observed over the Western United States for this period are primarily an artifact of decadal variability and the time period examined, or are due to longer-term effects such as global warming."

Andreadis and Lettenmaier (2006) examined drought-related parameters over the period 1915–2003, using model-generated data and found that the Southwest (including the LC Region) was one of the few coherent regions of increasing drought severity in the contiguous United States—despite evidence of increased soil moisture over the southeastern half of the LC region. Groisman and Knight (2008) show that the mean duration of prolonged dry spells in the Southwestern United States during the last 40 years (1951–2005) has increased. Sheppard et al. (2002), who examined moisture variations in the Southwest (a region that encompasses most of the LC Region) using the Palmer Drought Severity Index (PDSI) during the last 300 years (but prior to the 2000s drought in the Southwest), note no linear increase since 1700, but many substantial extended periods of drought. Other paleoclimate investigations of drought and streamflow also note multidecade variability and many periods of extended drought in the LC Region (e.g., Cook et al., 2004; MacDonald et al., 2008) and in streams feeding the LC Region, such as the Colorado River (Woodhouse et al., 2006; Meko et al., 2007). Recent investigations have shown strong connections between multiyear to multidecade drought and ocean-atmosphere variations in the Pacific and Atlantic Oceans (e.g., McCabe et al., 2004; MacDonald et al., 2008). The upshot of work examining historical and paleo-drought, is that drought and precipitation in the LC Region is primarily dominated by interannual and multidecade variations related to ocean-atmosphere interactions. T his conclusion is supported by detection and attribution studies by Hoerling and Eischeid (2007), who find that, during the last half century, it is likely that sea surface temperature anomalies have been important in forcing severe droughts in North America. Work by MacDonald et al. (2008) suggests that that ongoing radiative forcing (greenhouse gases, solar, and aerosols) and warming "could be capable of locking much of southwestern North America into an era of persistent aridity and more prolonged droughts." Hoerling and Eischeid (2007) partially agree with the aforementioned conclusion, as they state: "For the longer-term [drought] events, the effect of steady forcing through sea surface temperature anomalies becomes more important. Also, the accumulating greenhouse gases and global warming have increasingly been felt as a causative factor, primarily through their influence on Indian Ocean/West Pacific temperatures, conditions to which North American climate is sensitive. The severity of both short- and longterm droughts has likely been amplified by local greenhouse gas warming in recent decades."

Coincident with these trends, the Western United States and LC Region also experienced a general decline in spring snowpack, reduced fractions of winter precipitation occurring as snowfall, and earlier snowmelt runoff. Reduced

snowpack and snowfall fractions are indicated by analyses of 1949–2004 snowfall liquid water equivalent (SFE) and precipitation measurements at 207 Western U.S. National Weather Service cooperative observer stations (Knowles et al., 2007). Knowles et al. found that declines in the ratio of SFE to precipitation were greatest at mid-to-low elevations and during the months of January and March. They also determined that these declines were strongly related to warming trends, especially on wet days, and that multidecade variability, such as shifts in the Pacific Decadal Oscillation, could only partly explain the observed changes. Similarly, Mote et al. (2005) note strong correlations between temperature, winter season snowmelt events, and total April 1 SWE (snow water equivalent) at SNOTEL stations (USDA-NRCS automated Snowpack Telemetry) in the LC Region; SNOTEL stations are usually located in mountain environments and, thus, show observations at higher elevations than the stations examined by Knowles et al. These correlations imply that warming results in less April 1 SWE through the increased frequency of melt events and are consistent with evidence of declining spring snowpack across North America in the IPCC Fourth Assessment Report (IPCC, 2007). Mote (2006) used snow course, USHCN, and SNOTEL data to examine the causes of trends in April 1 SWE. Most of the LC Region snow course stations used by Mote are in Utah, Nevada, Arizona, and western New Mexico; and these show a mix of positive and negative trends; however, there are primarily negative SWE trends at low elevations, where there is a strong temperature dependence in the SWE declines. Regonda et al. (2005; figure 6) demonstrate that warm, dry “snow eating” temperature spells in the LC Region have been coming earlier in the year; dramatic impacts of dry spells were seen in the LC Region in 2004 (Pagano et al., 2004). These results are consistent with recent investigations by Barnett et al. (2008) and Bonfils et al. (2008) which show that Western U.S. declines in SWE and precipitation cannot be attributed to natural climate variability.

Knowles et al. (2007) note that warming during December–March have the greatest influence on snow deposition, whereas warming in April through June accelerate snow melt, which results in earlier center of mass of streamflow (Stewart et al., 2005). (Center of mass of streamflow is measured by the date when 50% of total annual streamflow is recorded). Earlier melt and center of mass have implications for reservoir storage and low flows following peak runoff Regonda et al. (2005) evaluated 1950–1999 data from 89 stream gauges in the Western United States and reports reduced SWE trends and peak runoff occurred earlier at most stations during the period; although, many of the sites examined in the LC region did not exhibit trends toward reduced SWE and earlier peak runoff. Stewart et al. (2005) demonstrates that trends toward earlier center of mass of spring streamflow in the Upper Colorado River Basin is well correlated with increasing temperatures, but this relationship is somewhat less robust in the LC Region.

These findings are significant for regional water resources management and reservoir operations because snowpack traditionally has played a central role in determining the seasonality of natural runoff. In many LC Region headwater basins, the precipitation stored as snow during winter accounts for a significant portion of spring and summer inflow to lower elevation reservoirs. The mechanism for how this occurs is that (with precipitation being equal) warmer temperatures in these watersheds cause reduced snowpack development during winter, more runoff during the winter season, and earlier spring peak flows associated with an earlier snowmelt.

2.3.2 Projected Future Climate and Hydrology

Given observed trends in regional warming and declining snowpack conditions, studies have been conducted to relate potential future climate scenarios to runoff and water resources management impacts.

There is greater agreement between model predictions, thus high confidence in future temperature change, but much less agreement in the sign of change, thus less confidence in projections for precipitation change for *middle latitude* regions (Dai, 2006) like the Upper Colorado River Basin. Projected precipitation changes for *subtropical* latitudes (e.g., the more southern parts of the LC Region) are generally more consistent and suggest a tendency toward less annual precipitation, reduced basin-wide runoff, decreased soil moisture, and increased evapotranspiration in the LC region (Milly et al., 2005; Seager et al., 2007; IPCC, 2007). It is important to note, however, that the GCMs used in the IPCC Fourth Assessment Report (FAR) poorly simulate characteristics of the summer monsoon circulation, which is important to the LC Region (Lin et al., 2008); the IPCC FAR shows a relative lack of agreement on summer precipitation projections over the LC Region for 14 models (A1B scenario) used in their end of 21st century projections (IPCC, 2007).

Diffenbaugh et al. (2005) used the RegCM3 regional climate model (SRES A2 scenario) to examine future changes in climate extremes, comparing 2071–2095 with 1961–1985 (reference). They found substantial and statistically significant increases in the number of days per year with maximum and minimum temperatures above the highest 5% of values in the reference period (i.e., extremely hot) as well as increases in the length of heat waves and an increased fraction of extreme precipitation events in the LC Region. Meehl et al. (2004), using the NCAR Parallel Climate Model (PCM) and an A2 emissions scenario noted a decrease in the annual number of frost days in the LC Region, when comparing 2080–2099 with 1961–1990. Tebaldi et al. (2006) also found an increasing incidence of heat waves over the LC Region, in experiments that used 9 GCMs with a variety of SRES scenarios. A detailed study of the aforementioned temperature-related parameters by Bell et al. (2004), using the RegCM2.5 regional climate model for a world with atmospheric CO_2 concentration doubled relative to *late 20th century conditions*, shows similar future trends for three

subregions of Southern California in the LC Region. These experiments essentially show that increases in extreme warm temperatures and decreases in extreme cool temperatures are consistent with mean warming due to human-caused climate change (enhanced radiative forcing). Moreover, increases in minimum and maximum temperatures, length of heat waves, and length of frost-free season suggest potential increases in demand for water and electric power.

Several studies have assessed hydrologic impacts on the Colorado River Basin based on future scenarios involving various temperature increases and precipitation changes. These studies include Revelle and Waggoner (1983), Nash and Gleick (1991 and 1993), Christensen et al. (2004), Milly et al. (2005), and Christensen and Lettenmaier (2007). All of these studies suggest some amount of runoff decrease in the Colorado River Basin due to climate change. However, estimates of potential decreases in inflows range broadly (6 to 45% by the middle of the 21st century). These studies were reviewed in Reclamation (2007), and the authors of that report offered some conclusions that put this projected runoff uncertainty into context. First, in order to sufficiently quantify the potential impacts of climate change, the information from climate projections needs to be evaluated at spatial scales relevant to those of hydrologic processes that control Colorado River Basin inflows. This raises questions about how spatial scale of analysis differed between these studies. For example, studies featuring relatively coarse scales of analysis, which tends to reduce nonlinear effects, such as higher runoff generation efficiency at high elevations (Lettenmaier et al., 2008), featured the relatively larger projected decreases (Milly et al., 2005; Hoerling and Eischeid ,2007), while those featuring a finer scale of hydrologic analysis, resulted in smaller projected decreases (e.g., Christensen and Lettenmaier, 2007).[4] In addition, the analysis by Milly et al. (2005) did not attempt to downscale GCM estimates of future climate parameters. Second, hydrologic impacts over the short-term future (e.g., 20 years or less) may be more significantly associated with climate variability than projected climate change over the near term, which bears influence on the scoping of planning analyses focused on short-term future decisions.[5] Third, the choice of GCMs and emissions scenarios used in the

[4] Subsequent to the completion of Reclamation (2007), four NOAA Regional Integrated Science and Assessment centers (Western Water Assessment, California Applications Program, Climate Impacts Group, and Climate Assessment of the Southwest) embarked on a collaborative effort to reconcile runoff projections for the Colorado River Basin. Their effort includes consideration for method differences related to scale, hydrologic process representation, and the decision whether to bias-correct climate model output. Information on project status is available at http://wwa.colorado.edu/current_projects/rcn_strmflw_corvr.htm.

[5] In addition to being complimented by appendix U, the Shortage Guidelines FEIS was also complimented by appendix N, a quantitatively sensitivity analysis relating an expanded sense of hydrologic variability to environmental impact statement (EIS) action alternatives and environmental impact analysis. Expanded assumptions of hydrologic variability were developed through stochastic modeling and the use of Colorado River (Lees Ferry) streamflow reconstructions based on roughly 1,200 years of tree ring records.

aforementioned studies also had some effect on the projected Colorado River Basin changes (Lettenmaier et al., 2008).

Two of the recent hydrologic impacts studies mentioned above went beyond Colorado River Basin hydrologic impacts to also assess operational impacts for the Colorado River system (Christensen et al. 2004; Christensen and Lettenmaier 2007). Reclamation 2007 summarizes operational impacts associated with these studies. Note that the operations models and various system assumptions featured in these studies differ from those used by Reclamation in development of the Shortage Guidelines FEIS. With that said; Christensen et al. (2004), using only the NCAR PCM and a "business as usual" emissions scenario, report that projected reservoir reliability and storage levels were extremely sensitive to inflow reductions, and average reservoir levels dropped significantly even with small reductions in runoff. The operations model results of Christensen and Lettenmaier (2007), using downscaled climate projections from an ensemble of 11 GCMs and multiple emissions scenarios, indicate 20 and 40% storage reductions result from respective 10 and 20% reductions in inflow, though projected reservoir storage for each time period analyzed by Christensen and Lettenmaier is sensitive to factors such as initial storage.

Subsequent to Reclamation 2007, two other studies were conducted, relating recent climate and runoff projections information to system impacts (McCabe and Wolock, 2007; Barnett and Pierce, 2008). McCabe and Wolock (2007) concluded that if future warming occurs in the basin and is not accompanied by increased precipitation and if consumptive water use in the Upper Colorado River Basin remains the same as at present, then the basin is likely to experience periods of water supply shortages more severe than those inferred from a tree ring reconstruction of annual Colorado River streamflow at Lees Ferry, for the period 1490–1997. Barnett and Pierce (2008) showed results that suggested similar but more severe impacts. They used a combined Lake Powell and Lake Mead water budget model to assess storage response to hydrologic scenarios involving 10 to 30% flow reductions occurring during 2008–2060. Their analysis indicates a 50% chance for the system to go dry by 2028 under a 20% flow reduction scenario (inspired by the range of reductions portrayed in the preceding runoff impacts studies). However, this result appears to be sensitive to their treatment of several assumptions, which differs significantly from the treatment of the same assumptions in Reclamation modeling studies involving the Colorado River Basin.[6]

Ellis et al. (2008) used downscaled GCM temperature and precipitation changes as inputs to a water balance model for Arizona's Salt and Verde River basins to assess runoff at mid-century; the Salt River is a tributary to the Colorado River.

[6] Assumptions in question are Lower Basin water supply (i.e., intervening inflows between Lake Powell and Lake Mead), reservoir evaporation, and reservoir management responses that would occur if low inflows were to persist for long periods of time.

Using a variety of Special Report on Emission Scenarios (SRES) scenarios, from B1 (low emissions) to the A1FI (the highest rate of emissions—so called "fossil intensive") and 6 GCMs, they found that in only 3 of 20 model-scenario combinations did Salt-Verde runoff increase; the mean runoff was 77.4% of 1961–1990 historical levels. Serrat-Capdevila et al. (2007) modeled recharge for the San Pedro River Basin, a second order tributary of the Colorado River, using a statistically downscaled ensemble of 17 GCMs for a variety of emissions scenarios. They processed the downscaled GCM outputs in a transient three-dimensional groundwater-surface flow model, maintaining groundwater extraction at current rates and found that recharge will decrease 17–30% by 2100, depending on the emissions scenario, and riparian area baseflow will decrease by 50%.

Switching from supply to demand impacts, Baldocchi and Wong (2006) evaluated how increasing air temperature and atmospheric CO_2 concentration may affect aspects of California agriculture, including crop production, water use, and crop phenology. They also offered a literature review and based their analysis on plant energy balance and physiological responses affected by increased temperatures and CO_2 levels, respectively. Their findings include that increasing air temperatures and CO_2 levels will extend growing seasons, stimulate weed growth, increase pests, and may impact pollination if synchronization of flowers/pollinators is disrupted.

2.3.3 Studies of Impacts on Environmental Resources

Projected climate changes are likely to have an array of interrelated and cascading ecosystem impacts with feedbacks to runoff volume, water quality, evapotranspiration, and erosion (Lettenmaier et al., 2008; Ryan et al., 2008). One of the most obvious effects of climate change on ecosystems and watershed hydrology is through observed and projected changes to disturbances, such as wildland fires and forest dieback. Warm season temperatures, which have increased in the Western United States, attenuate snow melt and soil and fuel moistures, which, in turn, affect wildland fire activity. Westerling et al. (2006) have documented large increases in fire season duration and fire frequency, especially at mid-elevations, in the Western United States Hot and dry weather allows fires to grow exponentially, covering more acreage (Lettenmaier et al., 2008). Brown et al. (2004) and McKenzie et al. (2004) project increases in numbers of days with high fire danger and acres burned, respectively, as a result of increasing temperatures and related climate changes. Miller and Schlegel (2006) project a longer fire season in coastal southern California as a result of changes in atmospheric circulation that control the timing and extent of Santa Ana winds. Fire disturbance can spread to new ecosystems as nonnative species, favored by increased temperatures (e.g., buffel grass in southern Arizona), colonize ecosystems that have no history of adaptation to fire (Ryan et al., 2008).

Climate changes can also trigger synergistic effects in ecosystems through triggering multiple nonlinear or threshold-like processes that interact in complex ways (Allen, 2007). For example, increasing temperatures and their affects on soil moisture are a key factor in conifer species die-off in western North America (Breshears et al., 2005). Increased temperatures are also a key factor in the spread and abundance of the forest insect pests that also have been implicated in conifer mortality (Logan et al., 2003; Williams et al., 2008). The one-two punch of temperature driven moisture stress on trees and the enhanced life cycles and ranges of insect pests kill large swaths of forest, triggering changes in ecosystem composition and flammability, hence a cascading series of impacts such as decreased soil retention, and increased aeolian and fluvial erosion. Combined with fire disturbance and projected increases in LC Region aridity, abrupt nonlinear ecosystem changes have the potential to impact water quality, sedimentation behind reservoirs, wildlife species abundance, and even mountain snowpack melt rates—as dust is transported from disturbed areas to distant mountains (Painter et al., 2007).

Chapter 5 of SAP 4.3 discusses how biodiversity may be affected by climate change (Janetos et al., 2008) and indicates that many studies have been published on the impacts of climate change for individual species and ecosystems. Cayan et al. (2001) document earlier blooming of lilacs and honeysuckles correlated to increasing spring temperatures.

2.4 Upper Colorado Region

Numerous studies have been conducted on observed climate change trends and potential impacts for water resources in Reclamation's UC Region. Many of these studies summarized already in a literature synthesis (Reclamation, 2007) focused on Colorado River Basin studies, which was prepared as appendix U for the *Final Environmental Impact Statement, Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead* (i.e., Shortage Guidelines FEIS). The synthesis included studies that had been published through early 2009.

The summaries of hydrologic and water resources trends and impacts pertaining to the Colorado River Basin in this section are consistent with the key themes offered in Reclamation (2007). They also summarize a representative mix of past studies focused on the Rio Grande Basin.

2.4.1 Historical Climate and Hydrology

It appears that much of the UC Region became warmer during the 20th century but precipitation trends are less evident. Cayan et al. (2001) reports that Western U.S. pring temperatures increased 1–3 ^{o}C (1.8–5.4 ^{o}F) between 1970 and 1998. Based

on data available from the Western Climate Mapping Initiative,[7] the change in the 11-year mean during the 20th century is roughly +1.2 °C (+2.2 ºF) for the Upper Colorado River Basin and +1.7 °C (+3.1 ºF) for the Lower Colorado River Basin.[8]

Regarding the Rio Grande Basin, D'Antonio (2006) reports that in northern New Mexico, recent annual average temperatures have been more than 2 ºF (1.1 ºC) above mid-20th century values.

Coincident with these trends, the Western United States and UC Region also experienced a general decline in spring snowpack, reduced fractions of winter precipitation occurring as snowfall, and earlier snowmelt runoff. Reduced snowpack and snowfall fractions are indicated by analyses of 1948–2001 snow SWE measurements at 173 Western U.S. stations (Knowles et al., 2007). Regonda et al. (2005) reports monthly SWE trends during 1950–1999 and suggests that there were statistically significant declines in monthly SWE over roughly half of the Western U.S. sites evaluated for the period 1970–1998. Among those sites, there was no regional consensus among SWE trends over southern Montana to Colorado; however, the regional consensus over western Montana appeared to be a decrease in monthly SWE.

Studies that document decreasing snowpack and earlier runoff in the Colorado River Basin include Hamlet et al. (2005) and Stewart et al. (2004). Passell et al. (2004) report a trend of increasing Rio Grande discharge for the months of January, February, and March during 1975–1999 relative to the 1895–1999 period of record; however, no peak flow trends were identified.

These findings are significant for regional water resources management and reservoir operations because snowpack has traditionally played a central role in determining the seasonality of natural runoff. In many UC Region headwater basins, the precipitation stored as snow during winter accounts for a significant portion of spring and summer inflow to lower elevation reservoirs. The mechanism for how this occurs is that (with precipitation being equal) warmer temperatures in these watersheds causes reduced snowpack development during the cold season, more runoff during the winter season, and earlier spring peak flows associated with an earlier snowmelt.

2.4.2 Projected Future Climate and Hydrology

Given observed trends in regional warming and declining snowpack conditions, studies have been conducted to relate potential future climate scenarios to runoff and water resources management impacts.

[7] http://www.cefa.dri.edu/Westmap/.

[8] Computed as difference in 11-year mean annual T during period centered on 2001 (i.e., 1996–2006) minus that during period centered on 1901 (i.e., 1896–1906).

There is high confidence in future warming, though some uncertainty in the magnitude of warming, resulting in a range of estimates from different models. For example, D'Antonio (2006) reports that the projected mean-annual temperatures over New Mexico would increase by 3.3 °C (about 6 °F) 2061–2090 compared to the 1971–2000 average, based on the multimodel average from 18 of the CMIP3 models. There is less consensus about future precipitation, and the amount of consensus that exists in current climate projections varies from the northern to southern portions of the UC Region. For example, while projected precipitation changes for subtropical latitudes (e.g., Southwestern United States) are generally more consistent and suggest a tendency toward drier conditions (Milly et al., 2005; Seager, 2007), there is little consensus among projections on whether mean-annual precipitation will increase or decrease over the northern, or *mid-latitude*, portions of the UC Region (e.g., Dai, 2006). However, it appears that future *winter* precipitation in the mountainous areas of the UC Region may increase (Christensen and Lettenmaier, 2007). The coarse spatial resolution of climate models limits their ability to represent topographic effects related to snowfall, snowpack evolution, and regional precipitation patterns (Grotch and MacCracken, 1991; Giorgi and Mearns ,1991; Pan et al., 2004; Reclamation, 2007). Downscaling techniques may be used to recover some of this spatial detail. Much summer precipitation in this region is associated with the North American Monsoon which is poorly simulated in most climate models (Lin et al., 2008, Gutzler et al., 2005).

Several studies have assessed hydrologic impacts on the Colorado River system based on future scenarios involving various temperature increases and precipitation changes. These studies include Revelle and Waggoner (1983), Nash and Gleick (1991 and 1993), Christensen et al. (2004), Milly et al. (2005), Hoerling and Eischeid (2007), and Christensen and Lettenmaier (2007). All of these studies suggest some amount of runoff decrease in the Colorado River Basin due to climate change. However, estimates of potential decreases in inflows range broadly (6 to 45% reductions in natural flow at Lees Ferry). These studies were reviewed in Reclamation (2007), and the authors of that report offered some conclusions that put this projected runoff uncertainty into context. First, in order to sufficiently quantify the potential impacts of climate change, the information from climate projections needs to be evaluated at spatial scales relevant to those of hydrologic processes that control Colorado River Storage System (CRSS) inflows. This raises questions about how spatial scale of analysis differed between these studies. For example, studies featuring relatively coarse scales of analysis featured the relatively larger projected decreases (Milly et al., 2005; Hoerling and Eischeid, 2007) while those featuring a finer scale of hydrologic analysis, preceded by climate projection downscaling, resulted in smaller projected decreases (e.g., Christensen and Lettenmaier, 2007).[9] Second,

[9] Subsequent to the completion of Reclamation (2007), four NOAA Regional Integrated Science and Assessment centers (Western Water Assessment, California Applications Program, Climate Impacts Group, and Climate Assessment of the Southwest) embarked on a collaborative

hydrologic impacts over the short-term future (e.g., 20 years or less) may be more significantly associated with climate variability than projected climate change over the near term, which bears influence on the scoping of planning analyses focused on short-term future decisions.[10]

Several of the hydrologic impacts studies mentioned above went beyond Colorado River Basin hydrologic impacts to also assess operational impacts for the Colorado River Storage System (CRSS) (Nash and Gleick 1991 and 1993; Christensen et al. 2004; Christensen and Lettenmaier 2007). Reclamation 2007 summarizes operational impacts associated with these studies, which follow hydrologic impact featured in each study[11].

Subsequent to Reclamation, 2007, two other studies were conducted, relating recent climate and runoff projections information to CRSS impacts (McCabe and Wolock, 2007; Barnett and Pierce, 2008; Barnett and Pierce, 2009; Rajagopalan et al., 2009; and Barsugli et al.,2009." McCabe and Wolock (2007) concluded that if future warming occurs in the basin and is not accompanied by increased precipitation, then the basin is likely to experience periods of water supply shortages more severe than those inferred from the long-term (1490–1998) historical tree ring reconstruction (Woodhouse et al., 2006). Barnett and Pierce (2009), Rajagopalan et al.(2009) and Barsugli et al. (2009) use combined Lake Powell and Lake Mead water budget models to assess storage response to hydrologic scenarios involving 10 to 30% flow reductions occurring during 1985–2060. These analyses are in close agreement as to the risks posed to the system as a whole. They indicate a 50% chance for the system to go dry (reservoir storage completely depleted) at least once by the mid 2030s under a scenario of 20% flow reduction by the end of the period. The chance of drying is substantially lower under a 10% reduction scenario.").

Switching from the Colorado River Basin to the Rio Grande Basin, Hurd and Coonrod (2007) used a water balance hydrology model (WATBAL) to estimate future annual average reductions in Rio Grande flow ranging from 3.5 to 13.7% in 2030 and 8.3 to 28.7% in 2080 based on three GCM outputs corresponding to wet, middle, and dry and the SRES A1B emissions scenario relative to baseline period 1971–2000. Marinec and Rango (1989) modeled snowmelt runoff effects

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effort to reconcile runoff projections for the Colorado River Basin. Their effort includes consideration for method differences related to scale, hydrologic process representation, and the decision whether to bias-correct climate model output. Information on project status is available at http://wwa.colorado.edu/current_projects/rcn_strmflw_corvr.htm.

[10] In addition to being complimented by appendix U, the Shortage Guidelines FEIS was also complimented by a quantitative sensitivity analysis relating an expanded sense of hydrologic variability to EIS action alternatives. Expanded assumptions of hydrologic variability were developed through stochastic modeling and the use of Colorado River (Lees Ferry) streamflow reconstructions based on roughly 700 years of tree ring records (appendix N of that final EIS.

[11] The CRSS models and various system assumptions featured in these studies differ from those used by Reclamation in the development of the Shortage Guidelines FEIS.

under a 3 ºC (5.4 ºF) temperature increase for the Rio Grande Basin and reported respective April and May runoff increases of 158 and 89% based on 1983 conditions. D'Antonio (2006) reports that drastic reductions in Rio Grande spring runoff by the end of the century are likely based on evaluation of an 18-GCM average relative to a 1971–2000 average baseline.

As for effects on water demands, Ramirez and Finnerty (1996) evaluated the effects of increased air temperatures and atmospheric carbon dioxide on crops in the San Luis Valley of southern Colorado. Their findings suggested significant increases in potential evapotranspiration and potential impacts on crop yields. Hurd and Coonrod (2007) predict increased reservoir evaporation at middle and low elevation reservoirs in New Mexico based on the GCM results and hydrology modeling discussed above. However, these results are difficult to interpret given the uncertainties of observed trends in pan evaporation, as discussed in section 3.4.7.

2.4.3 Studies of Impacts on Environmental Resources

Hurd and Coonrod (2007) report that the greatest climate change related risk in New Mexico is to ecosystems. They report that reduced snow pack, earlier runoff, and higher evaporative demands due to climate change will affect vegetative cover and species' habitat in New Mexico's Rio Grande Basin. They also discuss potential adverse water quality (including increased water temperatures) and reduced streamflow impacts that will affect aquatic habitat.

2.5 Great Plains Region

A limited number of studies have been conducted on the potential consequences of climate change for water resources that are specific to Reclamation's Great Plains (GP) Region. Most of the findings reviewed are for studies related to all of the Western United States and/or areas of the GP Region west of the 100th meridian. This section summarizes findings from recent studies (1997–2007) demonstrating evidence of regional climate change during the 20th century and exploring water resources impacts associated with various climate change scenarios.

2.5.1 Historical Climate and Hydrology

It appears that all areas of the GP Region have become warmer, and some areas received more winter precipitation during the 20th century. Cayan et al. (2001) reports that Western U.S. spring temperatures have increased 1–3 °C (1.8–5.4 °F) since the 1970s. Based on data from the USHCN, temperatures have risen approximately 1.85 °F (1.02 °C) in the northern GP to approximately 0.63 °F

(0.35 °C) in the southern GP since 1901.[12] That dataset also reveals an increase in annual precipitation of more than 4% in the northern GP and 10% in the southern GP over the same time period. The trend was more consistent in the southern GP. Regonda et al. (2005) reports increased winter precipitation trends during 1950–1999 at many Western U.S. sites, including numerous sites in the western GP Region, but a consistent region-wide trend is not apparent.

Coincident with these trends, the western GP Region also experienced a general decline in spring snowpack, reduced snowfall to winter precipitation ratios and earlier snowmelt runoff. Reduced snowpack and snowfall ratios are indicated by analyses of 1948–2001 SWE measurements at 173 Western U.S. stations (Knowles et al., 2007). Regonda et al. (2005) reports monthly SWE trends during 1950–1999 and suggests that there were statistically significant declines in monthly SWE over roughly half of the Western U.S. sites evaluated for the period 1970 to 1998. Among those sites, there was no regional consensus among SWE trends over southern Montana to Colorado; however, the regional consensus over western Montana appeared to be a decrease in monthly SWE

These findings are significant for regional water resources management and reservoir operations because snowpack traditionally has played a central role in determining the seasonality of natural runoff. In many GP Region headwater basins, the precipitation stored as snow during winter accounts for a significant portion of spring and summer inflow to lower elevation reservoirs. The mechanism for how this occurs (with precipitation being equal) is that warmer temperatures in these watersheds cause reduced snowpack development during winter, more runoff during the winter season, earlier spring peak flows associated with an earlier snowmelt.

Warming-induced increases in thunderstorm activity of the GP region (and most of contiguous United States) (Changnon, 2001) has led to an increase in heavy precipitation events since 1900 (Groisman, 2004). Further, most of that increase has occurred in the last three decades. Garbrecht et al. (2004) found increasing GP precipitation trends led to large increases in streamflow but lesser increases in evapotranspiration (ET).

2.5.2 Projected Future Climate and Hydrology

Given observed trends in regional warming and declining snowpack conditions, studies have been conducted to relate potential future climate scenarios to runoff

[12] Trend calculations described in the U.S. Environmental Protection Agency's 2009 "U.S. and Global Mean Temperature and Precipitation" (http://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=209827). The period-mean reference is notable. For this 2009 report, the temperature trends were computed relative to a 1971–2000 period-mean leading to the values of +1.85 and +0.63 °F listed above. In the 2006 version of this analysis, trends were computed relative to a 1961–1990 period-mean, leading to regional trends of +1.76 and +0.17 °F by comparison (http://oaspub.epa.gov/eims/eims.eimscomm.getfile?p_download_id=489528).

and water resources management impacts. Such studies are particularly relevant to the western GP headwaters and the central to northern High Plains. For the GP Region east of the High Plains, and especially in the southern GP, evapotranspirative demands and warm-season precipitation play a more prominent role in determining local hydrologic conditions relative to water management and generally more so relative to the influence of headwaters snowpack and snowmelt timing.

The findings of six case studies on the sensitivity of water resources to climate change are reported by Lettenmier et al. (1999). One of the case studies was for the Missouri River system. It found that snow accumulation, while important on the western headwaters of the Missouri system, plays only a modest role in total system runoff, and reduced precipitation combined with increasing potential evapotranspiration play a major role in system runoff reductions.

A study by Hotchkiss et al. (2000) addresses the ability to incorporate complex operation rules for multiple reservoirs into a hydrologic model capable of assessing climate change impacts on water resources of large, completely managed river basins. This study was part of an overall effort to address climate change related impacts within the Missouri River Basin A soil and water assessment numerical modeling tool was used to simulate surface water hydrology that was successfully calibrated to historical conditions; however, its snowmelt component was problematic, thus limiting useful results.

Loáiciga et al. (2000) identified potential impacts of climate change scenarios on management of the Edwards Aquifer system in western Texas. The study reports the Edwards Aquifer appears to be very vulnerable to warming trends based on current levels of extraction and projected future pumping rates.

Elgaali et al. (2007) and Ojima et al. (1999) report potential climate change impacts on water resources and demands in the GP Region. Changes in agricultural water demands were evaluated based on climate change scenarios using crop consumptive use methods. Both studies project future increases in crop water consumptive use ranging from 20 to 60% by the end of the 21st century.

Rosenberg et al. (1999) reports impacts on surface water runoff and associated water supplies in the Ogallala Aquifer region under several climate change scenarios including how changes in atmospheric CO_2 impact photosynthesis and ET. Water yield in the Arkansas-White-Red River Basin decreased under all scenarios.

Switching consideration to flood risk management, Lettenmier et al. (1999) reported improved flood control conditions for the Missouri River system under certain climate change scenarios where flood risk is driven by monthly to seasonal phenomena rather than storm or storm pattern phenomena. Hamlet and

Lettenmaier (2007) report that simulations suggest that warming over the 20th century has resulted in changes in flood risks in many parts of the Western United States that are broadly characterized by midwinter temperatures, and that colder, snowmelt basins typically show reductions in flood risks because of snowpack reductions. In any case, consideration of these results should be complemented by the understanding that many flood risk management situations in the GP Region are driven by potential for local, convective precipitation events. There are still many uncertainties associated with interpreting projected trends in local, convective precipitation potential based on results from current climate models.

2.5.3 Studies of Impacts on Environmental Resources

Johnson et al. (2005) used a wetland simulation model to predict significant climate change impacts to the northern pothole prairie region. The findings indicate that the most productive habitat for breeding waterfowl would shift to the eastern part of the region under warmer and drier conditions. Conly and Garth van der Kamp (2001) reported wetland and associated wildlife impacts related to climate and land use changes. Wetland water level data were coupled with meteorological data in a numerical model to simulate water level changes resulting from climate change. Poiani and Johnson (1993) also used a numerical model to simulate wetland hydrology and vegetation impacts due to climate change.

Covich et al. (1997) summarizes available information on patterns of spatial climate variability and identifies subregions of importance to ecological processes within the Great Plains. Climate sensitive areas of the Great Plains range from cold-water systems (springs, and spring fed streams) to warmer, temporary systems (intermittent streams, ponds, pothole wetlands, playas).

3.0 Summary of Potential Impacts on Planning Resource Areas

This chapter qualitatively summarizes potential climate change impacts related to various resources areas and operating objectives that might be relevant to Reclamation's long-range planning processes. Areas discussed include runoff and surface water supplies, flood control, hydropower, fisheries, surface water quality, and groundwater. The studies discussed in the previous chapter primarily support this chapter's discussion on impacts for runoff, surface water supplies, and hydropower. This chapter's discussion of impacts for flood control, fisheries, surface water quality, and groundwater primarily is based on information from the U.S. Climate Change Science Program (CCSP) Synthesis and Assessment Product reports.

Note that each region-specific summary is meant to serve as a standalone-narrative to support planning efforts in that region. However, many of the studies cited for each region's literature review have a "Western U.S." applicability. Further, many of the climate change impacts evident in recent studies are common among regions. Consequently, there are many common themes in each region-specific summary that follows.

3.1 Pacific Northwest Region

This section presents information on potential climate change impacts related to various resources areas and operating objectives relevant to Reclamation's PN Region.

3.1.1 Runoff and Surface Water Supplies

SAP 4.3 discusses the effects of climate change on agriculture, land resources, water resources, and biodiversity. Chapter 4 of SAP 4.3 focuses on water resources effects (Lettenmaier et al., 2008) and suggests that management of Western U.S. reservoir systems is very likely to become more challenging as runoff patterns continue to change as the result of climate change. Based on recent scenario studies of climate change impacts, it appears that *warming without precipitation change* would trigger a seasonal shift toward increased runoff during winter and decreased runoff during summer in basins historically having a significant accumulation of seasonal snowpack. Based on current reservoir operations constraints (e.g., capacity, flood control rules), it appears that such runoff shifts would lead to reduced scenario water supplies under the no action system.

Based on contemporary climate projections, it appears plausible that precipitation increase over the PN Region could occur with regional warming and offset some portion of summer runoff decreases associated with warming alone, yet scenarios consistently point to reduced springtime snowpack and substantial reductions in late spring and early summer runoff and streamflow in snowmelt-driven watersheds of the PN region (Lettemaier et al., 1999; Hamlet and Lettenmaier, 1999; Payne et al., 2004; and Elsner et al., 2009). Projected reductions in spring and summer snowmelt runoff are largely balanced by increases in winter runoff as more precipitaiton is projected to fall as rain rather than snow. This seasonal timing shift in runoff will present challenges in managing increasing winter streamflow and decreasing late spring and early summer streamflow (Paynet et al., 2004). The 21st century climate projections considered by Dettinger et al. (2004) suggest a modest future increase in precipitation with assessed hydrologic impacts suggesting long-term average streamflow similar to historical, with reduced growing season soil moisture and associated reduced evapotranspiration occurring. However, the majority of climate change scenarios from the IPCC's Fourth Assessment Report (AR4) predict relatively small long-term trends in seasonal and annual precipitation for the PN region compared with the year-to-year variations; this means that PN region precipitation in the future is likely to be highly variable between years and decades, just as it has in the past. On average, the AR4 models project increases in average annual PN temperature of approximately (~)1.1 °C by the 2020s, 1.8 °C by the 2040s, and 3 °C by the 2080s, with 2080s warming ranging from ~1.5 to 6 °C depending on the climate model and emissions scenario (compared to 1970–1999). Projected changes in annual precipitation, averaged over all models, are small (+1 to +2%), but some models project an enhanced seasonal precipitation cycle with changes toward wetter autumns and winters and drier summers. There is also a broad range of projected precipitation changes depending on the model and emissions scenario used, with decreases of up to 8% and increases of up to 20% in annual average precipitation by the 2080s (Mote and Salathe, 2009).

3.1.2 Flood Control

SAP 3.3 discusses the effects of climate change on precipitation extremes. Chapter 3 of SAP 3.3 focuses on mechanisms for observed changes in extremes to better interpret projected future changes in extremes (Gutowski et al., 2008), suggests that climate change will likely cause precipitation to be less frequent but more intense in many areas, and suggests that precipitation extremes are very likely to increase. Madsen and Figdor (2007) report 1948–2006 trends in extreme precipitation events for each state. Extreme runoff due to this phenomenon will present flood control challenges to varying degrees at many locations.

In Western U.S. reservoir systems with flood control objectives in currently snowmelt-dominated basins, warming without precipitation decreases could result in increased winter runoff volumes to manage during flood control operations. This could motivate adjustments to flood control strategies (e.g., Brekke et al.,

2009). For example, given existing reservoir capacities and current flood control rules (e.g., winter draft period, spring refill date), a pattern of more winter runoff might suggest an increased flooding risk. If current flood protection values are to be preserved, it could become necessary to make flood control rule adjustments as climate evolves (e.g., deeper winter draft requirements) which may further affect dry season water supplies (e.g., spring refill beginning with less winter carryover storage).

3.1.3 Hydropower

SAP 4.5 discusses the effects of climate change on energy production and use in the United States. Chapter 3 of SAP 4.4 discusses hydropower generation in the context of other energy production activities (Bull et al., 2007), indicates that hydroelectric generation is highly sensitive to climate change effects on precipitation and river discharge, and indicates that hydropower operations are also affected indirectly when climate change impacts air temperatures, humidity, or wind patterns. Hydropower demand generally trends with temperature (e.g., heating demand during cold days, air conditioning demand during warm days). Hydropower generation is generally a function of reservoir storage. Climate changes that result in decreased reservoir inflow or disrupt traditional timing of inflows could adversely impact hydropower generation. Alternatively, increases in average flows would increase hydropower production.

Chapter 2 of SAP 4.4 focuses on how energy use may respond to climate change (Scott et al., 2007) and suggests that, in terms of demand, warming could lead to decreased energy demand during winter and increased demand during summer. Such demand changes might motivate adjustments to reservoir operations for hydropower objectives (e.g., less winter production, more summer production), which may not be consistent with runoff impacts and/or potential flood control adjustments (e.g., more winter release, less summer release).

3.1.4 Fisheries and Wildlife

Chapter 5 of SAP 4.3 discusses how biodiversity may be affected by climate change (Janetos et al. ,2008) and indicates that many studies have been published on the impacts of climate change for individual species and ecosystems. Regional warming indicated many adverse effects on some salmon populations due to increased winter flows, reduced summer and fall flows, and warmer stream and estuary temperatures (e.g., Battin et al., 2007; Mantua et al., 2009). Further, if seasonal runoff patterns affect outward migration patterns of wild juveniles, they may be further affected by the ocean and estuary conditions they encounter after emigration because such conditions may not match the season-dependent conditions that they have evolved to exploit.

Reiners et al. (2003) and Covich et al. (2003) report predicted Rocky Mountain and Great Basin Region impacts, respectively, to terrestrial and aquatic

ecosystems based on two GCM-based climate change scenarios. Predicted terrestrial ecosystem impacts are based primarily on changes in vegetation and pests infestations. Predicted aquatic ecosystem impacts are based primarily on changes in water temperatures, nutrients, and food sources. Aquatic impacts prediction confidence is higher for the southern portion of the region.

3.1.5 Surface Water Quality

Chapter 4 of SAP 4.3 focuses on water resources, as mentioned above and includes discussion on impacts for surface water quality (Lettenmaier et al., 2008). Whether water quality conditions improve or deteriorate under climate change depends on several variables including water temperature, flow, runoff rate and timing, and the physical characteristics of the watershed. Climate change has the potential to alter all of these variables. Climate change impacts on surface water ecosystems very likely will affect their capacity to remove pollutants and improve water quality; however, the timing, magnitude, and consequences of these impacts are not well understood (Lettenmaier et al., 2008). Increased summer air temperatures could increase dry season aquatic temperatures and affect fisheries habitat.

3.1.6 Groundwater

Chapter 3 of SAP 4.3 discusses how land resources may be affected by climate change (Ryan et al., 2008) and indicates that depletions to groundwater recharge are sensitive to climate warming. Reduced mountain snowpack, earlier snowmelt, and reductions in spring and summer streamflow volumes originating from snowmelt likely would affect surface water supplies and could trigger heavier reliance on groundwater resources. However, warmer wetter winters could increase the amount of water available for groundwater recharge. It is has not been demonstrated how much of this additional winter runoff can be captured and utilized without using artificial recharge schemes.

3.1.7 Water Demand

Given that the atmosphere's moisture holding capacity increases when air temperature increases, it would seem intuitive that plant water consumption related to evapotranspiration and surface water potential evaporation would increase in a warming climate. However, several studies report historical trends of decreasing pan evaporation during the past 50 years (Lettenmaier et al., 2008). This latter result may be related to changes in other factors affecting surface energy balance (e.g., net radiation, wind speed) that are not congruous with the notion of increasing air temperatures. Consequently, there is uncertainty about how physically driven water demands may change under climate change. Further, agricultural water demand could decrease due to crop failures caused by pests and disease exacerbated by climate change. On the other hand, agricultural water demand could increase if growing seasons grow longer. This possibility is based

on studies suggesting that the average North American growing season length increased by about 1 week during the 20th century; and it is projected that, by the end of the 21st century, it will be more than 2 weeks longer than typical of the late 20th century (Gutowski et al., 2008). Although changes in water demands associated with natural processes may be difficult to quantify, consumption increases associated with population growth will occur unless water conservation measures are implemented.

As climate change might affect water supplies and reservoir operations, the resultant effects on PN Region water allocations from year to year could trigger changes in water use (e.g., crop types, cropping dates, environmental flow targets, transfers among different uses, hydropower production, and recreation). Such climate-related changes in water use would interact with market influences on agribusiness and energy management, demographic and land use changes, and other nonclimate factors.

3.2 Mid-Pacific Region

This section presents information on potential climate change impacts related to various resources areas and operating objectives relevant to Reclamation's MP Region.

3.2.1 Runoff and Surface Water Supplies

SAP 4.3 discusses the effects of climate change on agriculture, land resources, water resources, and biodiversity. Chapter 4 of SAP 4.3 focuses on water resources effects (Lettenmaier et al., 2008) and suggests that management of Western U.S. reservoir systems very likely is to become more challenging as runoff patterns continue to change as the result of climate change. Based on recent scenario studies of climate change impacts, it appears that warming without precipitation change would trigger a seasonal shift toward increased runoff during winter and decreased runoff during summer. Based on current reservoir operations constraints (e.g., capacity, flood control rules), it appears that such runoff shifts would lead to reduced scenario water supplies under the no action system.

There is not a majority consensus among contemporary climate projections that precipitation might increase over the MP Region. However, assuming such a possibility, an increase in mean-annual precipitation could offset a significant portion of summer runoff decreases associated with regional warming alone. The resultant affect could be minor change in dry season water supply (albeit with significantly increased winter runoff). The 21st century climate projections considered by Dettinger et al. (2004) suggest a modest future increase in precipitation with assessed hydrologic impacts suggesting long-term average

streamflow similar to historical, with reduced growing season soil moisture and associated reduced evapotranspiration occurring.

3.2.2 Flood Control

SAP 3.3 discusses the effects of climate change on precipitation extremes. Chapter 3 of SAP 3.3 focuses on mechanisms for observed changes in extremes to better interpret projected future changes in extremes (Gutowski et al., 2008), suggests that climate change will likely cause precipitation to be less frequent but more intense in many areas, and suggests that precipitation extremes are very likely to increase. Madsen and Figdor (2007) report 1948–2006 trends in extreme precipitation events for each State. Extreme runoff due to this phenomenon will present flood control challenges to varying degrees at many locations.

In Western U.S. reservoir systems with flood control objectives in currently snowmelt-dominated basins, warming without precipitation decreases could result in increased winter runoff volumes to manage during flood control operations. This could motivate adjustments to flood control strategies (e.g., Brekke et al., 2009). For example, given existing reservoir capacities and current flood control rules (e.g., winter draft period, spring refill date), a pattern of more winter runoff might suggest an increased flooding risk. If current flood protection values are to be preserved, it could become necessary to make flood control rule adjustments as climate evolves (e.g., deeper winter draft requirements) which may further affect dry season water supplies (e.g., spring refill beginning with less winter carryover storage).

3.2.3 Hydropower

SAP 4.5 discusses the effects of climate change on energy production and use in the United States. Chapter 3 of SAP 4.4 discusses hydropower generation in the context of other energy production activities (Bull et al., 2007), indicates that hydroelectric generation is highly sensitive to climate change effects on precipitation and river discharge, and indicates that hydropower operations are also affected indirectly when climate change impacts air temperatures, humidity, or wind patterns. Hydropower demand generally trends with temperature (e.g., heating demand during cold days, air conditioning demand during warm days). Hydropower generation is generally a function of reservoir storage. Climate changes that result in decreased reservoir inflow or disrupt traditional timing of inflows could adversely impact hydropower generation. Alternatively, increases in average flows would increase hydropower production.

Chapter 2 of SAP 4.4 focuses on how energy use may respond to climate change (Scott et al., 2007), and suggests that, in terms of demand, warming could lead to decreased energy demand during winter and increased demand during summer. Such demand changes might motivate adjustments to reservoir operations for hydropower objectives (e.g., less winter production, more summer production),

which may not be consistent with runoff impacts and/or potential flood control adjustments (e.g., more winter release, less summer release).

3.2.4 Fisheries and Wildlife

Chapter 5 of SAP 4.3 discusses how biodiversity may be affected by climate change (Janetos et al., 2008) and indicates that many studies have been published on the impacts of climate change for individual species and ecosystems. Regional warming would seem to indicate adverse effects on salmon due to increased winter flows, reduced summer and fall flows, and warmer stream and estuary temperatures. Further, if seasonal runoff patterns affect outward migration patterns of wild juveniles, they may be further affected by the ocean and estuary conditions they encounter after emigration because such conditions may not match the season-dependent conditions that they have evolved to exploit.

3.2.5 Surface Water Quality

Chapter 4 of SAP 4.3 focuses on water resources, as mentioned above and includes discussion on impacts for surface water quality (Lettenmaier et al., 2008). Whether water quality conditions improve or deteriorate under climate change depends on several variables including water temperature, flow, runoff rate and timing, and the physical characteristics of the watershed. Climate change has the potential to alter all of these variables. Climate change impacts on surface water ecosystems very likely will affect their capacity to remove pollutants and improve water quality; however, the timing, magnitude, and consequences of these impacts are not well understood (Lettenmaier et al., 2008). Increased summer air temperatures could increase dry season aquatic temperatures and affect fisheries habitat.

3.2.6 Groundwater

Chapter 3 of SAP 4.3 discusses how land resources may be affected by climate change (Ryan et al., 2008) and indicates that depletions to groundwater recharge are sensitive to climate warming. Reduced mountain snowpack, earlier snowmelt, and reductions in spring and summer streamflow volumes originating from snowmelt likely would affect surface water supplies and could trigger heavier reliance on groundwater resources. However, warmer wetter winters could increase the amount of water available for groundwater recharge. It has not been demonstrated how much of this additional winter runoff can be captured and utilized without using artificial recharge schemes.

3.2.7 Water Demand

Given that the atmosphere’s moisture holding capacity increases when air temperature increases, it would seem intuitive that plant water consumption related to evapotranspiration and surface water potential evaporation would

increase in a warming climate. However, several studies report historical trends of decreasing pan evaporation during the past 50 years (Lettenmaier et al., 2008). This latter result may be related to changes in other factors affecting surface energy balance (e.g., net radiation, wind speed) that are not congruous with the notion of increasing air temperatures. Consequently, there is uncertainty about how physically driven water demands may change under climate change. Further, agricultural water demand could decrease due to crop failures caused by pests and disease exacerbated by climate change. On the other hand, agricultural water demand could increase if growing seasons grow longer. This possibility is based on studies suggesting that the average North American growing season length has increased by about 1 week during the 20th century; and it is projected that, by the end of the 21st century, it will be more than 2 weeks longer than present day (Gutowski et al., 2008). Although changes in water demands associated with natural processes may be difficult to quantify, consumption increases associated with population growth will occur unless water conservation measures are implemented.

As climate change might affect water supplies and reservoir operations, the resultant effects on MP Region water allocations from year to year could trigger changes in water use (e.g., crop types, cropping dates, environmental flow targets, transfers among different uses, hydropower production, and recreation). Such climate-related changes in water use would interact with market influences on agribusiness and energy management, demographic and land use changes, and other nonclimate factors.

3.3 Lower Colorado Region

This section presents information on potential climate change impacts related to various resources areas and operating objectives relevant to Reclamation's LC Region.

3.3.1 Runoff and Surface Water Supplies

SAP 4.3 discusses the effects of climate change on agriculture, land resources, water resources, and biodiversity. Chapter 4 of SAP 4.3 focuses on water resources effects (Lettenmaier et al., 2008) and suggests that management of Western U.S. reservoir systems is very likely to become more challenging as runoff patterns continue to change as the result of climate change. Based on current reservoir operations constraints (e.g., capacity, flood control rules), it appears that such runoff shifts would lead to reduced scenario water supplies under the no action system.

A suite of climate simulations conducted for the IPCC AR4 shows that substantial decreases in Colorado River Basin annual runoff are likely (Lettenmaier et al., 2008). Based on recent scenario studies of climate change impacts, it appears that

warming without substantial precipitation increase will result in significant reductions in runoff and impact the ability to fully meet current LC Region demands over the long term. This is complicated by the uncertainties of predicting changes to *middle latitude* precipitation patterns resulting from climate change. Although most climate models indicate drier *subtropical latitude* conditions, which generally include the LC Region, this projected precipitation trend may not be relevant to the dominant source of supply regions serving the LC Region—the Upper Colorado River Basin and northern California. Both of these regions exist in the middle latitudes where there is less consensus about whether future precipitation conditions will be wetter or drier, but solid consensus that snow hydrology will change (earlier snow melt, declining fraction of winter precipitation falling as snow) and evapotranspiration will increase with increasing temperatures.

3.3.2 Flood Control

SAP 3.3 discusses the effects of climate change on precipitation extremes. Chapter 3 of SAP 3.3 focuses on mechanisms for observed changes in extremes to better interpret projected future changes in extremes (Gutowski et al., 2008), suggests that climate change likely will cause precipitation to be less frequent but more intense in many areas, and suggests that precipitation extremes are very likely to increase. Diffenbaugh et al. (2005), using a regional climate model, project increases in the fraction of annual precipitation falling as extreme precipitation for the LC Region, a result that is consistent with independent projections for the western part of the LC Region (Bell and Sloan, 2006). Madsen and Fignor (2007) report 1948–2006 trends in extreme precipitation events for each State. Extreme runoff due to this phenomenon will present flood control challenges to varying degrees at many locations.

In Western U.S. reservoir systems with flood control objectives in currently snowmelt-dominated basins, warming without precipitation decreases could result in increased winter runoff volumes to manage during flood control operations. This could motivate adjustments to flood control strategies (e.g., Brekke et al., 2009). For example, given existing reservoir capacities and current flood control rules (e.g., winter draft period, spring refill date), a pattern of more winter runoff might suggest an increased flooding risk. If current flood protection values are to be preserved, it could become necessary to make flood control rule adjustments as climate evolves (e.g., deeper winter draft requirements) which may further affect dry season water supplies (e.g., spring refill beginning with less winter carryover storage).

For LC Region areas existing within snowmelt-affected basins, it would appear that winter runoff increase under a scenario of regional warming and no annual precipitation may impact flood control operations.

3.3.3 Hydropower

SAP 4.5 discusses the effects of climate change on energy production and use in the United States. Chapter 3 of SAP 4.4 discusses hydropower generation in the context of other energy production activities (Bull et al., 2007), indicates that hydroelectric generation is highly sensitive to climate change effects on precipitation and river discharge, and indicates that hydropower operations are also affected indirectly when climate change impacts air temperatures, humidity, or wind patterns. Hydropower demand generally trends with temperature (e.g., heating demand during cold days, air conditioning demand during warm days). Hydropower generation is generally a function of reservoir storage. Climate changes that result in decreased reservoir inflow or disrupt traditional timing of inflows could adversely impact hydropower generation. Alternatively, increases in average flows would increase hydropower production.

Chapter 2 of SAP 4.4 focuses on how energy use may respond to climate change (Scott et al., 2007) and suggests that, in terms of demand, warming could lead to decreased energy demand during winter and increased demand during summer. Such demand changes might motivate adjustments to reservoir operations for hydropower objectives (e.g., less winter production, more summer production), which may not be consistent with runoff impacts and/or potential flood control adjustments (e.g., more winter release, less summer release).

In the LC Region, power generation fluctuations occur primarily on an annual frequency due to the relatively large capacities of Lake Powell and Lake Mead. Seasonal fluctuations due to decreasing inflows, although potentially significant, may be less significant than the anticipated overall reduction in total annual power production. In terms of demand, warming could lead to decreased energy demand during winter and increased demand during summer.

3.3.4 Fisheries and Wildlife

Chapter 5 of SAP 4.3 discusses how biodiversity may be affected by climate change (Janetos et al., 2008) and indicates that many studies have been published on the impacts of climate change for individual species and ecosystems. Increased summer air temperatures could increase aquatic temperatures and affect fisheries habitat. For example, Kennedy et al. (2009) show that projected decreases in summer precipitation and increases in maximum temperatures by mid-century (Leung et al., 2004) would decrease suitable summer habitat for the Gila trout (*Oncorhynchus gilae*), a species endemic to a tributary of the Colorado River. Warmer water temperatures also could exacerbate invasive species issues (e.g., quagga mussel reproduction cycles responding favorably to warmer water temperatures); moreover, climate changes could decrease the effectiveness of chemical or biological agents used to control invasive species (Hellman et al., 2008). Warmer water temperatures could also spur the growth of algae, which could result in eutrophic conditions in lakes, declines in water quality

(Lettenmaier et al., 2008), and changes in species composition. Rahel and Olden (2008) suggest that, as stream temperatures warm, some fish species may expand their range upstream or increase in abundance, displacing other species native to upstream reaches. In addition, if future streamflows drop below threshold levels that ensure their viability, some natural communities can suffer as water is allocated for human uses (CCSP, 2009).

In a more generic sense, wildlife population distributions likely are to change as plant species distributions and water availability changes. For example, McKinney et al. (2008) demonstrate that winter precipitation is the leading predictor of pronghorn antelope recruitment. Projected declines in winter precipitation in the LC Region will surely affect distribution and survivorship of antelope and other mammal populations. Researchers evaluating plant species phenology and migration in southern California (Santa Rosa Mountains) and southern Arizona (Santa Catalina Mountains) have noted rapid changes in species range (moving upslope) with increasing temperatures during the last few decades (Kelly and Goulden, 2008; Crimmins et al., 2009). The California researchers documented elevational increases of 65 meters in dominant plant species over a 30-year re-sampling period (Kelly and Goulden, 2008). In riparian areas in the LC Region, Stromberg et al. (2007) and Beauchamp and Stromberg (2007) document the spread of invasive riparian vegetation (saltcedar; *Tamarix ramosissima*) when streamflows drop below permanence thresholds of 50–75% (CCSP, 2009).

3.3.5 Surface Water Quality

Chapter 4 of SAP 4.3 focuses on water resources, as mentioned above, and includes discussion on impacts for surface water quality (Lettenmaier et al., 2008). Whether water quality conditions improve or deteriorate under climate change depends on several variables including water temperature, flow, runoff rate and timing, and the physical characteristics of the watershed. Climate change has the potential to alter all of these variables. Climate change impacts on surface water ecosystems very likely will affect their capacity to remove pollutants and improve water quality; however, the timing, magnitude, and consequences of these impacts are not well understood (Lettenmaier et al., 2008).

3.3.6 Groundwater

Chapter 3 of SAP 4.3 discusses how land resources may be affected by climate change (Ryan et al., 2008) and indicates that depletions to groundwater recharge are sensitive to climate warming. Reduced mountain snowpack, earlier snowmelt, and reductions in spring and summer streamflow volumes originating from snowmelt likely would affect surface water supplies and could trigger heavier reliance on groundwater resources. However, warmer wetter winters could increase the amount of water available for groundwater recharge. Projected groundwater recharge in the San Pedro River Basin (southern Arizona and

northern Mexico) declined even for the wettest downscaled GCM projection, due to a substantial increase in evapotranspiration (Serrat-Capdevila et al., 2007). Moreover, they found feedbacks between increasing ET leading to declining recharge, which increases depth to water table, which then decreases riparian area vegetation health; declining riparian vegetation health can lead to a cascade of ecosystem impacts related to stream temperatures and species habitat. It has not been demonstrated how much of this additional winter runoff can be captured and utilized without using artificial recharge schemes.

3.3.7 Water Demand

Given that the atmosphere's moisture holding capacity increases when air temperature increases, it would seem intuitive that plant water consumption related to evapotranspiration and surface water potential evaporation would increase in a warming climate. However, several studies report historical trends of decreasing pan evaporation during the past 50 years (Lettenmaier et al., 2008). This latter result may be related to changes in other factors affecting surface energy balance (e.g., net radiation, wind speed) that are not congruous with the notion of increasing air temperatures. Consequently, there is uncertainty about how physically driven water demands may change under climate change. Further, agricultural water demand could decrease due to crop failures caused by pests and disease exacerbated by climate change. On the other hand, agricultural water demand could increase if growing seasons lengthen. This possibility is based on studies suggesting that the average North American growing season length has increased by about 1 week during the 20th century; and it is projected that, by the end of the 21st century, it will be more than 2 weeks longer than present day (Gutowski et al., 2008). Weiss and Overpeck (2005) show an increase in the length of the frost-free season in the Sonoran Desert since the 1960s, suggesting a possible increase in ecosystem demands for water. Although changes in water demands associated with natural processes may be difficult to quantify, consumption increases associated with population growth will occur unless water conservation measures are implemented. Demands for field-scale irrigation water supplies might increase further to the extent that existing demands are partially satisfied by precipitation and that precipitation is projected to gradually decrease over the LC Region.

3.4 Upper Colorado Region

This section presents information on potential climate change impacts related to various resources areas and operating objectives relevant to Reclamation's UC Region.

3.4.1 Runoff and Surface Water Supplies

SAP 4.3 discusses the effects of climate change on agriculture, land resources, water resources, and biodiversity. Chapter 4 of SAP 4.3 focuses on water resources effects (Lettenmaier et al., 2008) and suggests that management of Western U.S. reservoir systems very likely is to become more challenging as runoff patterns continue to change as the result of climate change. Based on recent scenario studies of climate change impacts, it appears that warming without precipitation change would trigger a seasonal shift toward increased runoff during winter and decreased runoff during summer. Based on current reservoir operations constraints (e.g., capacity, flood control rules), it appears that such runoff shifts would lead to reduced scenario water supplies under the no action alternative.

Based on the latest generation of climate projections (CMIP3), it appears plausible that, in the northern portions of the UC Region, mean-annual precipitation could either increase or decrease. In the southern portions of the UC Region, there is more projection consensus that mean-annual precipitation would gradually decrease over time. Regardless, it is likely that snowpack-based predictions of streamflow volume and peaks will become more challenging under flow scenarios that have more winter runoff and smaller spring snowpack. Other potential impacts include increased reservoir and stream evaporation, streamflow timing-related water rights impacts, and water resource effects from ecosystem changes (e.g., pine beetle infestation).

3.4.2 Flood Control

SAP 3.3 discusses the effects of climate change on precipitation extremes. Chapter 3 of SAP 3.3 focuses on mechanisms for observed changes in extremes to better interpret projected future changes in extremes (Gutowski et al., 2008), suggests that climate change will likely cause precipitation to be less frequent but more intense in many areas, and precipitation extremes are very likely to increase. Madsen and Figdor (2007) report 1948–2006 trends in extreme precipitation events for each State. Extreme runoff due to this phenomenon will present flood control challenges to varying degrees at many locations.

In Western U.S. reservoir systems with flood control objectives in currently snowmelt-dominated basins, warming without precipitation decreases could result in increased winter runoff volumes to manage during flood control operations. This could motivate adjustments to flood control strategies (e.g., Brekke et al., 2009). For example, given existing reservoir capacities and current flood control rules (e.g., winter draft period, spring refill date), a pattern of more winter runoff might suggest an increased flooding risk. If current flood protection values are to be preserved, it could become necessary to modify infrastructure to preserve flood protection performance and/or make flood control rule adjustments as climate

evolves (e.g., deeper winter draft requirements) which may further affect dry season water supplies (e.g., spring refill beginning with less winter carryover storage).

3.4.3 Hydropower

SAP 4.5 discusses the effects of climate change on energy production and use in the United States. Chapter 3 of SAP 4.4 discusses hydropower generation in the context of other energy production activities (Bull et al., 2007), indicates that hydroelectric generation is highly sensitive to climate change effects on precipitation and river discharge, and indicates that hydropower operations are also affected indirectly when climate change impacts air temperatures, humidity, or wind patterns. Hydropower demand generally trends with temperature (e.g., heating demand during cold days, air conditioning demand during warm days). Hydropower generation is generally a function of reservoir storage. Climate changes that result in decreased reservoir inflow or disrupt traditional timing of inflows could adversely impact hydropower generation. Alternatively, increases in average flows would increase hydropower production.

Chapter 2 of SAP 4.4 focuses on how energy use may respond to climate change (Scott et al., 2007) and suggests that, in terms of demand, warming could lead to decreased energy demand during winter and increased demand during summer. Such demand changes might motivate adjustments to reservoir operations for hydropower objectives (e.g., less winter production, more summer production), which may not be consistent with runoff impacts and/or potential flood control adjustments (e.g., more winter release, less summer release).

In the UC Region, major fluctuations in power generation vary seasonally to annually, depending on the reservoir system being considered. Thus, for some UC systems, changes in seasonal runoff patterns might be more significant; while for others, changes in annual runoff might be more significant. In terms of demand, warming could lead to decreased energy demand during winter and increased demand during summer.

3.4.4 Fisheries and Wildlife

Chapter 5 of SAP 4.3 discusses how biodiversity may be affected by climate change (Janetos et al., 2008) and indicates that many studies have been published on the impacts of climate change for individual species and ecosystems. Increased summer air temperatures could increase aquatic temperatures and affect fisheries habitat. Warmer water temperatures also could exacerbate invasive species issues (e.g., quagga mussel reproduction cycles responding favorably to warmer water temperatures).

Reiners et al. (2003) and Covich et al. (2003) report predicted Rocky Mountain and Great Basin Region impacts, respectively, to terrestrial and aquatic

ecosystems based on two GCM based climate change scenarios. Predicted terrestrial ecosystem impacts are based primarily on changes in vegetation and pests infestations. Predicted aquatic ecosystem impacts are based primarily on changes in water temperatures, nutrients, and food sources. Aquatic impacts prediction confidence is higher for the southern portion of the region.

3.4.5 Water Quality

Chapter 4 of SAP 4.3 focuses on water resources, as mentioned above, and includes discussion on impacts for surface water quality (Lettenmaier et al., 2008). Whether water quality conditions improve or deteriorate under climate change depends on several variables including water temperature, flow, runoff rate and timing, and the physical characteristics of the watershed. Climate change has the potential to alter all of these variables. Climate change impacts on surface water ecosystems very likely will affect their capacity to remove pollutants and improve water quality; however, the timing, magnitude, and consequences of these impacts are not well understood (Lettenmaier et al., 2008).

3.4.6 Groundwater

Chapter 3 of SAP 4.3 discusses how land resources may be affected by climate change (Ryan et al., 2 008) and indicates that depletions to groundwater recharge are sensitive to climate warming. Reduced mountain snowpack, earlier snowmelt, and reductions in spring and summer streamflow volumes originating from snowmelt likely would affect surface water supplies and could trigger heavier reliance on groundwater resources. However, warmer wetter winters could increase the amount of water available for groundwater recharge. It has not been demonstrated how much of this additional winter runoff can be captured and utilized without using artificial recharge schemes.

3.4.7 Water Demand

Given that the atmosphere's moisture holding capacity increases when air temperature increases, it would seem intuitive that plant water consumption related to evapotranspiration and surface water potential evaporation would increase in a warming climate. However, several studies report historical trends of decreasing pan evaporation during the past 50 years (Lettenmaier et al., 2008). This latter result may be related to changes in other factors affecting surface energy balance (e.g., net radiation, wind speed) that are not congruous with the notion of increasing air temperatures. Consequently, there is uncertainty about how physically driven water demands may change under climate change. Further, agricultural water demand could decrease due to crop failures caused by pests and disease exacerbated by climate change. On the other hand, agricultural water demand could increase if growing seasons grow longer. This possibility is based on studies suggesting that the average North American growing season length has increased by about 1 week during the 20th century; and it is projected that, by the

end of the 21st century, it will be more than 2 weeks longer than present day (Gutowski et al., 2008). Also, mismatches in the impacts to runoff timing (earlier spring runoff) and agricultural demand (increase summer consumptive use) may negatively impact water available for agricultural use. Although changes in water demands associated with natural processes may be difficult to quantify, consumption increases associated with population growth will occur unless water conservation measures are implemented.

3.5 Great Plains Region

This section presents information on potential climate change impacts related to various resources areas and operating objectives relevant to Reclamation's GP Region.

3.5.1 Runoff and Surface Water Supplies

SAP 4.3 discusses the effects of climate change on agriculture, land resources, water resources, and biodiversity. Chapter 4 of SAP 4.3 focuses on water resources effects (Lettenmaier et al., 2008) and suggests that management of Western U.S. reservoir systems is very likely to become more challenging as runoff patterns continue to change as the result of climate change. Based on recent scenario studies of climate change impacts, it appears that warming without precipitation change would trigger a seasonal shift toward increased runoff during winter and decreased runoff during summer. Based on current reservoir operations constraints (e.g., capacity, flood control rules), it appears that such runoff shifts would lead to reduced scenario water supplies under the no action system.

Based on contemporary climate projections, it appears plausible that precipitation increase could occur with regional warming and offset a significant portion of summer runoff decreases associated with warming alone. The resultant affect could be minor change in dry season water supply (albeit with significantly increased winter runoff to manage).

Based on the warming-only scenarios, it appears that dry season runoff reductions would be experienced, which would seem to suggest coordinated supply reductions. This could influence operating objectives related to flood control, hydropower, fisheries, and surfaced water quality, as well as system water demands.

Garbrecht et al. (2004) suggest the fall through spring months would be most impacted by either a wetter or drier GP climate with streamflow experiencing the greatest impact.

3.5.2 Flood Control

SAP 3.3 discusses the effects of climate change on precipitation extremes. Chapter 3 of SAP 3.3 focuses on mechanisms for observed changes in extremes to better interpret projected future changes in extremes (Gutowski et al., 2008), suggests that climate change will likely cause precipitation to be less frequent but more intense in many areas, and suggests that precipitation extremes are very likely to increase. Madsen and Figdor (2007) report 1948–2006 trends in extreme precipitation events for each State. Extreme runoff due to this phenomenon will present flood control challenges to varying degrees at many locations.

In Western U.S. reservoir systems with flood control objectives in currently snowmelt-dominated basins, warming without precipitation decreases could result in increased winter runoff volumes to manage during flood control operations. This could motivate adjustments to flood control strategies (e.g., Brekke et al., 2009). For example, given existing reservoir capacities and current flood control rules (e.g., winter draft period, spring refill date), a pattern of more winter runoff might suggest an increased flooding risk. If current flood protection values are to be preserved, it could become necessary to make flood control rule adjustments as climate evolves (e.g., deeper winter draft requirements) which may further affect dry season water supplies (e.g., spring refill beginning with less winter carryover storage).

3.5.3 Hydropower

SAP 4.5 discusses the effects of climate change on energy production and use in the United States. Chapter 3 of SAP 4.4 discusses hydropower generation in the context of other energy production activities (Bull et al., 2007), indicates that hydroelectric generation is highly sensitive to climate change effects on precipitation and river discharge, and indicates that hydropower operations are also affected indirectly when climate change impacts air temperatures, humidity, or wind patterns. Hydropower demand generally trends with temperature (e.g., heating demand during cold days, air conditioning demand during warm days). Hydropower generation is generally a function of reservoir storage. Climate changes that result in decreased reservoir inflow or disrupt traditional timing of inflows could adversely impact hydropower generation. Alternatively, increases in average flows would increase hydropower production.

Chapter 2 of SAP 4.4 focuses on how energy use may respond to climate change (Scott et al. 2007) and suggests that, in terms of demand, warming could lead to decreased energy demand during winter and increased demand during summer. Such demand changes might motivate adjustments to reservoir operations for hydropower objectives (e.g., less winter production, more summer production), which may not be consistent with runoff impacts and/or potential flood control adjustments (e.g., more winter release, less summer release).

3.5.4 Fisheries and Wildlife

Chapter 5 of SAP 4.3 discusses how biodiversity may be affected by climate change (Janetos et al., 2008) and indicates that many studies have been published on the impacts of climate change for individual species and ecosystems. Climate change impacts on Great Plains pothole wetland areas have been studied (Johnson et al., 2005), and other sensitive environments have been identified. Studies to address effects of 21st century warming on prairie wetlands are few.

Reiners et al. (2003) and Covich et al. (2003) report predicted Rocky Mountain and Great Basin Region impacts, respectively, to terrestrial and aquatic ecosystems based on two GCM-based climate change scenarios. Predicted terrestrial ecosystem impacts are based primarily on changes in vegetation and pests infestations. Predicted aquatic ecosystem impacts are based primarily on changes in water temperatures, nutrients, and food sources. Aquatic impacts prediction confidence is higher for the southern portion of the region.

3.5.5 Surface Water Quality

Chapter 4 of SAP 4.3 focuses on water resources, as mentioned above and includes discussion on impacts for surface water quality (Lettenmaier et al., 2008). Whether water quality conditions improve or deteriorate under climate change depends on several variables including water temperature, flow, runoff rate and timing, and the physical characteristics of the watershed. Climate change has the potential to alter all of these variables. Climate change impacts on surface water ecosystems very likely will affect their capacity to remove pollutants and improve water quality; however, the timing, magnitude, and consequences of these impacts are not well understood (Lettenmaier et al., 2008). Increased summer air temperatures could increase dry season aquatic temperatures and affect fisheries habitat. Warmer water temperatures also could exacerbate invasive mussel species (zebra and quagga) problems.

3.5.6 Groundwater

Chapter 3 of SAP 4.3 discusses how land resources may be affected by climate change (Ryan et al., 2008) and indicates that depletions to groundwater recharge are sensitive to climate warming. Reduced mountain snowpack, earlier snowmelt, and reductions in spring and summer streamflow volumes originating from snowmelt likely would affect surface water supplies and could trigger heavier reliance on groundwater resources. Also, if a larger percentage of annual precipitation is in the form of intense rain events with high runoff, infiltration and aquifer recharge could be reduced. However, warmer wetter winters could increase the amount of water available for groundwater recharge. It has not been demonstrated how much of this additional winter runoff can be captured and utilized without using artificial recharge schemes.

3.5.7 Water Demand

Given that the atmosphere's moisture holding capacity increases when air temperature increases, it would seem intuitive that plant water consumption related to evapotranspiration and surface water potential evaporation would increase in a warming climate. However, several studies report historical trends of decreasing pan evaporation during the past 50 years (Lettenmaier et al., 2008). This latter result may be related to changes in other factors affecting surface energy balance (e.g., net radiation, wind speed) that are not congruous with the notion of increasing air temperatures. Consequently, there is uncertainty about how physically driven water demands may change under climate change. Further, agricultural water demand could decrease due to crop failures caused by pests and disease exacerbated by climate change. On the other hand, agricultural water demand could increase if growing seasons grow longer. This possibility is based on studies suggesting that the average North American growing season length has increased by about 1 week during the 20th century; and it is projected that, by the end of the 21st century, it will be more than 2 weeks longer than present day (Gutowski et al., 2008). Although changes in water demands associated with natural processes may be difficult to quantify, consumption increases associated with population growth will occur unless water conservation measures are implemented.

As climate change might affect water supplies and reservoir operations, the resultant effects on GP Region water allocations from year to year could trigger changes in water use (e.g., crop types, cropping dates, environmental flow targets, transfers among different uses, hydropower production, and recreation). Such climate-related changes in water use would interact with market influences on agribusiness and energy management, demographic and land use changes, and other nonclimate factors.

4.0 Graphical Resources

Given the evidence of recent climate trends and projected future climate conditions, there may be motivation to relate planning assumptions to projections of future temperature and precipitation. Appendix B provides graphical resources that summarize an assessment of current climate projections for decadal moving changes in 30-year mean precipitation and temperature relative to a "simulated" 1950–1979 base period (see appendix B). Such an assessment permits evaluating how climate is projected to evolve through time, in the context of how an ensemble of GCMs simulated both the past (1950–1999) and the "future" (projected 2000–2099). This section provides background on the data portrayed in the graphical resources and interpretation of assessment results.

4.1 Background on Available Downscaled Climate Projections

Survey of available and *current* climate projections started with the global dataset developed through the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (CMIP) phase 3 (CMIP3, served at http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php). The WCRP CMIP3 efforts were fundamental to the completion of the IPCC Fourth Assessment Report (IPCC, 2007). The CMIP3 dataset features simulation of future climates using multiple global climate models, considering multiple future pathways for GHG emissions, and simulating climate response to these GHG scenarios starting from different pre-industrial estimates of climate "state" (i.e., initial conditions, giving rise to different simulation "runs" using a given climate model for a given GHG scenario).

Current global climate models simulate climate at coarse spatial resolutions (200–500 kilometers); therefore, they are unable to resolve climate variations at much finer resolutions. The effect of fine-scale complex orography on precipitation and temperature cannot be adequately represented in coarse-resolution global climate models in regions with complex topography such as the Western United States; there are strong gradients in temperature and associated hydrologic structure. To relate these global climate projections to conditions, a regionalization process was necessary, involving the translation of spatially coarse output from the global climate models to basin-scale information (i.e., "downscaling"). Many CMIP3 projections have been downscaled for the contiguous United States using a statistical technique (Wood et al., 2002) and have been made available at a public-access Web site (i.e., Archive),[13] which discusses rationale for the downscaling

[13] "Statistically Downscaled WCRP CMIP3 Climate Projections," served at: http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/.

technique used, its limitations,[14] and strengths and weaknesses relative to other techniques. The downscaling technique underlying the Archive development features the subjective choice to compensate for climate model biases (bias-correction).[15] Philosophically, it might be expected that a climate model's simulation of the past should reflect chosen statistical aspects of the observed past. When this is not the case, a climate model "bias" is deemed to exist (i.e., tendency to simulate climates that are too wet or dry and/or too warm or cool). The regionalization procedure can be scoped to address the issue of climate model *bias*. Whether and how this bias is accounted for in using climate projection information is a matter of subjective choice. In the archive mentioned, each climate model's full range of climatology is mapped to observed climatology of 1950–1999, on a month-by-month and location-by-location basis. Thus, each climate projection is uniquely bias-corrected relative to the climate model used to generate the projection.

The Archive contains 112 bias-corrected and spatially downscaled CMIP3 projections produced collectively by 16 CMIP3 models. Model inclusion in this archive was based on a criterion, applied in summer 2007, that each model must have simulated three different GHG scenario pathways at least once (where multiple simulations reflect the simulations starting from different initial condition estimates of the climate system (i.e., "runs" reflecting different initializations)). Each projection dataset in the Archive includes monthly mean temperature and precipitation rate for the period of 1950–2099 and at a spatial resolution of 1/8°(~12 kilometers or ~7.5 miles) over the contiguous United States.

4.2 About the Map Summaries of Projected Regional Climate Change

Appendix B provides maps that illustrate climate change as it is projected to evolve in each Reclamation region through the 21st century. Each map shows change in period-mean annual temperature or precipitation. Maps vary by future period (indicated in map title), ranging from 1960–1989 to 2070–2099. These changes in period-mean climate are always assessed relative to the "simulated historical" reference period of 1950–1979. Note that the historical data in these maps are not "observed" historical climate data. They are simulated data reflecting the Archive's ensemble of "simulated historical" conditions, collectively generated by the 16 CMIP3 models listed above. In each historical simulation, the given GCM was forced by estimated time series atmospheric condition (1900–1999) and starting from an estimated initial climate condition in

[14] See: http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/#Limitations.

[15] See: http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/#About, subtab "Methodology."

year 1900 (sometimes from multiple initial conditions, leading to multiple historical "runs").[16] As a result, the Archive contains a set of "historical climates" that have been bias-corrected to be statistically consistent with 50-year climatology (1950–1999) but have not been constrained to reproduce observed frequency characteristics (e.g., drought spells and timing of occurrence). Thus, when these "simulated historical" climates are sampled for 30-year period means, the ensemble produces a range of period mean possibilities.

Change values are mapped uniquely for each downscaled location in the Archive. At any location, the change indicated is the median change surveyed among the 112 projections.[17] It is relevant to focus on the median change given that the projections do not all start from the same climate system state and because natural multidecadal climate variability can affect period-specific climate statistics like 30-year means.

4.3 Interpreting the Map Summaries for Each Region

It is recommended that the maps be interpreted as follows:

- All of the projections offer a plausible portrayal of how temperature and precipitation might have evolved historically and could evolve in the future (i.e., sequencing uncertainty).
- At any projection time-stage, we can focus on the middle condition among all of the projections' conditions to get a sense about mean climate state in the context of this sequencing uncertainty (i.e., multiprojection median).
- If we apply this view to the condition "change in period-mean climate" and track the middle change through time, we can evaluate the information for presence or absence of climate change trends.

The reader should bear in mind the following limitations when interpreting these map summaries for climate change trends:

The maps data are based on a multimodel ensemble of projections. The contributing climate models differ in their physical formulations. Because of this, their model-specific sets of projections differ in regional climate change signal.

[16] http://www-pcmdi.llnl.gov/ipcc/time_correspondence_summary.htm.

[17] The 112 climate projections included in this archive were considered to be equally plausible projections of the future given available literature suggesting difficulty in culling projections based on model skill (Reichler et al., 2008; Brekke et al. 2008; Gleckler et al. 2008) and given studies showing that regional climate projection uncertainty may not be significantly reduced even if projection sets are restricted to only include those from skill-based "better models" (Brekke et al. 2008)

Further, the model representation in the multimodel ensemble of projections is not equal, with some models contributing only three projections (one run for each of the three GHG scenario pathways mentioned above) while others contribute more (i.e., multiple runs for each GHG scenario pathway).

The maps invite focus on climate change trends and deter attention from the reality that there are uncertainties about such projected trends. Uncertainties arise from the future scenarios of GHG emissions forcing future climate (which becomes a more prominent issue beyond 2050 (IPCC, 2007)), climate model formulation (as described above), sequencing issues arising from initial condition uncertainties, and techniques for performing bias-correction on the climate model outputs as well as spatial downscaling. For planning purposes, it seems appropriate to consider a range of future climate changes, perhaps bracketing the median changes shown in these maps. Identifying an appropriate range of future climate changes remains a challenge. A simple approach has been used in some studies (e.g., Reclamation, 2007), which involves computing period-changes for each projection, assessing the spread of period-changes among the projections, and selecting a set of projections that have period-changes that bracket the spread of changes. However, it is cautioned that interpreting these period-changes as "climate change only" ignores the matter of multidecadal variability in the projections, as discussed above.

The mapped data are based on bias-corrected and spatially disaggregated climate projections. For this particular downscaling technique, the temperature change maps are identical to the spatially interpolated GCM temperature changes. The percentage precipitation changes in these maps are similar, but not identical, to corresponding changes at the GCM grid scale.

Using this viewpoint, the PN maps could be interpreted as follows:

- For *mean-annual precipitation*, weak tendency toward wetter conditions appear to develop by the early 21st century for northern portions of the region (i.e., Washington, northern Idaho, northern Oregon, and northwestern Montana). By late 21st century, this tendency becomes more pronounced and includes most of the regions southern portions.

- For *mean-annual temperature*, the projections suggest warming throughout the region, through the 21st century, with warming over the coastal portions of this region be slightly less than warming over interior portions.

The MP maps could be interpreted as follows:

- For *mean-annual precipitation*, there appears to be tendency toward drier conditions developing over southern portions of the region (i.e., southern Central Valley, southern Nevada). For the northern portions of the region,

there appears to be a tendency toward drier conditions in the early 21st century transitioning to a weak tendency toward wetter conditions by late 21st century.

- For *mean-annual temperature*, the projections suggest warming throughout the region, through the 21st century, with warming over the coastal portions of this region be slightly less than warming over interior portions.

The LC maps could be interpreted as follows:

- For *mean-annual precipitation*, the projections suggest an evolving tendency towards drier conditions for most of the region through the 21st century.

- For *mean-annual temperature*, the projections suggest warming throughout the region, through the 21st century, with warming over the coastal portions of this region be slightly less than warming over interior portions.

The UC maps could be interpreted as follows:

- For *mean-annual precipitation*, for much of the central and southern portions of the region (i.e., New Mexico, northeastern Arizona, southwestern Colorado, and southern Utah), the projections suggest an evolving tendency towards drier condition through the 21st century. For the northern portions of region (northwestern Colorado, northern Utah, southwestern Wyoming), the projections suggest wetter conditions.

- For *mean-annual temperature*, the projections suggest mostly uniform amounts of warming throughout the region through the 21st century.

The GP maps could be interpreted as follows:

- In terms of *mean-annual precipitation*, the projected trends suggest that for much of the central and northern portions of the region (e.g., Missouri Basin, Kansas, northeastern Colorado, portions of Oklahoma and Texas), the projection ensemble suggests gradually wetter conditions through the 21st century. For the southern and southwestern fringe portions of the region, there appears to be tendency for drier conditions through the 21st century (e.g., southeastern Colorado, central to western Texas).

- In terms of *mean-annual temperature*, the projected trends in warming are relatively uniform across the region through the 21st century.

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Appendix A. Literature Bibliographies

A.1 Pacific Northwest Region

This appendix section summarizes each article surveyed as part of this synthesis of climate change literature for Pacific Northwest Region. The survey is representative of articles published through early 2008, but is not exhaustive. The intent for each article summary is to give the reader a quick sense for study purpose, method highlights, and key findings. Study details are kept to a minimum; and it is suggested those readers interested in more detail should refer to the articles themselves.

Article summaries are organized in this attachment under the themes of: Historic Trends; Projected Hydrologic, Ecosystems and Water Demands Impacts; and Projected Operations Impacts. Under each theme, the articles are organized chronologically (most recent year first), then by author.

Historical Trends

2009, Hildalgo et al., "Detection and Attribution of Streamflow Timing Changes to Climate Changes in the Western United States"

Study Purpose

This study evaluates the relationship between anthropogenic climate change and observed changes in Western United States (U.S.) hydrology during the second half of the 20th century (1950–1999). The study focuses on the shift in runoff center timing (CT) caused by increasing temperatures and earlier snowmelt.

Method Highlights

- Three large hydrologic regions were evaluated (Upper Colorado River Basin, Columbia River Basin and California Region) using the Variable Infiltration Capacity (VIC) runoff model and downscaled output from three global climate models (GCMs).

- The GCM ouput were from the Community Climate System Model version 3.0, Finite Volume (CCSM3-FV; Collins et al., 2007; Bala et al., 2008), Parallel Climate Model version 2.1 (Parallel Climate Model [PCM]; Washington et al., 2000), and MIROC model (Hasumi and Emori, 2004; Nozawa et al., 2007).

- GCM output was downscaled to 1/8 degree (°) latitude/longitude using the method of constructed analogues (Hidalgo et al., 2008) and the method of Bias Correction and Spatial Disaggregation (Wood et al., 2004).

- Climate change GCM runs were evaluated against control runs with no anthropogenic forcings and with and without combined solar and volcanic forcings.

- Control run results were compared to naturalized historic river flow estimates by others.

- A method known as the optimal detection method, which reduces a multidimensional problem to a low-dimensional problem, was used to evaluate the relationship between anthropogenic climate change and observed changes in Western U.S. hydrology.

Key Findings

- Negative trends in CT in the naturalized flow estimates were found for all three areas, but the trend was significant only for the Columbia River Basin.

- Overall, the climate change modeled CT trends were comparable to the naturalized flow trends.

- All climate change modeled CT trends were not comparable to naturalized flow trends, and certain solar-volcanic forced trends were significantly positive.

- The authors found that the observed trends toward earlier CT of snowmelt-driven streamflows in the Western United States since 1950 are detectably different from natural variability (significant at the $p < 0.05$ level).

- The signal from the Columbia River Basin dominates the analysis, and it is the only basin that showed a detectable signal when the analysis was performed on individual basins.

2008, Bonfils et al., "Detection and Attribution of Temperature Changes in the Mountainous Western United States"

Study Purpose

This article reports on a rigorous detection and attribution analysis that was performed to determine the causes of the late winter/early spring changes in hydrologically relevant temperature variables over mountain ranges of the Western United States during 1950–1999.

Method Highlights

- The study used three climate models and all GCM output was downscaled to 1/8° latitude/longitude using two techniques and compared to historical observations.

- The GCM ouput were from the Community Climate System Model version 3.0, Finite Volume (CCSM3-FV; Collins et al., 2007; Bala et al. 2008), Parallel Climate Model version 2.1 (PCM; Washington et al. 2000), and MIROC model (Hasumi and Emori, 2004; Nozawa et al., 2007).

- GCM temperature output was downscaled to 1/8° latitude/longitude using the method of constructed analogues (Hidalgo et al., 2008) and the method of Bias Correction and Spatial Disaggregation (Wood et al., 2004).

- Maximum and minimum temperature data for the period 1950–99 from the University of Washington Land Surface Hydrology Research were interpolated into a 1/8° latitude/longitude grid.

- The evaluation was performed on nine subregions: the Washington Cascades, the northern Rockies, the Oregon Cascades, the Blue Mountains, the northern Sierras, the southern Sierras, the Great Basin, the Wasatch area, and the Colorado Rockies.

- January–March minimum temperatures, the number of frost days, and the degree-days above freezing were evaluated.

- Sensitivity analyses were performed on the results.

Key Findings

- In most of the regions examined, observed changes in hydrologically related temperature variables are inconsistent with natural internal variability alone and consistent with the response to anthropogenic forcings.

- The authors found that the overall interregional anthropogenic fingerprint can be positively identified in all four observed temperature indices evaluated irrespective of the model used, the downscaling method, or the end points values.

- Natural variability in the western climate system was ruled out by the analysis as the major cause of observed changes.

- Solar variability and volcanic forcings were also ruled out by the analysis.

- In the 48 scenarios evaluated, the detection time for an anthropogenic fingerprint occurs as early as 1986 and no later than 1994.

2008, Pierce et al., "Attribution of Declining Western U.S. Snowpack to Human Effects"

Study Purpose

This article reports on a formal model-based detection and attribution analysis of changes in Western U.S. snowpack conditions based the ratio of April 1 snow water equivalent (SWE) to October–March precipitation.

Method Highlights

- The study compared 1950–1999 observed SWE and precipitation data to hydrologic modeling output. GCM output was input to the hydrologic model. The intent was to isolate the signature of anthropogenically forced changes in SWE to precipitation ratio from historical model runs, determine how similar the observed changes are to the fingerprint, and calculate the likelihood a signal of the observed strength could have occurred by chance in the control run.

- Ouput from two climate models was downscaled to 1/8° latitude/longitude using two techniques and input to the VIC hydrologic model.

- The GCMs used were the Community Climate System Model version 3.0, (CCSM3; Bala et al., 2008) and Parallel Climate Model version 2.1 (PCM; Washington et al., 2000). Multiple anthropogenic scenario runs were compared to 1,600 years of control run data.

- GCM output was downscaled to 1/8° latitude/longitude using the method of constructed analogues (Hidalgo et al., 2008) and the method of Bias Correction and Spatial Disaggregation (Wood et al., 2004).

- Historic snowpack observations included snow course data from the National Waterand Climate Center and data from the California Cooperative Snow Surveys obtained from the California Data Exchange Center for a total of 661 stations.

- Historic precipitation observations consisted of the gridded (1/8° latitude/longitude) daily precipitation dataset of Hamlet and Lettenmaier (2005), which was adjusted for gauge undercatch.

Key Findings

- The mean model estimate is that approximately half of the observed changes in snowpack over the Western United States during the period 1950–1999 arise from climate responses to anthropogenic forcings.

- The authors report the above finding did not depend on whether the snow course stations were grouped geographically (by mountain range across the west) or in equally weighted or area-weighted elevation bands.

- The signal indicating decreasing ratios of SWE to precipitation caused by anthropogenic forcing is detectable at the 95% significance level by the early 1990s: a record length of about 40 years.

- Only elevations below approximately 2,000 meters (6,560 feet) have statistically significant trends of decreasing ratios of SWE to precipitation.

2008, Mote et al., "Has Spring Snowpack Declined in the Washington Cascades?"

Study Purpose

This paper addressed questions that arose during a discussion at the University of Washington regarding actual decline in snowpack in the Washington Cascade Mountains. Addressed questions included those related to sampling bias, suitability of linear fits for describing change over time, effects of the choice of analysis period, and influences of Pacific climate variability.

Method Highlights

- The analysis considered 49 long-term snow survey records in the study region, available with uneven spatial coverage, particularly before 1938 when most snow courses were at higher elevations.

- Time series smoothing was performed with a locally weighted regression scheme (referenced as the "loess") using a least-squares linear fit on weighted adjacent data points.

- Two-sided t-test used to calculate statistical significance.

- The VIC model was used to provide spatially complete data fields and to evaluate climate factors influencing snowpack variability.

- The VIC model was simulated on a daily time step, forced by gridded daily precipitation, daily minimum temperature, and daily maximum temperature.

Key Findings

- VIC results largely agree with observed data in about 75% of all courses.
- Observed streamflows also agree well with modeled results.
- Within a decade of 1955, starting date selection plays an unimportant role in the results.
- Linear fits of the data tend to obscure interesting and significant features of a time series.
- Rising temperatures dominate the determination of regionally average snow water equivalent over periods longer than 30 years.
- Precipitation variability was found to explain much of the interannual variability, but was not found to significantly explain long-term trends in SWE.
- The effects of Pacific decadal variability can be seen in the SWE declines.
- The warming trends, present in the analysis and their effects on SWE trends, are largely unrelated to Pacific climate variability but are congruent with trends expected from rising greenhouse gas emissions.

2007, Knowles et al., "Trends in Snowfall Versus Rainfall for the Western United States, 1949–2001"

Study Purpose

The purpose of this study was to examine whether a trend is occurring in the ratio of snowfall to total winter precipitation in the Western United States.

Method Highlights

- The analysis considered daily snowfall depth, precipitation, and maximum and minimum temperature data from Western U.S. climate stations for 1948–2001.
- The analysis also considered temperature data from 647 stations and precipitation data from 173 stations.
- The liquid water equivalent of snowfall was calculated as the total precipitation measured on a day when snowfall was reported.
- Winter and monthly ratios of snowfall water equivalent to total precipitation were then calculated.

- Trend analyses were performed on both sets of these ratios (winter and monthly for 1948–2001).

Key Findings

- Pronounced trends were found toward reduced winter period ratios of snowfall to total winter precipitation in the Sierra Nevada and Pacific Northwest. Results were less clear for the Rocky Mountain region.

- Where found, the trends toward reduced ratios of snowfall to total winter precipitation correspond with a warming trend in the Western United States.

- Winter period ratio trends correspond to reduced snow water equivalent values rather than to changes in overall precipitation, with the exception of the southern Rocky Mountain region where both snowfall and precipitation have increased.

- Focusing on the months of January and March, trends toward reduced ratio of snowfall water equivalent to precipitation are most pronounced in March, throughout the Western United States, and in January near the west coast. The geographic constraint on the latter trend may be related to the decreasing trend in mean temperature found during January was found at higher elevations, potentially restricting the trends toward reduced ratio of January snowfall water equivalent to precipitation to occur in the lower elevations near the west coast. In contrast, March trends toward increasing air temperature were found throughout the region, which corresponded to the March reductions in ratio of snow water equivalent to total precipitation.

2007, Hamlet and Lettenmaier, "Effects of 20th Century Warming and Climate Variability on Flood Risk in the Western United States"

Study Purpose

This study investigates changes in flood risk in the Western United States associated with century-wide warming and interannual climate variations. Additionally, implications of increases in precipitation variability since the mid 1970s are explored.

Method Highlights

- The VIC model with a spatial resolution of 1/8º was used.

- A daily time step streamflow routing model (described by Lohmann et al. [1998]) was used to postprocess the runoff generated by VIC.

- The driving meteorological data was the gridded 1/8º data set for the Western United States described by Hamlet and Lettenmaier (2005).

- 5-, 10-, 20-, 50-, and 100-year return flood periods were calculated for each model forcing data set.

Key Findings

- Simulations suggest that the warming over the 20th century has resulted in changes in flood risks in many parts of the region broadly characterized by midwinter temperatures.

- Colder, snowmelt basins typically show reductions in flood risks because of snowpack reductions.

- The precipitation data sets show clear increases in the variability of cool season precipitation.

2007, Hamlet et al., "20th Century Trends in Runoff, Evapotranspiration, and Soil Moisture in the Western United States"

Study Purpose

The VIC model is used to produce a long time series of key hydrologic variables (evapotranspiration, runoff, soil moisture) across the Western United States. The objective was to quantify hydrologic trends from simulations forced by observed temperature and precipitation over two time periods: the entire period of record (1916–2003), and a period that covers one full cycle of the Pacific decadal oscillation (1947–2003).

Method Highlights

- VIC was applied to the area west of the U.S. Continental Divide using a 1/8º spatial resolution.

- A gridded daily time step precipitation and temperature dataset from 1915–2003 used to drive the model.

- The first 9 months of VIC simulation were used as a simulation spin-up period (January to September 1915) to remove the effects of initial system conditions.

Key Findings

- VIC-simulated snowpack agreed well with snowpack derived using statistical approaches.

- A relationship was found between midwinter temperatures and the simulated seasonal snowmelt cycles.
- The model produced high quality streamflow simulations capturing hydrologic variability associated with different climate regimes.
- The model was well suited in identifying long-term trends in the streamflow seasonality.
- The model reproduced well the seasonal soil moisture and evapotranspiration dynamics.

2006, Andreadis and Lettenmaier, "Trends in 20th Century Drought Over the Continental United States"

Study Purpose

The purpose of the study was to determine if changes in drought characteristics have occurred over the continental United States in the past 80 years. For changes that were found, the nature of such changes was explored.

Method Highlights

- The VIC model used to simulate soil moisture and runoff over the continental United States at a ½º spatial resolution and daily time step.
- Forcing data included precipitation, air temperature, and wind speed obtained and extended from 1915 to 2003, and the data were corrected for temporal heterogeneities.
- The study investigates agricultural and hydrological droughts indicated by soil moisture and runoff.
- The seasonal Mann-Kendall test was applied to monthly simulated soil moisture and runoff data for the study using a 0.05 significance level on a two-sided test.

Key Findings

- 43.6% of the cells display an increasing trend in soil moisture; 2.9% showed a decreasing trend in soil moisture and were located primarily in the Southwest.
- 41.5% of the cells display an increasing trend in runoff; 2.3% showed a decreasing trend.

- Time series of drought duration was constructed showing 47 upward (increased duration) runoff trends and 102 downward (decreased duration). Similarly for soil moisture 62 upward and 161 downward trends.

- Decreasing trends for drought severity levels were found in the Pacific Northwest, while increasing trends were found in Texas and the intermountain West.

2006, Mote, "Climate-driven Variability and Trends in Mountain Snowpack in Western North America"

Study Purpose

Multiple linear regression techniques are used to evaluate the sensitivity to temperature and precipitation of April 1 SWE using nearly 1,000 locations in the Western United States. This analysis allows the separation of the temperature and precipitation influences on the observed trends.

Method Highlights

- Snow course data through 2002 was obtained. In some instances, manual snow courses have been replaced with automated snow telemetry equipment. Both manual and telemetered data were used.

- 995 snow records were obtained and used representing the time period 1960–2002.

- For each snow course location, reference time series temperature and precipitation data were developed by combining observations of the five nearest climate stations during November through March.

- A regression model of April 1 SWE values was developed as a function of seasonal (November–March) means of temperature and precipitation.

Key Findings

- For most snow courses, the regression approach suggests that the long-term April 1 SWE variations can be reasonably explained by antecedent seasonal climate summaries at nearby locations.

- The study found general agreement between observed and climate derived SWE.

- Findings imply that other sources of long-term trends are secondary.

- From mid-century to the early 2000s, general winter and spring warming caused a reduced snow pack at most locations. This was offset by precipitation increases in the southern Sierra Nevada of California resulting in a net increase in SWE.

- Some of the trends might be explained by variations in North Pacific climate, which was shown to explain approximately 50% of the SWE variability through regression modeling.

2005, Regonda et al., "Seasonal Cycle Shifts in Hydroclimatology Over the Western United States"

Study Purpose

The purpose of this study was to examine the relationship between the timing of snowmelt in the mountain basins of the Western United States relative to trends in temperature, precipitation and snow pack conditions.

Method Highlights

- The analysis considered data during 1950–1999 from 89 stream gauges in Western U.S. river basins having a significant snowmelt season.

- Stream gauge data were analyzed for runoff timing trends.

- Trend analyses were performed on March, April, and May SWE data from Western U.S. snow-course surveys and on winter precipitation and spring temperature.

Key Findings

- Peak runoff occurred earlier at most stations during the period, and significant trends toward earlier runoff were found in the Pacific Northwest.

- Significant trends toward increasing spring temperature were found throughout the region, with larger trends found in the Pacific Northwest and Rocky Mountain regions.

- Increasing winter precipitation trends were identified for much of the study area; however, the fact that the data did not show a significant increase in total spring runoff suggests as total winter precipitation increases, more of it is coming in the form of rain.

2001, Cayan et al., "Changes in the Onset of Spring in the Western United States"

Study Purpose

The purpose of this study was to evaluate the affects of spring climate conditions in the Western United States on blooming plants and the timing of snowmelt-runoff pulses. Statistical methods were used to determine whether correlations exist between spring temperatures, first bloom dates, and runoff timing.

Method Highlights

- Statistical methods were used to determine whether correlations exist between spring temperatures, first bloom dates, and runoff timing.
- The analysis considered data from 105 lilac observation stations with 20 years or more of data during 1957–94 and from 87 honeysuckle stations with 15 or more years of data during 1968–94.
- These plant observation stations were located throughout the Western United States at elevations ranging from 15 to 2,927 meters.
- The analysis also considered streamflow records from 110 Western U.S. rivers for periods beginning in 1948 and ending between 1988 and 1995, focusing on the annual date of first major pulse of spring runoff (defined as the day when the cumulative departure from that year's mean flow is most negative, equivalent to finding the day after which most flows are greater than average).
- Temperature and precipitation averages for regions corresponding to plant observation stations were used for correlation analyses.

Key Findings

- Lilac and honeysuckle first bloom dates are highly correlated with each other.
- The first bloom dates of both plants were found to positively correlate with initial runoff pulse dates and temperature anomaly.
- Authors suggested that earlier onset of spring is remarkable from the late 1970s to mid-1990s, as spring temperatures were found to have increased from 1–3 degree Celsius (°C) in western North America between the late 1970s and late 1990s.

- Earlier and warmer-than-normal spring temperatures were related to larger scale atmospheric conditions across North America and the North Pacific.

1999, Lettenmaier et al., "Water Resources Implications of Global Warming: A U.S. Regional Perspective"

Study Purpose

This report presents the summarization of six studies of the sensitivity of water resources to climate change. Of the six, the Columbia and Tacoma systems apply to the Pacific Northwest (PN) Region. Study attempted to reflect the most current transient general circulation model (GCM) predictions, investigate end user effect of climate change on water resources (not just the sensitivity of the hydrologic system), and to use models and methods of analysis that are somewhat standard.

Method Highlights

- Three transient coupled ocean-atmosphere CGMs were used (GFDL89, ECHAM1-A, and UKMO).

- Each climate model was used to simulate current climate conditions and carbon dioxide (CO_2) levels as a base run and then to simulate a transient climate forced by annually increasing CO_2 concentrations to double in 60 and 70 years.

- Rather than performing a true transient analysis, five steady-state analyses were preformed with each GCM, where the five analyses tracked the transient nature of the climate forcing.

- The impacts assessment approach was consistent for each basin: 1) downscaling of GCM precipitation, temperature, and solar radiation; 2) translation of downscaled climate projections to weather forcings for hydrologic simulations of streamflow; 3) translation of streamflow results into water supply changes for water resource management models in the case study basins.

- Climate change effects were, when available, compared against other, nonclimate, system impacts (demand growth and other plausible future operational considerations).

- Systems modeled for five decades.

Key Findings (focusing on the Columbia Basin portion of the study)

- Precipitation changes are at least as important to system performance as temperature changes.

- Large decreases in streamflow under the ECHAM1-A and UKMO scenarios degraded power production, instream flow reliability, and irrigation withdraw.
- The increased streamflows resulting from the GFDL89 scenario had an opposite effect on system performance.
- The performance of the Columbia system is fairly robust to the effects of climate change.
- Tacoma system headwaters, in the Washington Cascade Mountains, are sensitive to a strong spring snowmelt signal. As the snowmelt becomes progressively earlier, adjustments in management are required.
- The effects of runoff timing and changes in runoff magnitude were the primary factors influencing system performance.
- Municipal and industrial (M&I) supply was unaffected by the climate change scenarios because of protection by legal priority.
- Instream flow requirements were met less frequently as the water supply for M&I uses took larger proportions of the flow under warmer conditions.

Projected Hydrologic, Ecosystem, and Water Demand Impacts

2009, Mote and Salathe, "Future Climate in the Pacific Northwest"

Study Purpose

This study included evaluation of potential mid-21st century climate change impacts to the Pacific Northwest Region based on a subset of IPCC AR4 climate model output. Predicted parameters include air temperature, precipitation, sea level rise, and sea surface temperature changes.

Method Highlights

- GCM output from 20 models under emissions scenarios A1B, A2, and B1 were used for a total of 56 runs.
- Area-averaged historic observations data were used over the same domain as the climate models (monthly means for 1901–2000) for bias analysis.
- The authors applied two downscaling methods, each guided by a 1/16°- gridded dataset of observed temperature and precipitation.

- Ranges of projected changes were presented from model simulations as well as weighted average changes using the Reliability Ensemble Averaging approach.

Key Findings

- By the 2080s, the predicted weighted average air temperature change is almost 3.4 °C (6.1 °F) for A1B and only 2.5 °C (4.5 °F) for B1. The range for these two scenarios is 1.5–5.8 °C (2.8–9.7 °F).

- For both B1 and A1B scenarios, warming is projected to be largest in the summer.

- The predicted annual mean of the weighted average precipitation change for the Pacific Norwest is practically zero throughout the 21st century, though individual models produce changes of as much as -10% and +20% by the 2080s.

- The most consistent changes in predicted precipitation are in the summertime, with a large majority of models (68–90% depending on decade and scenario) projecting decreases and the summer weighted average value reaching -14% by the 2080s.

- A majority of the projections (50–80% depending on decade and scenario) suggest increases in winter precipitation with the weighted average reaching +8% (about 3 centimeters [cm]) by the 2080s for the A1B scenario.

- No correspondence was found between air temperature change and precipitation change in the Pacific Northwest.

- The modeled change in sea surface temperature for the east Pacific coastal area between 46° and 49° north latitude by 2059 is about 1.2 °C (2.2 °F).

- A low-probability high-impact estimate of Puget Sound Basin sea level rise is 55 cm (22 inches) by 2050 and 128 cm (50 inches) by 2100. Low-probability, high impact estimates are smaller for the central and southern Washington coast (45 cm [18 inches] by 2050 and 108 cm [43 inches] by 2100), and even lower for the northwest Olympic Peninsula (35 cm [14 inches] by 2050 and 88 cm [35 inches] by 2100) due to tectonic uplift.

2007, Battin et al., "Projected Impacts of Climate Change on Salmon Habitat Restoration"

Study Purpose

Using a series of linked models (climate, land cover, hydrology, and Chinook salmon population), this study investigates the impacts of climate change on the effectiveness of proposed habitat restoration efforts in the Snohomish River Basin of western Washington State.

Method Highlights

- Climate change scenarios were simulated under the Intergovernmental Panel on Climate Change Special Report on Emissions Scenario's A2 Scenario using two CGMs: GFDL R30 and HadCM3.

- Three land use scenarios were considered: current conditions, moderate restoration (based on linear future projection of land use and population trends), full restoration (where all restoration plan targets are met). Land use scenarios and restoration plan targets were developed by Snohomish River Basin planners.

- GCM results were downscaled and converted into future climate scenarios by the Wiley method which is based on the quantile mapping method.

- Surface water response was simulated using the Distributed Hydrology Soil Vegetation Model (DHSVM) with an added groundwater layer and radiative and conductive heat balance routine.

- The DHSVM model was forced using a 72-year meteorology time series consistent with the downscaled climate change scenarios.

- The Shiraz population model was used to simulate the effects of flow changes, temperature, and habitat capacity on salmon population. The model is based on a multistage Beverton-Holt routine where fish productivity and habitat capacity determine the number of fish that survive from one life-stage to another.

Key Findings

- Climate models estimated mean air temperature increases of 0.7 to 1.0 ºC (1.8 ºF) by 2025 and 1.3 to 1.5 ºC (2.3 to 2.7 ºF) in 2050 relative to 2001 conditions.

- GFDL scenario resulted in larger projected changes in incubation (October 15–February 15) peak flow and smaller changes in prespawning

(August 15–September 15) temperature and spawning (September 15–November 15) than the HadCM3 scenario.

- Land use changes had little effect on basin-wide average values for primary hydrologic variables.

- Modeled impacts of climate change on freshwater salmon habitat and productivity were consistently negative, while habitat restoration scenarios were found capable of substantially or even fully mitigating the projected negative impacts of climate change.

2007, Slaughter and Wiener, "Water, Adaptation, and Property Rights on the Snake and Klamath Rivers"

Study Purpose

The study examines Snake and Klamath River institutions for their ability to resolve conflict created by demand growth, drought, and environmental constraints on water use. The article focuses on the implementation of the prior appropriation doctrine in the two river basins.

Method Highlights

- Both basins use prior appropriation water law.

- Idaho (Snake River) water disputes have primarily centered on irrigation use. Oregon's development of water banks suggests that the primary motivation for innovation has been environmental concerns.

Key Findings

- Property rights relative to water diversions on the Snake River are somewhat stronger that on the Klamath.

- The Idaho system is characterized by a very high level of ownership and decisionmaking participation.

- To date, the Snake system has been fairly robust in creating settlements in the face of crisis-like reduced allocations because of climate induced shortages.

2004, Lettenmaier "The Role of Climate in Water Resources Planning and Management"

Study Purpose

This paper is designed to track the evolution of modern water management methods and their relationship to climate and to indicate the potential and role of new methods for predicting climate variability and change. Especially considered are new and evolving information about climate variability and change.

Method Highlights

- Early development of methods for sizing reservoirs was based on mass curve analysis applied to observed sequences of reservoir inflows.
- Stochastic hydrology can now be considered a mature field.
- Though this is true, the standard practice is still to use an analysis of historic records for design purposes.
- The stochastic model of long-term persistence, while challenging the idea of stationarity, became the precursor of climate change assessments.

Key Findings

- Opportunities for the development of procedures to account for climate change in water resources planning and management are two fold: 1) development of stochastic models that account for climate change through the use of estimates that are weighted more toward recent observations instead of the historic (some times distant) past, 2) methods for planning water management systems under uncertainty.

2003, Reiner et al., "Natural Ecosystems I: The Rocky Mountains"

Study Purpose

This peer reviewed assessment of climate-change effects on Rocky Mountain and Great Basin terrestrial ecosystems is based on research efforts discussed at a series of workshops conducted as part of the U.S. Global Change Research Program.

Method Highlights

- The ecosystem analysis was based on two climate change scenarios for each of two subregions. The subregions are defined

as 1) Northern, North-centra,l and West-central Rockies and 2) East-central and Southern Rockies.

- The subregion climate change scenarios included the same seasonal temperature changes, but with differing precipitation and snowpack conditions.

- Under Scenario 1 for the East-central and Southern Rockies subregion, there is increased winter precipitation and decreased growing-season precipitation and under Scenario 2, increased precipitation only in the summer.

- Under Scenario 1 for the Northern, North-central, and West-central Rockies subregion, there is significantly increased winter precipitation and under Scenario 2, increased precipitation predominantly in the spring and summer.

- The results of several cases studies are presented.

Key Findings

- General vegetation-related predictions include: where vegetation zones have the same character (e.g., alpine zone), their boundaries will move down in elevation with increasing latitude; the effect of slope-aspect will increase with latitude; and the nature of the zones themselves change with latitude through the addition and loss of dominant species.

- Under Scenario 1 for the East-central and Southern Rockies subregion, significant decreases in plant productivity, losses of area in forested ecosystems, and some local losses of native species are predicted. Under Scenario 2, less impact is predicted.

- Under Scenario 1 for the Northern, North-central and West-central Rockies subregion, relatively more drought-tolerant species such as Douglas fir might expand into higher elevations while maintaining populations in their current elevation zone and early season crops in intermountain basins could benefit. Under Scenario 2, vegetation in the Northern Rockies would experience more favorable conditions for growth in general due to more moisture and longer growing season.

- It is discussed that all of the scenarios would increase forest fires in that warmer temperatures help to produce more fuel in wet periods and to dry fuels in dry periods.

- There is evidence that pest infestations and diseases such as white pine blister rust may be exacerbated by warming temperatures, but many other factors must be considered.

- The authors discuss that animal species may appear in new locations and become extinct in others and the ability to adapt to heat and water stress are difficult to predict.

2003, Covich et al., "Natural Ecosystems II: Aquatic Ecosystems"

Study Purpose

This peer reviewed assessment of climate change effects on Rocky Mountain and Great Basin aquatic ecosystems is based on research efforts discussed at a series of workshops conducted as part of the U.S. Global Change Research Program.

Method Highlights

- The goals of this effort were to 1) summarize important points needed to understand ways in which large-scale, long-term dynamics of climate would affect inland aquatic ecosystems, 2) provide examples and case studies that illustrate general relationships of how climate change has already affected aquatic species and ecosystems in the Rocky Mountain/Great Basin (RMGB) region, and 3) identify gaps in current understanding that need more study in order to improve future forecasts regarding the expected consequences of climate change on freshwater ecosystems.

- Past and current climate variability, as well as spatial variability of impacts, is discussed.

- The RMGB region was divided into northern and southern subregions for future climate change impacts assessments. The southern subregion includes the southern halves of Utah and Colorado and the northern New Mexico portions of the RMGB region. The northern subregion includes virtually all of the Great Basin and those portions of the Rocky Mountain system north of central Utah and central Colorado.

- The climate change scenario considered for the northern region consists of warmer fall, winter and spring temperatures, and increased winter precipitation. The climate change scenario considered for the southern region consists of warmer winter and late summer temperatures, reduced winter rain, and increased summer rain.

Key Findings

- The authors report climate change will almost certainly alter the aquatic ecosystems of the RMGB region, and some changes can be anticipated, especially for the southern subregion.

- Warmer spring temperatures are expected to extend the growing seasons of some species of fishes and invertebrates and alter food-web dynamics.

- Warmer surface waters (epilimnion) and slightly warmer bottom waters (hypolimnion) of stratified lakes and reservoirs will likely alter phytoplankton and zooplankton community structure and productivity by increasing metabolic rates and shifting competitive and feeding relationships.

- Higher water temperatures may well shift the distributions of cold-water species northward and to higher elevations and favor some nonnative species which are likely to compete more stringently with species that are now threatened or endangered.

- Warmer and more nutrient-rich waters (from various human effluents) will likely modify many different types of aquatic ecosystems by accelerating nutrient cycling and increasing primary and secondary productivity while at the same time impacting individual species.

- Firm quantitative predictions await the development of coupled hydrologic and ecosystem models and increased information on many aspects of the RMGB aquatic ecosystems.

2003, Mote et al., "Preparing for Climate Change: the Water, Salmon, and Forests of the Pacific Northwest"

Study Purpose

This paper examines the influences of past climate variability on fresh water resources, salmon, and forests of the Pacific Northwest as well as the potential impacts of expected future climate variability. The assessment is placed in the context of other stresses including population growth, reductions in many salmon runs and the required reductions of timber and salmon harvesting.

Method Highlights

- Climate change scenarios were simulated using eight coupled ocean-atmosphere GCMs (CCSR, CGCM1, CSIRO, ECHAM4/OPYC, GFDL, HadCM2, HadCM3, NCAR PCM3), where each simulation was forced by transient CO_2 and anthropogenic sulfate aerosol emissions.

- The study only considered regionally averaged climate change simulated by the GCMs, which was considered appropriate given that interannual and longer timescale variations in Pacific Northwest climate is spatially coherent.

- Output was examined in two ways: complete history of three models to determine their performance compared to observations, differences between the control (20th century) to the 2020s and 2040s using all eight models.

- Regressions and correlations were calculated between climate and Columbia River flow anomalies.

- Surface water response was simulated using a VIC model application for the Columbia River basin.

Key Findings

- Fresh Water
    - Average annual Columbia River flows were found to decrease by about 10% during warm phases of the El Niño Southern Oscillation (ENSO) and Pacific decadal oscillation (PDO).
    - Annual Columbia River flows were found to increase by about 10% during cool phases of ENSO and PDO.

- Salmon
    - Pacific Northwest stocks were found to decrease during warm phases of the PDO.
    - Mechanisms linking PDO to these salmon stock reductions are not reliably known.

- Forests
    - Snowpack reductions during warm phase years had differing effects on trees growing at different elevations and in different moisture regimes.
    - PDO phase was found to associate well with growth variability in forests near their upper and lower elevation limits (opposite in sign).
    - The study results suggest that the three regional resources have a greater sensitivity to climate relative to what was previously understood.

Projected Operations Impacts

2004, Payne et al., "Mitigating the Effects of Climate Change on the Water Resources of the Columbia River Basin"

Study Purpose

This paper reports the results from a sequence of modeling steps (climate, hydrology, water resources) used to explore mitigation options for Columbia River Basin water management under climate change, necessary to balance the needs of the various users (hydropower, irrigation, recreation, instream flows).

Method Highlights

- Study was based on three climate change scenarios, simulated by one GCM (the DOE/NCAR PCM).
- The three climate change scenarios were defined by different levels of greenhouse gas forcing on climate: (1) Historical (transient CO_2 and aerosols evolving from pre-industrial levels), (2) Climate control (constant CO_2 and aerosols at 1995 estimated levels), and (3) Climate Change (business-as-usual future scenario forcing).
- Each climate change scenario, simulated at GCM spatial resolution, was statistically downscaled to basin scale and bias-corrected during a 50-year historical period (1950–1999).
- Surface water response was simulated using a VIC application for the Columbia basin, applied at 1/4° spatial resolution, forced by gridded daily precipitation, daily minimum temperature, and daily maximum temperature.
- Columbia River reservoir system response was simulated using the ColSim model, which included operational components of the system: streamflows, hydropower, flood control, agricultural withdrawals, and recreation.
- ColSim uses naturalized flows derived from VIC results and a "perfect foresight" approach to generate a set of rule curves used to operate all of the reservoirs in the system.

Key Findings

- The climate change scenarios feature a moderate warming by the end of the 21st century approaching 2.1 ºC (3.8 ºF) relative to the

1950–1999 average conditions, leading to a gradual shift towards reduced snow packs and earlier runoff.

- Average annual runoff changes were unsubstantial, only about 5%.
- Seasonal runoff changes were significant. Increased winter runoff seemed to necessitate earlier dates of winter flood control drawdown relative to current dates.
- The most significant operational result was an increased competition for water supply between demands associated with instream flows and hydropower production. In order to maintain current levels of instream flows, a 10–20% reduction in firm hydropower production would be required.

1999, Hamlet and Lettenmaier, "Effects of Climate Change on Hydrology and Water Resources in the Columbia River Basin"

Study Purpose

This study explores potential future changes to Pacific Northwest climate, surface water response of the Columbia River Basin, and the ability of the Columbia River reservoir system to meet regional resource objectives.

Method Highlights

- Originally, four climate change scenarios were considered, as simulated by four global climate models: CGCM1, CGCM, HadCM2, ECHAM4. Only the scenarios simulated by HadCM2 and ECHAM4 were used in detailed analysis because they had the highest spatial resolution, the most realistic land surface schemes, and simulated the seasonal changes in temperature and precipitation that brackets that collective changes from the four scenarios originally considered. For each of the global climate simulations, a 1%-per-year compounding increase in atmospheric CO_2 was assumed. The effects of sulfate aerosols were also included.
- The "delta" method of downscaling the CGM simulations was used to map the changes to the historic record.
- Surface water response was simulated using a VIC model applied at 1/8º resolution to the Columbia basin.
- VIC-forcing data were derived from interpolated station data recorded from 1961–1997.

- Columbia River reservoir system response was simulated using the ColSim model, which included operational components of the system: streamflows, hydropower, flood control, agricultural withdrawals, and recreation.

- Key dates used to measure system response are: 2025, 2045, 2095.

Key Findings

- Average winter and summer temperature changes are consistent between GCMs.

- Future precipitation differences simulated between the GCMs were substantial.

- Maximum average basin SWE decreased in VIC simulations forced by climate change weather relative to VIC forced by historical.

- Temperature changes are the primary driver for differences in evapotranspiration.

- Summer streamflow decreased in all simulations (except HadCM2 in 2025) by as much as 26% creating an increased competition for water between different demands.

A.2 Mid-Pacific Region

This appendix section summarizes each article surveyed as part of this synthesis of climate change literature for Mid-Pacific (MP) Region. The survey is representative of articles published through early 2008 but is not exhaustive. The intent for each article summary is to give the reader a quick sense for study purpose, method highlights, and key findings. Study details are kept to a minimum; and it is suggested those readers interested in more detail should refer to the articles themselves.

Article summaries are organized in this attachment under the themes of: Historic Trends; Projected Hydrologic, Ecosystems and Water Demands Impacts; and Projected Operations Impacts. Under each theme, the articles are organized chronologically (most recent year first), then by author.

Historical Trends

2009, Hildalgo et al., "Detection and Attribution of Streamflow Timing Changes to Climate Changes in the Western United States"

Study Purpose

This study evaluates the relationship between anthropogenic climate change and observed changes in Western U.S. hydrology during the second half of the 20th century (1950–1999). The study focuses on the shift in runoff CT caused by increasing temperatures and earlier snowmelt.

Method Highlights

- Three large hydrologic regions were evaluated (Upper Colorado River Basin, Columbia River Basin, and California Region) using the VIC runoff model and downscaled output from three GCMs.
- The GCM ouput were from the Community Climate System Model version 3.0, Finite Volume (CCSM3-FV; Collins et al., 2007; Bala et al., 2008), Parallel Climate Model version 2.1 (PCM; Washington et al. 2000), and MIROC model (Hasumi and Emori, 2004; Nozawa et al., 2007).
- GCM output was downscaled to 1/8° latitude/longitude using the method of constructed analogues (Hidalgo et al., 2008) and the method of Bias Correction and Spatial Disaggregation (Wood et al., 2004).
- Climate change GCM runs were evaluated against control runs with no anthropogenic forcings and with and without combined solar and volcanic forcings.
- Control run results were compared to naturalized historic river flow estimates by others.
- A method known as the optimal detection method, which reduces a multidimensional problem to a low-dimensional problem, was used to evaluate the relationship between anthropogenic climate change and observed changes in Western U.S. hydrology.

Key Findings

- Negative trends in CT in the naturalized flow estimates were found for all three areas, but the trend was significant only for the Columbia River Basin.
- Overall, the climate change modeled CT trends were comparable to the naturalized flow trends.

- All climate change modeled CT trends were not comparable to naturalized flow trends, and certain solar-volcanic forced trends were significantly positive.

- The authors found that the observed trends toward earlier CT of snowmelt-driven streamflows in the Western United States since 1950 are detectably different from natural variability (significant at the $p < 0.05$ level).

- The signal from the Columbia River Basin dominates the analysis, and it is the only basin that showed a detectable signal when the analysis was performed on individual basins.

2008, Bonfils et al., "Detection and Attribution of Temperature Changes in the Mountainous Western United States"

Study Purpose

This article reports on a rigorous detection and attribution analysis that was performed to determine the causes of the late winter/early spring changes in hydrologically relevant temperature variables over mountain ranges of the Western United States during 1950–1999.

Method Highlights

- The study used three climate models and all GCM output was downscaled to 1/8° latitude/longitude using two techniques and compared to historical observations.

- The GCM ouput were from the Community Climate System Model version 3.0, Finite Volume (CCSM3-FV; Collins et al., 2007; Bala et al., 2008), Parallel Climate Model version 2.1 (PCM; Washington et al., 2000), and MIROC model (Hasumi and Emori, 2004; Nozawa et al., 2007).

- GCM temperature output was downscaled to 1/8° latitude/longitude using the method of constructed analogues (Hidalgo et al., 2008) and the method of Bias Correction and Spatial Disaggregation (Wood et al., 2004).

- Maximum and minimum temperature data for the period 1950–99 from the University of Washington Land Surface Hydrology Research were interpolated into a 1/8° latitude/longitude grid.

- The evaluation was performed on nine subregions: the Washington Cascades, the northern Rockies, the Oregon Cascades, the Blue Mountains, the northern Sierras, the southern Sierras, the Great Basin, the Wasatch area, and the Colorado Rockies.

- January–March minimum temperatures, the number of frost days, and the degree-days above freezing were evaluated.

- Sensitivity analyses were performed on the results.

Key Findings

- In most of the regions examined, observed changes in hydrologically related temperature variables are inconsistent with natural internal variability alone and consistent with the response to anthropogenic forcings.

- The authors found that the overall interregional anthropogenic fingerprint can be positively identified in all four observed temperature indices evaluated irrespective of the model used, the downscaling method, or the end points values.

- Natural variability in the western climate system was ruled out by the analysis as the major cause of observed changes.

- Solar variability and volcanic forcings were also ruled out by the analysis.

- In the 48 scenarios evaluated, the detection time for an anthropogenic fingerprint occurs as early as 1986 and no later than 1994.

2008, Pierce et al., "Attribution of Declining Western U.S. Snowpack to Human Effects"

Study Purpose

This article reports on a formal model-based detection and attribution analysis of changes in Western U.S. snowpack conditions based the ratio of April 1 SWE to October–March precipitation.

Method Highlights

- The study compared 1950–1999 observed SWE and precipitation data to hydrologic modeling output. GCM output was input to the hydrologic model. The intent was to isolate the signature of anthropogenically forced changes in SWE to precipitation ratio from historical model runs, determine how similar the observed changes are to the fingerprint, and calculate the likelihood a signal of the observed strength could have occurred by chance in the control run.

- Ouput from two climate models was downscaled to 1/8° latitude/longitude using two techniques and input to the VIC hydrologic model.

- The GCMs used were the Community Climate System Model version 3.0, (CCSM3; Bala et al. 2008) and Parallel Climate Model version 2.1 (PCM; Washington et al., 2000. Multiple anthropogenic scenario runs were compared to 1,600 years of control run data.

- GCM output was downscaled to 1/8° latitude/longitude using the method of constructed analogues (Hidalgo et al., 2008) and the method of Bias Correction and Spatial Disaggregation (Wood et al., 2004).

- Historic snowpack observations included snow course data from the National Waterand Climate Center and data from the California Cooperative Snow Surveys obtained from the California Data Exchange Center for a total of 661 stations.

- Historic precipitation observations consisted of the gridded (1/8° latitude/longitude) daily precipitation dataset of Hamlet and Lettenmaier (2005), which was adjusted for gauge undercatch.

Key Findings

- The mean model estimate is that approximately half of the observed changes in snowpack over the Western United States during the period 1950–1999 arise from climate responses to anthropogenic forcings.

- The authors report the above finding did not depend on whether the snow course stations were grouped geographically (by mountain range across the West) or in equally weighted or area-weighted elevation bands.

- The signal indicating decreasing ratios of SWE to precipitation caused by anthropogenic forcing is detectable at the 95% significance level by the early 1990s: a record length of about 40 years.

- Only elevations below approximately 2,000 meters (6,560 feet) have statistically significant trends of decreasing ratios of SWE to precipitation.

2008, Peterson et al., "Principal Hydrologic Responses to Climatic and Geologic Variability in the Sierra Nevada, California"

Study Purpose

The purpose of this study was to analyze hydrologic measurements from Sierra Nevada watersheds to explore how variations in snowmelt-driven stream discharge relate to climatic change and geologic conditions.

Method Highlights

- The analysis considered daily streamflow data from 24 Sierra Nevada stream gauges in 18 river basins, focusing on initiation of spring pulse, peak runoff, and base flow by trend analysis.
- The analysis also considered snow station data from 18 Sierra Nevada river basins.
- SWE trends were evaluated relative to runoff trends.
- Bedrock compositions for the 18 study basins were estimated from geologic maps and used to evaluate correlation between observed runoff trends and basin geology.

Key Findings

- Most basins showed trends for earlier spring runoff.
- Intrabasin runoff trends (base, peak, and pulse flow magnitude and timing within a basin) are due to many factors in addition to geology and require further study.
- Evidence was found that watersheds with proportionally more base flow contribution to total runoff also happen to store more soil water than watersheds exhibiting a stronger peak-flow response to SWE.
- Evidence was found that the influence of antecedent wet or dry years is greater in watersheds with relatively greater base flow contribution.
- Results showed strong correlation between magnitude of peak flow and SWE and suggested that this relationship might be used to predict peak flow weeks in advance.

2008, Bindoff et al. "Observations: Oceanic Climate Change and Sea Level"

Study Purpose

This document summarizes the findings of recent studies pertaining to climate change effects on sea level. It discusses global and regional effects observed over time spans ranging from the last decade to the past century and the mechanisms associated with the effects.

Method Highlights

- Changes in sea level are based on measurements using tide gauges and satellite altimetry.

- Extreme sea level changes are based on measurements of surge-at-high-water during storm events.

- Ocean salinity changes are considered with regard to regional sea level changes.

Key Findings

- There is significant evidence indicating that the overall global sea level gradually rose during the 20th century following a period of little change between AD 0 and AD 1900.

- Global mean sea level change results primarily from thermal expansion and exchange of water between oceans and other reservoirs.

- Both geographically nonuniform sea level changes and global mean sea level changes have been documented.

- The 20th century global average sea level rose at a rate of about 1.7 millimeters per year (mm/yr); and since 1993, the rate has been about 3 mm/yr.

- It is estimated that thermal expansion and glacial melting each account for about half of the observed sea level rise during recent years (1993–2003); however, the budget for the remainder of the century is problematic.

- Some regional sea level change observations have been related to processes other than thermal expansion and glacial melting (e.g., changes in circulation and salinity conditions).

2007, Beckley et al., "A reassessment of Global and Regional Mean Sea Level Trends from TOPEX and Jason-1 Altimetry Based on Revised Reference Frame and Orbits"

Study Purpose

In this study, the authors calculated regional and mean sea level values from altimetry data using methods improved over past calculations and performed trend analyses on these data.

Method Highlights

- Mean sea level values were calculated from altimetry data for the period 1993–2007 using the 2005 international Terrestrial Reference Frame and updated gravity field information.

- Altimetry data were from the Topex satellite for January 1993 to August 2002 and the Jason-1 satellite for January 2002 to December 2006.
- A range of geophysical corrections were applied to the data.
- Instrument-dependant drifts and biases were identified by comparing the altimetry based sea level values to tide gauge data; drifts and biases were then corrected.
- Ten-day cycle mean sea level values were computed from the altimetry data, and a linear trend analysis was performed.

Key Findings

- The linear trend analysis shows a mean seal level increase rate over the 14-year period of 3.36 mm/year, which is about 0.6 mm/year higher than previous estimates.
- The 1993–2000 mean sea level increase rate calculated was 2.53 mm/year, and the 2000–2007 rate was 3.99 mm/year.
- Regional trend analyses results show short-period variability indicative of phenomena such as El Nino Southern Oscillation interdecadal variability.
- The authors discuss that recent glacial ice melt could explain, in part, the post-1997 increasing sea level rise rate, and that several decades of data are needed to adequately resolve the acceleration term.

2007, Vicuna and Dracup, "The Evolution of Climate Change Impact Studies on Hydrology and Water Resources in California"

Study Purpose

The purposes of this effort were to review past studies pertaining to climate change impacts on California hydrology and water resources and to identify potential topics for future study.

Method Highlights

- Review findings were subdivided into three categories: historical trends and evidence of climate change; future predicted impacts of climate change on hydrology; and predicted economic, ecologic, and institutional impacts associated with climate change impacts on hydrology.
- Findings are tabulated according to basins studied and methods used.
- Reviews placed emphasis on methodological procedures.

Key Findings

- Since 1983, more than 60 studies have been conducted on the impacts of climate change on California hydrology and water resources. Most studies focused on predicting hydrology impacts.

- Many studies identified past trends toward earlier timing of spring runoff in the California Sierra Nevada and associated this trend with an increasing temperature trend in California.

- Studies that focused on predicting future climate change impacts on hydrology were based on future climate change assumptions that were either hypothetical or developed from GCM simulation reflecting assumptions about future global greenhouse gas (GHG) emissions and associated future GHG concentrations. In both scenario cases, global climate change scenarios were translated into the regional meteorological variables serving as inputs to statistically or physically based hydrologic response models.

- Prediction studies consistently reported projected changes toward proportionally more runoff during winter and early spring and less runoff during late spring and summer, with cause attributed to increasing air temperature resulting in more winter rainfall and runoff, less winter snowfall, less spring snowpack, and less spring/summer runoff from snowmelt. Studies did not show consensus trends in projected annual runoff volume.

- Following the progression of methods through the studies, it is evident that methods have improved in terms of downscaling outputs from GCMs and characterizing uncertainty.

2007, Knowles et al., "Trends in Snowfall Versus Rainfall for the Western United States, 1949–2001"

Study Purpose

The purpose of this study was to examine whether a trend is occurring in the ratio of snowfall to total winter precipitation in the Western United States.

Method Highlights

- The analysis considered daily snowfall depth, precipitation, and maximum and minimum temperature data from Western U.S. climate stations for 1948 to 2001.

- The analysis also considered temperature data from 647 stations and precipitation data from 173 stations.

- The liquid water equivalent of snowfall was calculated as the total precipitation measured on a day when snowfall was reported.
- Winter and monthly ratios of snowfall water equivalent to total precipitation were then calculated.
- Trend analyses were performed on both sets of these ratios (winter and monthly for 1948–2001).

Key Findings

- Pronounced trends were found toward reduced winter period ratios of snowfall to total winter precipitation in the Sierra Nevada and Pacific Northwest. Results were less clear for the Rocky Mountain region.
- Where found, the trends toward reduced ratios of snowfall to total winter precipitation correspond with a warming trend in the Western United States.
- Winter period ratio trends correspond to reduced snow water equivalent values rather than to changes in overall precipitation, with the exception of the southern Rocky Mountain region where both snowfall and precipitation have increased.
- Focusing on the months of January and March, trends toward reduced ratio of snowfall water equivalent to precipitation are most pronounced in March, throughout the Western United States, and in January near the west coast. The geographic constraint on the latter trend may be related to the decreasing trend in mean temperature found during January was found at higher elevations, potentially restricting the trends toward reduced ratio of January snowfall water equivalent to precipitation to occur in the lower elevations near the west coast. In contrast, March trends toward increasing air temperature were found throughout the region, which corresponded to the March reductions in ratio of snow water equivalent to total precipitation.

2007, Bonfils et al., "Identification of External Influences on Temperatures in California"

Study Purpose

The purpose of this study was to examine and characterize California's climate trends and identify specific factors associated with the trends.

Method Highlights

- Eight different observational datasets were used to estimate temperature trends during 1950–1999 and 1914–1999.
- Trend analyses were performed on monthly mean temperatures, monthly mean night and daytime temperatures, and the diurnal temperature range.
- Significance testing methods were used to compare observed trends with modeled linear trends from unforced control simulations of climate during the evaluation period.

Key Findings

- Large positive trends were found for monthly mean and daytime temperatures in late winter and early spring, as well as increases in night temperatures from January to September
- The observed trends are inconsistent with model-based estimates of natural internal climate variability, which suggests that there were external agents forcing climate during the evaluation period.
- Based on findings, the authors suggest that the warming of California's winter over the second half of the 20th century is associated with human induced changes in large-scale atmospheric circulation. Authors further hypothesize that the lack of a detectable increase in summer daytime temperature may be due to cooling associated with large-scale irrigation.

2005, Regonda et al., "Seasonal Cycle Shifts in Hydroclimatology Over the Western United States"

Study Purpose

The purpose of this study was to examine the relationship between the timing of snowmelt in the mountain basins of the Western United States relative to trends in temperature, precipitation, and snow pack conditions.

Method Highlights

- The analysis considered data during 1950–1999 from 89 stream gauges in Western U.S. river basins having a significant snowmelt season.
- Stream gauge data were analyzed for runoff timing trends.
- Trend analyses were performed on March, April, and May SWE data from Western U.S. snow-course surveys and on winter precipitation and spring temperature.

Key Findings

- Peak runoff occurred earlier at most stations during the period, and significant trends toward earlier runoff were found in the Pacific Northwest.
- Significant trends toward increasing spring temperature were found throughout the region, with larger trends found in the Pacific Northwest and Rocky Mountain regions.
- Increasing winter precipitation trends were identified for much of the study area; however, the fact that the data did not show a significant increase in total spring runoff suggests as total winter precipitation increases, more of it is coming in the form of rain.
- Significant decreasing trends in spring snow water equivalent were found at approximately 50% of the sites.

2004, Stewart et al., "Changes in Snowmelt Runoff Timing in Western North America Under a 'Business as Usual' Climate Change Scenario"

Study Purpose

The purpose of this study was to evaluate trends in western North America snowmelt-runoff relative and to predict future trends based on the output of a global climate model.

Method Highlights

- The analysis considered data from 279 stream gauges on North American river basins having a significant snowmelt season.
- Trends were evaluated for runoff "center timing" defined as the "day of water year" (i.e., October through September) when 50% of the given water year's annual runoff has passed the reporting gauge.
- Gridded (5° X 5°) average monthly temperature and precipitation anomaly trends from 1951–1980 observations were correlated to runoff CT data.
- Parallel Climate Model results for 1995–2099 under a business-as-usual greenhouse gas emissions scenario were used to predict future runoff CT conditions.
- The results of the statistical runoff CT model were compared to detailed, physically based hydrologic models under the same climatic conditions for several rivers where such models and simulations were available.

Key Findings

- 1995–2099 runoff CT trends are predicted to be earlier at most locations and especially so in the Pacific Northwest, Sierra Nevada, and Rocky Mountains.

- Projected CT runoff changes are consistent with observed rates and directions of change during the past five decades.

- Predicted responses of CT to the simultaneous effects of projected temperature and precipitation trends are dominated by the temperature changes.

- Regression based CT predictions agree with physically based simulation results of rivers in the Pacific Northwest and Sierra Nevada.

2001, Cayan et al., "Changes in the Onset of Spring in the Western United States"

Study Purpose

The purpose of this study was to evaluate the affects of spring climate conditions in the Western United States on blooming plants and the timing of snowmelt-runoff pulses. Statistical methods were used to determine whether correlations exist between spring temperatures, first bloom dates, and runoff timing.

Method Highlights

- Statistical methods were used to determine whether correlations exist between spring temperatures, first bloom dates, and runoff timing.

- The analysis considered data from 105 lilac observation stations with 20 years or more of data during 1957–94 and from 87 honeysuckle stations with 15 or more years of data during 1968–94.

- These plant observation stations were located throughout the Western United States at elevations ranging from 15 to 2,927 meters.

- The analysis also considered streamflow records from 110 Western United States rivers for periods beginning in 1948 and ending between 1988 and 1995, focusing on the annual date of first major pulse of spring runoff (defined as the day when the cumulative departure from that year's mean flow is most negative, equivalent to finding the day after which most flows are greater than average).

- Temperature and precipitation averages for regions corresponding to plant observation stations were used for correlation analyses.

Key Findings

- Lilac and honeysuckle first bloom dates are highly correlated with each other.

- The first bloom dates of both plants were found to positively correlate with initial runoff pulse dates and temperature anomaly.

- Authors suggested that earlier onset of spring is remarkable since the late 1970s, as spring temperatures were found to have increased from 1–3 ^{o}C (1.8–5.5 ºF) in western North America since the late 1970s.

- Earlier and warmer-than-normal spring temperatures were related to larger scale atmospheric conditions across North America and the North Pacific.

1995, Dettinger and Cayan, "Large-scale Atmospheric Forcing of Recent Trends Toward Early Snowmelt Runoff in California"

Study Purpose

The purpose of this study was to identify and evaluate runoff, weather conditions, and atmospheric forcing trends associated with California's recent past hydrologic conditions.

Method Highlights

- Statistical methods were used to analyze streamflow records, mean monthly temperature, total monthly precipitation, and oceanic and atmospheric conditions.

- The analysis considered nearly unimpaired streamflow records during 1948–91 from five California river basins situated at relatively low, medium, high (two), and very high altitudes.

- The analysis also considered variance-weighted average temperature and precipitation from four long-term climate stations in or near the western slope of the central Sierra Nevada.

- Atmospheric circulation patterns over the northern Pacific Ocean and western North America, as well as northern Pacific Ocean surface temperatures, were analyzed for potential association with hydroclimatic trends found over California.

Key Findings

- Earlier spring runoff trends were identified beginning in the late 1940s for all basins evaluated.
- Warmer winter temperature trends were identified of about 0.5 °C per decade.
- The most predominant runoff-timing trends were found in the middle-altitude basins and are correlated with winter temperature trends.
- Winter temperature and runoff timing trends appear to be associated with changes in atmospheric circulation changes.
- The identified runoff timing trends were not found to be reflective of a single, monolithic warming trend over all of the North Pacific and North American sector.
- Results suggest that hydrologic responses to atmospheric circulation pattern changes may be spatially variable.

1994, Stine, "Extreme and Persistent Drought in California and Patagonia During Mediaeval Time"

Study Purpose

The purpose of this study was to explore the potential relationship of periods of anomalous temperatures and precipitation-runoff during the 12th through the 14th centuries.

Method Highlights

- The analysis considered remains of trees and tree stumps within areas either currently or previously inundated that were apparently dry areas during past periods due to different hydrologic conditions.
- Dendrochronological records were sampled from trees and tree stumps, with dating corroborated using radiocarbon methods.

Key Findings

- Data suggests occurrence of two mega-droughts at three sites in California, lasting 220 and 141 years, respectively. Droughts apparently ended in A.D. 1112 and 1350, respectively.
- These drought occurrences coincide with previously reported periods of anomalous temperatures.

- Hypothesis for cause of California droughts is northward shift of mid-latitude storm track caused by either contraction of circumpolar vortex or persistent high-pressure ridge.

- Authors suggest that such storm track re-orientation could have been related to increased temperatures, which would imply future long-term drought conditions may result from global warming.

Projected Hydrologic, Ecosystem, and Water Demand Impacts

2008, Cayan et al., "Climate Change Projections of Sea Level Extremes Along the California Coast"

Study Purpose

This article presents the findings of a scenarios analysis of California coastal sea level rise over the 21st century (2005–2100). Ranges of estimated mean sea level rise values are presented, as well as hourly values that include extreme seal level rises associated with tides, storms and other episodic events.

Method Highlights

- The analysis included estimated ranges of mean sea level rise consisting of thermal expansion and land-ice melt components.

- The thermal expansion component is based on two GCMs (GFDL and PSM) output under lower, middle-upper, and higher emissions scenarios.

- The land-ice melt component was developed using the MAGICC "simple climate model" (Hulme et al., 1995 and Wigley, 2005).

- The authors developed models of hourly sea level variations at three California coastal tide gauge stations (Crescent City, San Francisco, and La Jolla) that included astronomical tides, weather effects, an El Niño influence, and secular sea level rise.

- The hourly models were calibrated to 1950–2002 observed conditions and predict extreme short-term episodic rises.

Key Findings

- By mid-century (2035–2064), mean sea level rise projections range from approximately 6–32 cm (2.4–12.6 inches) above 1990 levels, with no discernable interscenario differences. End-of-century (2070–2100)

projections range from 10–54 cm (3.9–21.3 inches) under B1, to 14–61 cm (5.5–24.0 inches) under A2, and 17–72 cm (6.7–28.3 inches) under A1fi.

- The hourly model predicts significant increases in the frequency of extreme short-term episodic sea level rises.

- For the San Francisco model with 30-cm-per-century (11.8-inch-per century) rate of rise, the occurrence of events above historical increases from just less than 1 hourly event in 1 year to about 1.3 events per year averaged over 2005–2034, to about 7 events per year during 2035–2064, and to about 17 events per year in 2070–2099.

- For the San Francisco model with 60-cm-per-century rise, the incidence of hourly events exceeding historical climbs to 4.6 per year during 2005–2034, to about 41 per year during 2035–2064, and to about 235 per year during 2070–2099.

- Similar occurrence of extremes with hypothetical sea level rise was found in the modeled sea levels at La Jolla and Crescent City.

- The authors discuss that seal level rise may have severe impacts on low-lying land bordering the San Francisco Bay and Delta causing damage to marginal ecosystems as well as degrading the quality and reliability of the fresh water supply pumped from the southern edge of the San Francisco Delta.

- The authors also discuss that in the San Francisco Bay estuary, sea level rise effects may be compounded by riverine floods that feed into the northern reaches of the Bay from the Sacramento/San Joaquin Delta.

2007, Maurer, "Uncertainty In Hydrologic Impacts of Climate Change in the Sierra Nevada, California Under Two Emissions Scenarios"

Study Purpose

This study examined the statistical significance of the results of hydrologic simulations of climate change impacts for four river basins in the western Sierra Nevada. The simulations were done using numerous 21st century GCM outputs under two emissions scenarios that were analyzed relative to 1961–1990 baseline conditions.

Method Highlights

- Output from 11 GCMs from the IPCC 4th Assessment Report with emissions scenarios SRES A2 (high) and SRES B1 (low) were bias corrected and downscaled to a common 1/8° grid and input to the VIC hydrologic model.

- Four Sierra Nevada basins were modeled; two higher elevation and two lower elevation.
- Streamflow and snowpack VIC results for all GCMs were assembled for each of the two emissions scenarios.
- A statistical analysis was performed on the VIC results using the nonparametric Mann-Whitney U test (Haan, 2002) for equality of means.
- The statistical analysis determined the confidence levels associated with the changes from baseline conditions and the differences in the two scenarios results for each GCM.
- Results are presented for the periods 1961–1990, 2011–2040, 2041–2070, and 2071–2100.

Key Findings

- The majority of GCMs show increased winter precipitation, but this is quite variable among the models, while the temperature increases appear more consistent. Resulting SWE declines are clear and more severe later in the century as temperatures continue to rise.
- There were small but significant increases in average annual precipitation under the B1 emissions scenario in 2011–2040 and comparable decreases for 2041–2070.
- The lower elevation basin results show high statistical confidence for increases in December–February flows in all time periods, and the increases rise in magnitude through the century.
- Increases in winter flows are markedly greater for the A2 scenario than B1, especially for 2071–2100.
- Under the A2 scenario, increases in winter flow more than offset the declines in summer, producing a small increase in annual flow. The B1 scenario shows a similar effect for 2011–2040 with an increase in annual flow of 7–8%; by 2071–2100 the B1 scenario shows a slight but low confidence decline in annual flow.
- The A2 and B1 emissions scenarios do not produce streamflows differing with a high degree of confidence.
- All snow losses by mid-century are high confidence, and the confidence level that the April 1 SWE loss projected under the two scenarios differs exceeds 80% for the lower elevation basins.

- Continuing shifts to earlier arrival of runoff later in the 21st century were identified and were robust for all basins.

2007, Mauer et al., "Detection, Attribution, and Sensitivity of Trends Toward Earlier Streamflow in the Sierra Nevada"

Study Purpose

The purpose of this study was to evaluate estimated historical and predicted future runoff CT trends in the west-central Sierra Nevada to determine whether the trends can be statistically attributed to climate change forced by atmospheric GHG change.

Method Highlights

- Four sites were modeled within the Sacramento-San Joaquin river basin at points where inflow from tributaries enter large reservoirs.

- The general circulation PCM was used to develop a continuous 629-year preindustrial control run (PIctrl) with constant 1870 atmospheric composition.

- Results from the PCM climate simulation of the PIctrl scenario were then bias corrected and downscaled to produce meteorological inputs to the VIC hydrologic model.

- Runoff CT results from the VIC simulation of the PIctrl climate were evaluated to identify trends for each possible 50-year period.

- PCM and VIC results from other studies were used in comparisons to control run results and in evaluations of runoff timing and temperature sensitivity.

Key Findings

- Although observed 1950–1999 earlier runoff CT trends are statistically significant (50-year average CT standard deviation range of 12.4–15.1 days), they do not exceed the estimated trends from the 629-year preindustrial control run (50-year average CT trend would need to shift 17–19 days for 90% statistical confidence).

- Based on PCM-driven VIC results and depending on emissions scenarios used, it is estimated that future trends toward earlier runoff will exceed the 90% statistical confidence level indicating that future runoff-timing trends will be partially attributable to atmospheric GHG changes. Authors estimated that attribution will become apparent in 10 to 80 years.

- River basins at elevations from 2000 to 2800 meters were found to be most prone to show earlier runoff-timing, with shifts exceeding 45 days relative to 1961–1990 by the end of the 21st century.

2007, Rahmstorf, "A Semi-empirical Approach to Projecting Future Sea-Level Rise"

Study Purpose

In this study, the author developed a semi-empirical relationship between global sea level rise and global mean air temperature that is based on historical observations. This relationship was then used to project future sea level rise based on global climate model temperature projections.

Method Highlights

- The relationship was developed using observed sea level and air temperature data for the period 1881–2001.
- Global mean sea level values were calculated from tide gauge observations and global average near-surface air temperature.
- The relationship assumes a linear increase in sea level during the initial stage of climate change induced rise.
- The analysis was tested by applying the relationship to embedded periods of 2–17 years within the record period (1881–2001).
- Future sea level projections were calculated using the range of temperature projections from the IPCC Third Assessment Report (TAR).

Key Findings

- The correlation between historic global average air temperature and global sea level rise was highly significant ($r = 0.88$, $P = 1.6E-8$).
- The relationship developed was found to be robust based on its relatively accurate prediction of observed sea level rise in the embedded periods evaluated.
- Based on the range of 1990–2100 IPCC TAR temperature increase projections (1.4 to 5.8 °C), the analysis results indicate a range of global sea level rise from 50 to 140 cm by 2100.
- The author acknowledges the weakness of the linear increase assumption given the dynamical response of ice sheet melting in recent decades.

- The author also discusses that the uncertainty in future sea level rise is likely larger than previously estimated and the possibility for faster rise should be considered in adaptation measures planning.

2004, Hayhoe et al., "Emissions Pathways, Climate Change, and Impacts on California"

Study Purpose

The purpose of this study was to evaluate the output from two general circulation models under high and low greenhouse gas emissions scenarios and identify predicted impacts to California using statistical methods and a hydrologic modeling tool.

Method Highlights

- The analysis considered climate projections reflecting assumed GHG emissions scenarios B1 and A1fi (as defined by the Intergovernmental Panel on Climate Change, Special Report on Emissions Scenarios (SRES), 2000), representing respective low and high rates of atmospheric GHG accumulation among SRES scenarios.

- The PCM and Hadley Centre Climate Model, version 3 (HadCM3) general circulation models were used to simulate global climate response to these GHG emissions scenarios.

- PCM and HadCM3 climate projections were then bias corrected and downscaled over California to produce meteorological inputs for the VIC hydrologic model.

Key Findings

- Results are presented for the periods 2020–2049 and 2070–2099.

- The range of 2099 annual statewide average temperature increases was 2.3–3.3 °C for scenario B1 and 3.8–5.8 °C for scenario A1fi.

- All but the PCM B1 results show some decrease in summer and winter precipitation during 2070–2099.

- Snow water equivalent levels are reduced in 2099 by 30–70% under the B1 scenario and 73–90% under the A1fi scenario with associated reductions in runoff.

- Earlier runoff is most dramatic for the southern Sierra Nevada where the 2099 B1 range is 22–34 days and the A1fi range is 34–43 days.

2004, Dettinger et al., "Simulated Hydrologic Responses to Climate Variations and Change in the Merced, Carson, and American River Basins, Sierra Nevada, California, 1900–2099"

Study Purpose

The purpose of this study was to evaluate hydrologic responses of Sierra Nevada river basins under historical and projected future climate.conditions by simulating daily streamflow and water-balance responses to simulated climate conditions.

Method Highlights

- The study references global climate simulations produced by the PCM for the periods 1870–1999 assuming realistic historical radiative forcings (i.e., greenhouse-gas and sulfate-aerosol concentrations in the atmosphere), 1995–2048 assuming fixed 1995 greenhouse gas levels, and 1995–2099 with increasing greenhouse gas scenarios reflecting a "business-as-usual" scenario.

- PCM output was downscaled to estimate simulated climate conditions at the six meteorological stations used to calibrate hydrologic models for the Merced, Carson, and American Rivers.

- Weather input sequences were then generated at these locations, consistent with PCM output temperature and precipitation, for each of the hydrologic models.

- Hydrologic model results were analyzed for changes in the amount and timing of streamflow, snowmelt, evapotranspiration and soil moisture.

Key Findings

- Simulated runoff during the 1870–1999 period reasonably matched observed runoff during that period.

- The 1995–2099 PCM temperature responses to greenhouse gas increases were significant but near the low end of projections by other climate models (2.4-°C increase by 2099). Precipitation responses were relatively modest.

- Simulated runoff during the 1995–2099 period for each basin showed increased proportion of rain rather than snow, earlier snowmelt (up to a month), increased winter flooding, and reduced late-season low flows.

- The 1995–2099 results showed reduced growing season soil moisture content and associated reduced evapotranspiration.

- The 1995–2099 results indicate that long-term average totals of streamflow and other hydrologic fluxes remain similar to historical.

Projected Operations Impacts

2009, Brekke et al., "Assessing Reservoir Operations Risk Under Climate Change

Study Purpose

In this report, the authors present a framework for assessing reservoir operation risks associated with climate change. The framework is demonstrated in a Northern California case study. The framework is applied multiple times to evaluate how assessed risk is sensitive to analytical design choices other than scenario definition.

Method Highlights

- The first part of the analysis involves applying a traditional risk assessment framework (i.e., scenarios, scenario-impacts, scenario-likelihoods) to the subject of climate change and future reservoir operations (i.e., climate change scenarios, hydrologic and operations response per scenario, and estimates of relative scenario likelihoods). The second part of the analysis explores how assessed risk is sensitivity to analytical design choices other than scenario definition (i.e., whether to weight climate change scenarios, whether to modify flood control assumptions given hydrologic impacts).

- The case study focuses on watersheds tributary to the California Central Valley Project (CVP) and State Water Project (SWP) systems.

- Scenarios were defined as changes in period mean-monthly temperature and precipitation, sampled from climate projections during two future periods (2011–2040 and 2041–2070) relative to a common historical period (1963–1992). A larger collection of climate projections was considered to determine the context for scenario weighting (Uncertainty Ensemble). A smaller, nested ensemble was considered for detailed scenario-impact analyses (Impacts Ensemble).

- Scenario-impact analyses focused on hydrologic and operations effects. Hydrologic impacts were simulated using process simulation models provided by the National Weather Service California-Nevada River Forecast Center, with input meteorology being scaled historical meteorology to be consistent with monthly mean conditions in the given climate change scenario. Operations impacts were simulated using the

California Department of Water Resources and Reclamation joint CVP-SWP planning model, CalSim II.

- Scenario-operations results were aggregated into probabilistic impacts information on water supply reliability (e.g., mean annual water delivery to CVP and SWP and end-of-September storage).

- Scenario-operations results were repeated for several analytical designs based on assumptions involving: (1) future flood control rules under climate change, and (2) how to weight climate change scenarios (i.e., how to estimate relative scenario-likelihood). Hydrologic impacts results supported assumptions of possibly greater drafting during winter, without necessarily earlier refill opportunity during spring.

Key Findings

- Projected precipitation uncertainty played the dominant role in determining impacts uncertainty for the performance metrics considered.

- In general, assessed risk was sensitivity to both analytical design choices considered (i.e., current or modified flood control rules, consensus- or equal-weighting of climate change scenarios); the choice involving assumed future flood control had considerably more influence on the assessed risk than choice on how to weight scenarios.

- Water supply reliability risks were found to be greater in the CVP than SWP, possibly due to more conveyance flexibility in SWP system.

2008, Purkey et al., "Robust Analysis of Future Climate Change Impacts on Water for Agriculture and Other Sectors: A Case Study in the Sacramento Valley"

Study Purpose

This study evaluated the impact of climate change on agricultural water management in the Sacramento River Basin and the potential for adaptation.

Method Highlights

- Temperature and precipitation projections output from two GCMs under two emissions scenarios were downscaled and input to the Water Evaluation and Planning (WEAP) system model.

- The Parallel Climate Model and the Coupled Model 2 model developed at the Geophysical Fluid Dynamics Laboratory (GFDL), were used to estimate future climate conditions under the A2 and B1 emissions scenarios.

- GCM output were downscaled based on Maurer et al. (2007) to create a 1/8° gridded data set for daily climate variables.

- The WEAP model is a dynamically integrated watershed hydrology/water resources systems modeling tool that uses as input data information on future climate time series and future land use/land cover patterns to simulate associated natural patterns of stream discharge, evapotranspiration (ET), groundwater recharge and stream-aquifer interactions; upon which the simulated impact of reservoir operations, cropping decisions, surface water diversions and groundwater pumping were superimposed.

- WEAP simulations were run for each of the climate change scenarios with two adaptation strategies implemented across all agricultural areas of the Sacramento Valley: improved irrigation efficiency and changed cropping patterns.

Key Findings

- Results suggest that increasing temperatures and declining precipitation will result in similar spatial and temporal patterns of agricultural water supply and delivery impacts whether or not adaptation occurs, but adaptation strategies would reduce the absolute effect.

- Improved irrigation efficiency and increased land fallowing in dry years would result in substantial reductions in agricultural water demand for all climate change scenarios and reduce the average annual surface water deliveries and groundwater pumping to agriculture.

- In general, modification of agricultural demands as a result of implementing adaptation strategies would improve the reliability of surface water deliveries for all water users in the basin.

- Central Valley Project and State Water Project reservoirs would show little change in their operation as a result of implementing adaptation, suggesting that other water users in the basin would capture the water savings realized as a consequence of reducing consumptive demands in agricultural areas.

- Some of the additional water resulting from adaptation strategies would shift to Sacramento Valley urban areas and delta exporters, and the remaining water would be used to satisfy various environmental requirements.

2008, Anderson et al., "Progress on Incorporating Climate Change into Management of California's Water Resources"

Study Purpose

The purpose of this study was to identify potential future climate change impacts on California's State Water Project and the Federal Central Valley Project in order to assist agencies in their water resource planning and management.

Method Highlights

- Twenty-first century impact assessments were done for four climate change scenarios defined by climate projections from two general circulation models (GFDL, PCM) each simulating two future greenhouse gas emissions scenarios (A2, B1, as labeled by the Intergovernmental Panel on Climate Change). Results from two of the climate change scenarios (most and least warming) were presented: GFDL-A2 and PCM-B1.

- Climate projection outputs on surface temperature and precipitation were biased corrected and downscaled and translated into weather inputs (i.e., precipitation, air temperature, wind speed, surface air humidity) for a Central Valley application of the VIC hydrology model.

- Runoff output from the Central Valley VIC model was translated into adjusted reservoir inflows for the CalSim-II water supply planning simulation model. Unadjusted inflows in CalSim-II match the historical variability experienced during 1922–1994. Adjusted inflows reflect the same sequence of variability, but with monthly means scaled to reflect climate change impacts on monthly runoff, as simulated using VIC, and for each climate projection scenario.

- CalSim-II was simulated using an estimated 2020 land use and water demand scenario. Comparative CalSim II simulations using unadjusted and adjusted inflows were used to reveal impacts to SWP and CVP operations under climate change.

- Impacts to the Sacramento-San Joaquin Delta due to climate changed SWP and CVP operations and a 0.3 meter sea-level rise were also evaluated, using the California Department of Water Resources' (DWR) Delta Simulation Model 2 (DSM2).

- DWR's HED71 hydrologic model was used to estimate Feather River watershed runoff under three snow level scenarios associated with 1-, 3-, and 5-°C air temperature increases.

- Potential evapotranspiration response to increases in air temperature and CO_2 were evaluated using DWR's Consumptive Use Model that employs an energy balance analysis of the Penman-Monteith equation.

Key Findings

- SWP and CVP north-of-delta water deliveries were reduced under the GFDL A2 scenario and the lower range of deliveries were increased under the PCM B1 scenario.

- Carryover storage was reduced for SWP and CVP under the GFDL A2 scenario, increased for CVP under the PCM B1 scenario.

- Sacramento-San Joaquin Delta chloride mass loading increases by 11% due to sea-level rise combined with hydrologic effects.

- Increased winter runoff would result in more uncontrolled releases from SWP and CVP reservoirs to maintain flood control.

- Modeled Feather River watershed runoff increases for a 10- to 15-year return period event relative to a base case were by 23, 83, and 131% respectively for 1-, 3-, and 5-°C temperature increases.

- The highest increase in modeled ET (18.7%) was produced by increasing only the air temperature by 3 °C and increasing both the air temperature and the dew point temperature by 3 °C and using a CO_2 concentration of 550 parts per million (ppm) produced the lowest modeled increase in ET (3.2%).

2006, Baldocchi and Wong, "An Assessment of the Impacts of Future CO_2 and Climate on California Agriculture"

Study Purpose

The purpose of this study was to evaluate how increasing air temperature and CO_2 concentration may affect aspects of California agriculture, including crop production, water use, and crop phenology.

Method Highlights

- A literature review was conducted to determine the documented effects of warming and increased CO_2 levels on plants and associated water use.

- The energy balance relationship associated with plant transpiration was evaluated with regard to water use at increased temperature and CO_2 levels.

- The biophysical model CANVEG was used to evaluate changes in water consumption and potential for exceeding critical temperatures at an irrigated walnut orchard in California's Central Valley at a 3-°C air temperature increase and 500-parts-per-million CO_2 level.

- Degree hours were analyzed at selected Central Valley and coast range and foothills sites to evaluate potential for impact to fruit trees.

Key Findings

- Increasing air temperatures and CO_2 levels will extend growing seasons, stimulate weed growth, increase pests, and may impact pollination if synchronization of flowers/pollinators is disrupted.

- Elevated CO_2 causes an initial growth spurt and then transpiration is down-regulated by stomata closure.

- Increased growing season temperatures may produce negative forcing on crop production due to emission of volatile organic hydrocarbons from certain crops.

- Based on the CANVEG modeling results, it appears only a slight increase in walnut orchard water consumption would occur and the potential for exceeding critical leaf temperature is small.

- Results of the general circulation climate model developed at the Hadley Centre in the United Kingdom (emissions scenario not discussed) indicate a small deduction (-7%) in evapotranspiration across the Pacific region.

- Increasing trends for reduced degree hours were found and if these trends continue fruit tree production may be affected.

2004, Van Rheenen et al., "Potential Implications of PCM Climate Change Scenarios for Sacramento-San Joaquin River Basin Hydrology and Water Resources"

Study Purpose

The purpose of this study was to identify potential impacts of climate change on Sacramento-San Joaquin River Basin hydrology and water resources and evaluate alternatives that could reduce these impacts.

Method Highlights

- Five climate change scenarios were considered, based on global climate projection output from the PCM.

- The PCM climate simulations included three 1995–2099 runs with a 'business as usual' emissions scenario but each with different initial conditions; a 1995–2099 'control climate' scenario with constant 1995 emissions levels; and an 1870–2000 run with observed emissions levels.

- Climate projection data were bias corrected, spatially downscaled and then translated into weather inputs for evaluation of hydrologic and water resources response to each of the five climate change scenarios.

- Hydrologic response was evaluated using a Central Valley application of the VIC hydrology model. VIC streamflow output was translated into reservoir inflows input for a Central Valley reservoir operations model (CVmod).

- CVmod results on reservoir levels and releases were evaluated under six management alternatives given the following labels: current operations, 1-month (earlier reservoir refill) shift, 2-month (earlier reservoir refill) shift, volume shift (increase flood control space earlier in the season), comprehensive management and water year shift (best alternative for each reservoir based on sensitivity analysis).

Key Findings

- PCM climate projections featured temperature increases up to 2.2 °C by 2099, reductions in winter and spring precipitation from 10 to 25%.

- VIC simulation under these climate scenarios showed reduced late spring snowpack by up to 50% on average by 2099. Modeled streamflow reductions were less severe in the northern part of the study area relative to the southern part.

- CVmod results indicate that historic system performance in the future would not be possible under any of the evaluated alternatives.

- Under current operations, releases to meet fish targets and historic hydropower levels would be reduced 11% by 2099.

- Under the best case comprehensive management alternative, aggregate annual future system performance to meet fish targets would improve over current operations slightly to 8%; but in separate months and in individual systems (Sacramento or San Joaquin), larger impairments would occur (e.g., San Joaquin system January hydropower production decreases by nearly 65%).

A.3 Lower Colorado

This appendix summarizes each article surveyed as part of this synthesis of climate change literature for Lower Colorado (LC) Region. The survey is representative of articles published through early 2008 but is not exhaustive. The intent for each article summary is to give the reader a quick sense for study purpose, method highlights, and key findings. Study details are kept to a minimum; and it is suggested those readers interested in more detail should refer to the articles themselves.

The article summaries for each of Reclamation's five regions are organized under the themes of: Historic Trends; Projected Hydrologic, Ecosystems and Water Demands Impacts; and Projected Operations Impacts. Under each theme, the articles are organized chronologically (most recent year first), then by author. For the LC Region, the review was limited to 2007–2008 based on the existing information discussed below, and the only articles reviewed and summarized are under the Projected Hydrologic, Ecosystems, and Water Demands Impacts category.

Numerous studies have been conducted on observed climate change trends and potential impacts for water resources in Reclamation's LC Region. Many of these studies have been summarized already in two available literature syntheses. The first focuses on California hydrology and water resources and summarized studies completed through 2005 (Vicuna and Dracup, 2007). Although the majority of the information in this document pertains to central and northern California, some studies have geographic focus that extends into the LC Region. The second literature synthesis (Reclamation, 2007) focuses on Colorado River Basin studies, addressing water resources in both the Upper and Lower Colorado Regions. It was prepared as appendix U for the *Final Environmental Impact Statement, Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead* (Shortage Guidelines FEIS). It includes studies that had been published through early 2009, some of which are summarized in this document.

Historical Trends

2009, Hildalgo et al., "Detection and Attribution of Streamflow Timing Changes to Climate Changes in the Western United States"

Study Purpose

This study evaluates the relationship between anthropogenic climate change and observed changes in Western U.S. hydrology during the second half of the 20th century (1950–1999). The study focuses on the shift in runoff CT caused by increasing temperatures and earlier snowmelt.

Method Highlights

- Three large hydrologic regions were evaluated (Upper Colorado River Basin, Columbia River Basin, and California Region) using the VIC runoff model and downscaled output from three GCMs.

- The GCM ouput were from the Community Climate System Model version 3.0, Finite Volume (CCSM3-FV; Collins et al., 2007; Bala et al., 2008), Parallel Climate Model version 2.1 (PCM; Washington et al., 2000), and MIROC model (Hasumi and Emori, 2004; Nozawa et al., 2007).

- GCM output was downscaled to 1/8° latitude/longitude using the method of constructed analogues (Hidalgo et al., 2008) and the method of Bias Correction and Spatial Disaggregation (Wood et al., 2004).

- Climate change GCM runs were evaluated against control runs with no anthropogenic forcings and with and without combined solar and volcanic forcings.

- Control run results were compared to naturalized historic river flow estimates by others.

- A method known as the optimal detection method, which reduces a multidimensional problem to a low-dimensional problem, was used to evaluate the relationship between anthropogenic climate change and observed changes in Western U.S. hydrology.

Key Findings

- Negative trends in CT in the naturalized flow estimates were found for all three areas, but the trend was significant only for the Columbia River Basin.

- Overall, the climate change modeled CT trends were comparable to the naturalized flow trends.

- All climate change modeled CT trends were not comparable to naturalized flow trends and certain solar-volcanic forced trends were significantly positive.

- The authors found that the observed trends toward earlier CT of snowmelt-driven streamflows in the Western United States since 1950 are detectably different from natural variability (significant at the $p < 0.05$ level).

- The signal from the Columbia River Basin dominates the analysis, and it is the only basin that showed a detectable signal when the analysis was performed on individual basins.

2008, Bonfils et al., "Detection and Attribution of Temperature Changes in the Mountainous Western United States"

Study Purpose

This article reports on a rigorous detection and attribution analysis that was performed to determine the causes of the late winter/early spring changes in hydrologically relevant temperature variables over mountain ranges of the Western United States during 1950–1999.

Method Highlights

- The study used three climate models and all GCM output was downscaled to 1/8° latitude/longitude using two techniques and compared to historical observations.

- The GCM ouput were from the Community Climate System Model version 3.0, Finite Volume (CCSM3-FV; Collins et al., 2007; Bala et al., 2008), Parallel Climate Model version 2.1 (PCM; Washington et al., 2000), and MIROC model (Hasumi and Emori, 2004; Nozawa et al., 2007).

- GCM temperature output was downscaled to 1/8° latitude/longitude using the method of constructed analogues (Hidalgo et al., 2008) and the method of Bias Correction and Spatial Disaggregation (Wood et al., 2004).

- Maximum and minimum temperature data for the period 1950–99 from the University of Washington Land Surface Hydrology Research were interpolated into a 1/8° latitude/longitude grid.

- The evaluation was performed on nine subregions: the Washington Cascades, the northern Rockies, the Oregon Cascades, the Blue Mountains, the northern Sierras, the southern Sierras, the Great Basin, the Wasatch area, and the Colorado Rockies.

- January–March minimum temperatures, the number of frost days, and the degree-days above freezing were evaluated.

- Sensitivity analyses were performed on the results.

Key Findings

- In most of the regions examined, observed changes in hydrologically related temperature variables are inconsistent with natural internal variability alone and consistent with the response to anthropogenic forcings.

- The authors found that the overall interregional anthropogenic fingerprint can be positively identified in all four observed temperature indices evaluated irrespective of the model used, the downscaling method, or the end points values.

- Natural variability in the western climate system was ruled out by the analysis as the major cause of observed changes.

- Solar variability and volcanic forcings were also ruled out by the analysis.

- In the 48 scenarios evaluated, the detection time for an anthropogenic fingerprint occurs as early as 1986 and no later than 1994.

2008, Pierce et al., "Attribution of Declining Western U.S. Snowpack to Human Effects"

Study Purpose

This article reports on a formal model-based detection and attribution analysis of changes in Western U.S. snowpack conditions based the ratio of April 1 SWE to October–March precipitation.

Method Highlights

- The study compared 1950–1999 observed SWE and precipitation data to hydrologic modeling output. GCM output was input to the hydrologic model. The intent was to isolate the signature of anthropogenically forced changes in SWE to precipitation ratio from historical model runs, determine how similar the observed changes are to the fingerprint, and calculate the likelihood a signal of the observed strength could have occurred by chance in the control run.

- Ouput from two climate models was downscaled to 1/8° latitude/longitude using two techniques and input to the VIC hydrologic model.

- The GCMs used were the Community Climate System Model version 3.0, (CCSM3; Bala et al., 2008) and Parallel Climate Model version 2.1 (PCM; Washington et al., 2000. Multiple anthropogenic scenario runs were compared to 1,600 years of control run data.

- GCM output was downscaled to 1/8° latitude/longitude using the method of constructed analogues (Hidalgo et al., 2008) and the method of Bias Correction and Spatial Disaggregation (Wood et al., 2004).

- Historic snowpack observations included snow course data from the National Waterand Climate Center and data from the California Cooperative Snow Surveys obtained from the California Data Exchange Center for a total of 661 stations.

- Historic precipitation observations consisted of the gridded (1/8° latitude/longitude) daily precipitation dataset of Hamlet and Lettenmaier (2005), which was adjusted for gauge undercatch.

Key Findings

- The mean model estimate is that approximately half of the observed changes in snowpack over the Western United States during the period 1950–1999 arise from climate responses to anthropogenic forcings.

- The authors report the above finding did not depend on whether the snow course stations were grouped geographically (by mountain range across the West) or in equally weighted or area-weighted elevation bands.

- The signal indicating decreasing ratios of SWE to precipitation caused by anthropogenic forcing is detectable at the 95% significance level by the early 1990s: a record length of about 40 years.

- Only elevations below approximately 2,000 meters (6,560 feet) have statistically significant trends of decreasing ratios of SWE to precipitation.

2007, Hamlet et al., "20th Century Trends in Runoff, Evapotranspiration, and Soil Moisture in the Western United States"

Study Purpose

The VIC model is used to produce a long time series of key hydrologic variables (evapotranspiration, runoff, soil moisture) across the Western United States. The objective was to quantify hydrologic trends from simulations forced by observed temperature and precipitation over two time periods: the entire period of record (1916–2003), and a period that covers one full cycle of the Pacific decadal oscillation (1947–2003).

Method Highlights

- VIC was applied to the area west of the U.S. Continental Divide using a 1/8º spatial resolution.

- A gridded daily time step precipitation and temperature dataset from 1915–2003 used to drive the model.

- The first 9 months of VIC simulation were used as a simulation spin-up period (January to September, 1915) to remove the effects of initial system conditions.

Key Findings

- VIC-simulated snowpack agreed well with snowpack derived using statistical approaches and produced high quality streamflow simulations capturing hydrologic variability associated with different climate regimes.

- A relationship was found between midwinter temperatures and the simulated seasonal snowmelt cycles.

- ET trends in the LC are determined primarily by trends in precipitation and snowmelt that determine water availability.

- Trends found in the annual runoff ratio are determined primarily by trends in cool season precipitation, rather than changes in the timing of runoff or ET.

- The signature of temperature-related trends in runoff and soil moisture is strongly keyed to mean midwinter temperatures.

2006, Mote, "Climate-driven Variability and Trends in Mountain Snowpack in Western North America"

Study Purpose

Multiple linear regression techniques are used to evaluate the sensitivity to temperature and precipitation of April 1 SWE using nearly 1,000 locations in the Western United States. This analysis allows the separation of the temperature and precipitation influences on the observed trends.

Method Highlights

- Snow course data through 2002 was obtained. In some instances, manual snow courses have been replaced with automated snow telemetry equipment. Both manual and telemetered data were used.

    - A total of 995 snow records were obtained and used representing the time period 1960–2002.

- For each snow course location, reference time series temperature and precipitation data were developed by combining observations of the five nearest climate stations during November through March.

- A regression model of April 1 SWE values was developed as a function of seasonal mean temperature and precipitation during November through March.

Key Findings[1]

- For most snow courses, the regression approach suggests that the long-term April 1 SWE variations can be reasonably explained by antecedent seasonal climate summaries at nearby locations.

- The study found general agreement between observed and climate derived SWE.

- Findings imply that other sources of long-term trends are secondary.

- Since mid-century, general winter and spring warming has caused a reduced snow pack at most locations. This has been offset by precipitation increases in the southern Sierra Nevada of California resulting in a net increase in SWE.

- Some of the trends might be explained by variations in North Pacific climate, which was shown to explain approximately 50% of the SWE variability through regression modeling.

2005, Hamlet et al. "Effects of Temperature and Precipitation Variability on Snowpack Trends in the Western United States"

Study Purpose

In this study, the authors developed simulations of spring SWE conditions throughout the Western United States based on observed climate data from 1916–2003 and evaluated the simulated conditions. Linear SWE trends were analyzed in an attempt to identify the influence of temperature and precipitation separately and to differentiate effects due to climate change versus those associated with the PDO.

[1] These findings primarily apply to areas where hydrologic impacts manifest through climate change impacts on snowpack and snowmelt timing. For some Reclamation areas like much of the LC region, these findings are less applicable. However, these findings are relevant to LC water management influenced by supply that originates from the Upper Colorado headwaters and/or higher-elevation areas along the Arizona-New Mexico border.

Method Highlights

- 1915–2003 daily temperature and precipitation data from National Weather Service Observer stations were interpolated using the Symap algorithm to obtain 1/8° latitude-longitude grid values for the Western United States and southern British Columbia.

- In the interpolation, temperatures were lapsed by 6.1 °C per kilometer, and precipitation was scaled for topographic effects using monthly precipitation maps produced by the Precipitation Regression on Independent Slopes Method (PRISM).

- The VIC (version 4.0.5) model was used to develop 1916–2003 daily SWE values for the 1/8° grid under three scenarios (base run, fixed precipitation and fixed temperature) using the interpolated climate data.

- In the base run, unperturbed interpolated climate data were input to VIC, and the resulting SWE trends were the result of both temperature and precipitation.

- In the fixed precipitation run, the precipitation data were fixed (for each month) at the climatological value for each grid cell, and daily temperature was allowed to vary as in the base run with resulting SWE trends due to temperature only.

- In the fixed temperature run, the temperature data were fixed (for each month) at the climatological value for each grid cell, and daily precipitation was allowed to vary as in the base run with resulting SWE trends due to precipitation only.

- March 1, April 1, and May 1 SWE values and trends were evaluated for the following time periods: 1916–2003 (full period); 1925–1976 (warm PDO to cool PDO); 1947–2003 (cool PDO to warm PDO); and 1925–1946 concatenated with 1977–2003 (warm PDO to warm PDO).

- The date of peak SWE and the days associated with 10% of peak accumulation and 90% melt were evaluated for each scenario and time period.

Key Findings[1]

- Overall, the results show that March 1, April 1, and May 1 SWE trends are affected more by temperature and strongly suggest global warming is apparent in the observations evaluated in the study. Precipitation variability appears most strongly associated with decadal variability rather than long-term trends.

- The model shows that the widespread warming that has occurred in the Western United States during 1916 to 2003 has resulted in downward spring SWE over large areas.

- Model results for certain high-elevation areas with upward precipitation trends show upward SWE trends.

- The period from 1925 to 1976 was characterized by widespread increases in precipitation, which apparently dominated temperature trends to produce widespread upward trends in SWE.

- From 1947 to 2003, the model indicates regionally specific precipitation trends associated with decadal variability combined with strong downward trends in SWE due to widespread warming.

- The model results for the 1925–1946 concatenated with 1977–2003 period (warm PDO to warm PDO) combined with the 1916–2003 results strongly suggest that widespread regional warming trends are not well explained by PDO, but that decadal variability doe affect trends in winter precipitation that are apparent over shorter periods of the record.

- The trend for modeled dates of peak snow accumulation and 90% melt are generally earlier.

- The trend for modeled date of 10% peak SWE is also generally earlier, but appears to be due to trends in fall precipitation.

2005, Regonda et al., "Seasonal Cycle Shifts in Hydroclimatology Over the Western United States"

Study Purpose

The purpose of this study was to examine the relationship between the timing of snowmelt in the mountain basins of the Western United States relative to trends in temperature, precipitation and snow pack conditions.

Method Highlights

- The analysis considered data during 1950–1999 from 89 stream gauges in Western U.S. river basins having a significant snowmelt season.

- Stream gauge data were analyzed for runoff timing trends.

- Trend analyses were performed on March, April, and May SWE data from Western U.S. snow-course surveys and on winter precipitation and spring temperature.

Key Findings

- Peak runoff occurred earlier at most stations during the period and significant trends toward earlier runoff were found in the Pacific Northwest.
- Significant trends toward increasing spring temperature were found throughout the region, with larger trends found in the Pacific Northwest and Rocky Mountain regions.
- Increasing winter precipitation trends were identified for much of the study area; however, the fact that the data did not show a significant increase in total spring runoff suggests as total winter precipitation increases, more of it is coming in the form of rain.
- Significant decreasing trends in spring snow water equivalent were found at approximately 50 percent of the sites.

2004, Stewart et al., "Changes in Snowmelt Runoff Timing in Western North America Under a 'Business as Usual' Climate Change Scenario"

Study Purpose

The purpose of this study was to evaluate trends in western North America snowmelt-runoff relative and to predict future trends based on the output of a global climate model.

Method Highlights

- The analysis considered data from 279 stream gauges on North American river basins having a significant snowmelt season.
- Trends were evaluated for runoff CT defined as the "day of water year" (i.e., October through September) when 50% of the given water year's annual runoff has passed the reporting gauge.
- Average monthly temperature and precipitation anomaly trends from 1951–1980 observations were computed at each location in a 5° spatial grid, and then correlated to runoff CT data.
- PCM results for 1995–2099 under a business- as-usual greenhouse gas emissions scenario were used to predict future runoff CT conditions.
- The results of the statistical runoff CT model were compared to detailed, physically based hydrologic models under the same climatic conditions for several rivers where such models and simulations were available.

Key Findings

- 1995–2099 runoff CT trends are predicted to be earlier at most locations and especially so in the Pacific Northwest, Sierra Nevada, and Rocky Mountains.
- Projected CT runoff changes are consistent with observed rates and directions of change during the past five decades.
- Predicted responses of CT to the simultaneous effects of projected temperature and precipitation trends are dominated by the temperature changes.

Projected Hydrologic, Ecosystem, and Water Demand Impacts

2009, Rajagoplan et al., 2009, "Water Supply Risk on the Colorado River: Can Management Mitigate?"

Study Purpose

The purpose of this study was to investigate the potential for water management policies to mitigate the risk of depleting major reservoirs in the Colorado River Basin due to reduced streamflow associated with climate change. Results show risk of depleting system storage over a 50-year horizon for a variety of climatic scenarios and management alternatives.

Method Highlights

- A simple, annual water balance model was employed in which the total basin storage (60 MaF) is represented with a single reservoir.
- System inflows were: (1) natural flow above Lee's Ferry, Arizona, (2) natural inflow below Lee's Ferry and above Hoover Dam, and (3) natural inflow below the Hoover Dam.
- System outflows were: (1) obligations to Mexico, Upper and Lower basins, (2) reservoir evaporation, computed as a function of storage and (3) transmission losses below the Hoover Dam.
- Using data from 2008, the initial reservoir storage was 30 MaF (approximately [~] 50%).
- Synthetic streamflow data was first developed to reflect historical climate and variability. The data were generated using a method developed by

Prairie et al. (2008) in which variability from paleo-reconstructed streamflow data is combined with magnitudes from historic data.

- Potential future climate change effects were next considered using a range of trends in mean-annual runoff: (1) No reduction in flow over the model horizon, (2) a 10% linear reduction in flow over the model horizon and (3) a 20% linear reduction in flow over the model horizon. The rates of reduction for (2) and (3) reflect recent climate change impacts assessments on Colorado River hydrology.

- A variety of management alternatives were explored, which were combinations of shortage policy and demand growth.

- The shortage policies differ in trigger thresholds for shortage and the shortage magnitudes. (Note: Interim EIS shortage policies were employed until 2026 for all model runs.)

- Two demand growth scenarios were considered: (1) annual demand increase per the shortage EIS depletion schedule and (2) annual demand increase at a rate of 50% as compared to the shortage EIS depletion schedule.

- For each management alternative/climate combination, 10,000 model simulations were made, each 50 years in length.

- Risk of depleting storage in a given year was computed as number of times storage depletion occurred (for that year), divided by 10,000 (total number of simulations).

- An additional set of model runs was made with a reduced initial demand, consistent with a recent estimate of consumptive use. All other components (demand growth rate, policies, initial storage, etc.) remained unchanged.

Key Findings

- Risk of depleting storage during the interim period (until 2026) was found to be relatively low for all climatic scenarios, relative to risk at the end of the modeling horizon.

- Aggressive (more frequent) shortage policy coupled with slower demand growth was shown to significantly reduce risk of depleting active storage (e.g., ~30% reduced to near 10%).

- Model runs with initial demand beginning at 2006 consumptive use estimate showed substantial reduction in risk, particularly in

later years. (The difference in initial demand of 6% resulted in 33% risk reduction at the end of the model horizon.)

- Shortage volume distributions indicated that policies with more frequent shortages reduced the shortage magnitude variability.

2009, Barsugli et al., "Comment on 'When Will Lake Mead Go Dry?'"

Study Purpose

The purpose of this study was to address several modeling assumptions in "When will Lake Mead go dry?" by Barnett and Pierce (2008) (BP2008). The authors of the comment asserted that these assumptions do not accurately reflect the Colorado River Basin system and consequently resulted in elevated risk of reservoir drying due to reduced flows associated with climate change. The comment paper offers a modified system model and the resulting, updated risk profiles.

Method Highlights

- This study developed a simple, lump water balance model for the Colorado River Basin, similar to that employed in BP2008. The authors demonstrated that using the assumptions from BP2008, their model produces reservoir drying risk profiles consistent with those in BP2008.

- The first assumption addressed is that BP2008 neglects system inflow below Lee's Ferry, Arizona. Between Lakes Powell and Mead, an annual average of about 860 KaF enters the system. Below the Hoover Dam, an additional estimated 450 KaF enters the system. The comment authors also identify transmission loss, estimated to be about 1 MaF. This results in a net gain of roughly 300 KaF which was neglected in BP2008.

- Another assumption addressed was BP2008's treatment of reservoir evaporation and a bank loss term. In BP2008, both evaporation and bank loss were fixed terms (-1.4 and -0.3 MaF, respectively). The comment authors showed that by modeling reservoir evaporation as a function of storage, risk of drying was reduced; no longer is the "full reservoir evaporation" taxed when storage is dwindling. Regarding the bank loss term, this study indicated that during initial reservoir filling, this loss was likely relevant, however, data now suggests more of a steady state, such that there is no substantial long-term net gain or loss.

- A third critique of BP2008 was the failure to implement the shortage component of the recent EIS policies. It was shown that although the shortage values may seem small relative to the total demand, implementing these policies in the simple water balance model also reduced the risk of reservoir drying.

- The issue of long-term mean flow at Lee's Ferry, Arizona, is addressed. BP2008 assessed scenarios where this was assumed to be 15 MaF and then an implied value closer to 14.2 MaF. Although the latter was justified in BP2008 by citing the early part of the 20th century as abnormally wet and suggesting that anthropogenic warming has already began to reduce flows, the comment states that a lack of scientific consensus on the subject suggests the historic mean (15 MaF) is likely the most reliable estimate at this time.

- Two additional points of discussion in this study were the current consumptive use and also the metric by which the risk of drying is computed. A recent consumptive use estimate was approximately 800 KaF less compared to the demand per the EIS depletion schedule (12.7 MaF versus 13.5 MaF). It is also clarified that the drying metric employed by BP2008 represents probability of experiencing a drying event *by a given year*, not the risk of drying *in that specific year*.

Key Findings

- The model revisions made in this paper resulted in reduced risk of drying profiles, as compared to those in BP2008. For example, BP2008 cited a 50% risk of drying by 2021, whereas this study found the 50% risk to occur in 2035. Risks of being below power pool were also lower in the revised modeling.

- The risk profiles from model runs with initial demand set at 12.7 MaF and 13.5 MaF are presented as a window, in which the true risk profile likely lies.

- Though simply a matter of metrics and presentation of results, the risk calculation method used by BP2008 produces higher risk values than the probability of drying in each specific year.

- It is indicated that the purpose of the comment is to offer the most accurate representation of the system at this coarse resolution and the reduced risk profiles should not serve as justification to dismiss the threat posed by climate change.

2009, Barnett and Pierce, "Sustainable Water Deliveries From the Colorado Riverin a Changing Climate"

Study Purpose

This study is a follow-up to the authors' previous study (Barnett and Pierce, 2008). It re-evaluated effects of climate change on the Colorado River system based on a water budget analysis. Changes to the water budget model and associated results are discussed.

Method Highlights

- The authors revised their Colorado River Budget Model (CRBM) which calculates the net effect of inflows and outflows at a monthly time step under climate change scenarios for the combined Lake Powell and Lake Mead system.

- Future climate change scenarios represented by 10 and 20% inflow reductions were evaluated relative to 20th century naturalized Colorado River flow at Lees Ferry, Arizona, and to a baseline representing the average of 10 paleoclimate flow estimates by others that are based on tree-ring data.

- Significant changes to CRBM from the previous version include:

    - The future climate change period used was 1985 to 2050 rather than 2008 to 2060.

    - Initial reservoir storage conditions were for 1960 (near capacity) rather than for 2007 (approximately 50% of capacity).

    - Evaporation and infiltration quantities for Lake Mead and Lake Powell are a function of reservoir surface area rather than being fixed.

    - Evaporation rates increase as a function of increasing temperature rather than being fixed.

    - The ‘‘preferred alternative’’ schedule of future delivery cuts from Reclamation (2007) are used rather than “idealized” delivery cuts.

    - Tributary inflows between Lake Powell and Lake Mead are included rather than assumed negligible.

    - The minimum Lake Mead elevation is held at the Southern Nevada Water Authority intake level regardless of Lake Powell levels and delivery cuts rather than allowing Lake Mead and Lake Powell levels to drop in unison.

- Modeled impacts to future deliveries were evaluated probabilistically.

Key Findings

- Under the 20th century naturalized flow baseline, if climate change reduces runoff by 10%, model results indicate scheduled deliveries will be missed 58% of the time by 2050; and if runoff is reduced by 20%, they will be missed 88% of the time. With no climate change, mid-century delivery shortfalls occur 40% of the time.

- Again under the 20th century naturalized flow baseline, the mean shortfall when full deliveries cannot be met increases from 0.5– 0.7 billion cubic meters per year (bcm/yr) (0.4–0.6 million acre-feet per year [maf/yr]) in 2025 to 1.2–1.9 bcm/yr (1.0–1.5 maf/yr) by 2050 out of a scheduled delivery amount of 7.3 bcm/yr (5.9 maf/yr).

- Under the paleoclimate baseline, mid-century shortfalls increase an additional 1–1.5 bcm/yr (0.8–1.2 maf/yr) over the above amounts.

- Model results suggest long-term sustainable deliveries from the Colorado River are likely in the range of 14–17 bcm/yr (11–13.5 maf/yr), and these amounts represent a reduction of 0–20% relative to current deliveries.

2008, Barnett and Pierce, "When Will Lake Mead Go Dry?"

Study Purpose

The purpose of this study was to evaluate the potential effects of climate change on the Colorado River reservoir system, specifically Lake Powell and Lake Mead. Results include estimates of when reservoir storage may be depleted and when hydroelectric power production may cease as a function of climate change.

Method Highlights

- The water storage conditions for the combined Lake Powell and Lake Mead system were evaluated for the period 2008–2060 using a water budget method.

- A *simple* flow analysis was done without accounting for natural flow variability and assuming 10 to 30% percent reductions to the 1906–2004 annual average runoff amount of 15-million-acre-foot (MAF) flow passing Lees Ferry.

- A *variable* flow analysis was also done which included natural flow variability at Lees Ferry developed from statistically modeled simulations based on 1906–2004 observations and flow estimates from approximately 1,250 years of tree ring data.

- The modeled annual flow reductions are assumed to occur incrementally beginning in 2007 and increasing linearly.

- System water supplies: Inflow is based on flow passing Lees Ferry and does not account for intervening inflows between Lake Powell and Lake Mead.

- System loss assumptions included: net annual evaporation/ infiltration is assumed to be constant in all analyses at -1.7 MAF, and annual delivery to Mexico is constant at 1.5 MAF.

- System demand assumptions: Upper and Lower Basin total scheduled depletion is consistent with values assumed in the Shortage Guidelines FEIS.

- System initial conditions: reservoir system at 50% capacity.

- Drying metric determined by which year 50% of the 10,000 simulations went dry (deplete active storage) at least once since 2008. That is, recovery from a drying period was not considered in their risk analysis.

Key Findings[2]

- In the simple flow analysis (no natural flow variability), storage is depleted in 2030 and 2047 respectively for the 30 and 10% flow reduction scenarios. The results also showed a 50% chance hydroelectric power generation would not be possible by 2021 due to low reservoir levels.

- In the variable flow analysis, the results indicate that even without climate change there is 50% chance the system will go dry by 2037. With a 20% reduction in flows, results indicate a 50% chance of the system going dry by 2028 and power production ceasing by 2017.

- Analyses results indicate that 10% and 20% reductions in future depletions would postpone system dry-up by 6 and 10 years, respectively, under the climate change flow reduction scenario.

2007, McCabe and Wolock, "Warming May Create Substantial Water Supply Shortages in the Colorado River Basin"

Study Purpose

The purpose of this study was to evaluate the potential effects of increasing air temperatures on the annual flow volume of the Colorado River. Impacts are presented in terms of percentage flow reductions and the frequency at which the Colorado River Compact flow requirements would not be met.

[2] Assumptions are inconsistent with those in Reclamation modeling studies of the Colorado River Basin. Specifically, those in question are Lower Basin water supply (i.e., intervening inflows between Lake Powell and Lake Mead), reservoir evaporation, and reservoir management responses that would occur if low inflows were to persist for long periods of time.

Method Highlights

- A water balance method was used under two temperature increase scenarios using 1490–1998 tree ring based reconstructed Colorado River flows as a baseline.
- Hydrologic unit temperature and precipitation values were input to the water balance model for estimation of inflows and depletions.
- Water balance model parameters were adjusted for calibration, and correlation between estimated and measured flow for the period 1906–2004 was 0.93.
- Changes in precipitation, reservoir evaporative losses and consumptive demands due to population increases were not included in the water balance analysis.
- Temperature increase scenarios included increasing 1901–2000 measured values uniformly by 0.86 and 2 °C.
- The water balance estimated flow values were input to a flow/surplus water supply model that simulated storage and consumption conditions.
- The simple flow/surplus model was developed by the authors and then evaluated by comparing estimated 1985–2000 storage in Lake Powell with measured storage data obtained from Reclamation, and the root-mean-squared error of the estimates was 16.8% of mean measured storage.
- The flow values for the driest 100-year period occurring in the 1490–1998 reconstructed period were adjusted using reduction factors from the temperature increase scenarios, and these flows were also input to the flow/surplus model to evaluate worst case scenarios.
- The flow/surplus model output was used to calculate the fraction of time flow failed to meet the Colorado River Compact flow requirements (failure rate).

Key Findings

- Under the 0.86-°C temperature increase scenario, 1901–2000 mean annual flow is reduced by 8% which is near the lower quartile level of the 1490–1998 reconstructed flows.
- Under the 2-°C temperature increase scenario, 1901–2000 mean annual flow is reduced by 17% to a level which is unprecedented in 1490–1998 reconstructed flows period.

- Under the 0.86-°C temperature increase scenario, the calculated Colorado River Compact failure rate increased from 0.07 to 0.22.

- Under the 2-°C temperature increase scenario, the calculated Colorado Compact failure rate increased from 0.07 to 0.3.7.

- The Colorado River Compact failure rates calculated for the driest 100-year period occurring in the 1490–1998 reconstructed period increased from 0.30 to 0.50 and 0.77 with the increased temperature scenarios flow reduction factors applied.

Projected Operations Impacts

2007, Christensen and Lettenmaier, "A Multimodel Ensemble Approach to Assessment of Climate Change Impacts on the Hydrology and Water Resources of the Colorado River Basin"

Study Purpose

This study predicts climate change impacts to the Colorado River Basin reservoir system based on climate projections included in the 2007 IPCC Fourth Assessment. It essentially an application of the approach demonstrated in Christensen et al., 2004 (see below) but featuring a larger ensemble of climate models and their respective climate projections.

Method Highlights

- The authors used output from 11 major climate models and 2 different future emissions scenarios and evaluated maximum, minimum, and average projections relative to current conditions.

- The GCM results were input to the VIC hydrologic model, and river inflow values from VIC were input to the Colorado River Reservoir Model (CRRM) to predict reservoir effects.

- VIC was calibrated to 1950–1999 data and generated a less than 1% under-prediction of streamflow at Imperial Dam and +3% and -9% errors at Green River and Cisco, respectively, based on reconstructed natural flow at these points.

- CRRM was modified from the version used by Christensen et al. (2004) to reflect the Basin States' then current proposal with regard to how Lower Basin shortages should be tied to Lake Mead levels and the model calculates shortages when necessary to all major Lower Basin entities.

- The emissions scenarios used are A2, a relatively high scenario with 2100 CO_2 levels of 850 ppm and B1, a relatively low level scenario with 2100 CO_2 levels of 550 ppm.

- Results were presented relative to historical conditions for three periods: (1) 2010–2039; (2) 2040–2069; and (3) 2070–2099.

Key Findings

- Temperatures increases (ºC) for the B1 runs during periods 1–3, shown as "average (minimum, maximum)," were 1.28 (0.53, 1.83), 2.05 (1.13, 2.99), and 2.74 (1.13, 2.99), respectively.

- For the A2 runs during the same periods, the temperature increases (ºC) by 1.23 (0.63, 1.82), 2.56 (1.61, 3.65), and 4.35 (2.77, 6.06).

- Annual precipitation percent change for the B1 runs during periods 1–3 were +1% (-8, 11), -1% (-11, 9), -1% (-11, 19), respectively.

- For the A2 runs and same periods, percent precipitation changes were -1% (-9, 7), -2% (-21, 13) and -2% (-16, 13), respectively.

- October to March average precipitation increased by +5%, +1%, and +2% for B1 and by +6%, +5% and +4% for the A2 scenario.

- April 1 SWE change for the B1 runs was -15% (-41, 0), -25% (-48, -1), and -29% (-53, -18) and for the A2 runs, SWE change was -13% (-36, 1), -21% (-52, 6) and -38% (-66, -15).

- Changes in mean-annual runoff during periods 1–3 were 0% (-23, 17), -7% (-27, 12) and -8% (-30, 29) for the B1 runs, respectively, and by 0% (-16, 14), -6% (-39, 18), and -11% (-37, 11) for the A2 runs.

- A decrease of 10% in average streamflow is magnified into a 20% change of the same sign in Lake Mead reservoir storage and a 20% inflow change results in a 40% storage impact.

- The authors state that because of the large ratio of storage to inflow in the basin, neither increase in storage nor change in operating rules will likely change the storage impacts under declining inflows.

2004, Christensen, et al., "The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin"

Study Purpose

This study predicts climate change impacts to the Colorado River Basin reservoir system based on output from the National Center for Atmospheric Research Parallel Climate Model (PCM).

Method Highlights

- Three PCM runs for the 21st century were used with slightly different initial atmospheric conditions and a 50-year control climate run starting in 1995 with greenhouse gas emissions fixed at the 1995 level was also completed.

- The PCM results were downscaled to 1/8° daily data and input to the VIC hydrologic model and river inflow values from VIC were input to the monthly CRRM to predict reservoir effects.

- VIC was calibrated to 1950–1989 data and generated a less than 1% error of streamflow at Imperial Dam, and +3% and -9% errors at Green River and Cisco, respectively, based on reconstructed natural flow at these points.

- The CRRM was based roughly on Reclamation's Colorado River Simulation System model.

- PCM 21st century results averaged over the three runs were compared to the control run and to historical observed data or calculated natural flow in the historical period.

- Results were presented relative to historical conditions for three periods: (1) 2010–2039; (2) 2040–2069; and (3) 2070–2099.

Key Findings

- The control run showed warming of about 0.5 ºC (0.9 ºF) which is in rough agreement with what many believe to be 'committed warming' should greenhouse gas emissions stop immediately. The three 21st century runs showed average increases of approximately 3 ºC (5.4 ºF) over the observed average temperature of 10 ºC (18 ºF). In general, the warming was concentrated in spring and summer.

- Average annual precipitation in the control run was 1% less than historical, and in the three 21st century runs was 3, 6, and 3% lower in periods 1, 2, and 3, respectively. The seasonal precipitation pattern in the

control run was very similar to the historical observed, and the 21st century runs showed a similar pattern but with less precipitation in the spring.

- April 1 SWE in the control run was only 86% of the observed historical SWE, while SWE was 76, 71, and 70% in periods 1–3, respectively. Southern Colorado suffered the highest reductions and those occurred in periods 2 and 3.

- Runoff was reduced by 10% in the control run, and by 14, 18, and 17% in periods 1–3, respectively, in the 21st century runs. Peak runoff advanced from June in the historical data to May in the latter parts of the control and 21st century runs.

- Reservoir storage in the control run dropped by 7%, and periods 1–3 showed reductions of 36, 32, and 40%, respectively, relative to simulated historical conditions.

- Deliveries from Lake Powell were met 92% of the time in the historical data, and 72% in the control run and 59, 73, and 77% in periods 1–3, respectively.

A.4 Upper Colorado Region

This appendix section summarizes each article surveyed as part of this synthesis of climate change literature for Upper Colorado (UC) Region. The survey is representative of articles published through early 2008, but is not exhaustive. The intent for each article summary is to give the reader a quick sense for study purpose, method highlights, and key findings. Study details are kept to a minimum; and it is suggested those readers interested in more detail should refer to the articles themselves.

The article summaries are organized under the themes of: Historic Trends; Projected Operations Impacts; and Projected Hydrologic, Ecosystems, and Water Demands Impacts. Under each theme, the articles are organized chronologically (most recent year first), then by author. The Rio Grande Basin specific summaries are separated from Colorado River Basin and Western U.S. summaries at the end of subsection.

Numerous studies have been conducted on observed climate change trends and potential impacts for water resources in Reclamation’s UC Region. Many of these studies have been summarized already in an available literature synthesis. Reclamation (2007) focuses on Colorado River Basin studies, addressing water resources in both the Upper and Lower Colorado Regions. It was prepared as appendix U for the Shortage Guidelines FEIS. It includes studies that have been published through early 2009, some of which are summarized in this document.

Historical Trends (Upper Colorado River Basin)

2009, Hildalgo et al., "Detection and Attribution of Streamflow Timing Changes to Climate Changes in the Western United States"

Study Purpose

This study evaluates the relationship between anthropogenic climate change and observed changes in Western U.S. hydrology during the second half of the 20th century (1950–1999). The study focuses on the shift in runoff center timing (CT) caused by increasing temperatures and earlier snowmelt.

Method Highlights

- Three large hydrologic regions were evaluated (Upper Colorado River Basin, Columbia River Basin and California Region) using the VIC runoff model and downscaled output from three GCMs.
- The GCM ouput were from the Community Climate System Model version 3.0, Finite Volume (CCSM3-FV; Collins et al., 2007; Bala et al., 2008), Parallel Climate Model version 2.1 (PCM; Washington et al., 2000), and MIROC model (Hasumi and Emori, 2004; Nozawa et al., 2007).
- GCM output was downscaled to 1/8° latitude/longitude using the method of constructed analogues (Hidalgo et al., 2008) and the method of Bias Correction and Spatial Disaggregation (Wood et al., 2004).
- Climate change GCM runs were evaluated against control runs with no anthropogenic forcings and with and without combined solar and volcanic forcings.
- Control run results were compared to naturalized historic river flow estimates by others.
- A method known as the optimal detection method, which reduces a multidimensional problem to a low-dimensional problem, was used to evaluate the relationship between anthropogenic climate change and observed changes in Western U.S. hydrology.

Key Findings

- Negative trends in CT in the naturalized flow estimates were found for all three areas, but the trend was significant only for the Columbia River Basin.

- Overall, the climate change modeled CT trends were comparable to the naturalized flow trends.

- All climate change modeled CT trends were not comparable to naturalized flow trends, and certain solar-volcanic forced trends were significantly positive.

- The authors found that the observed trends toward earlier CT of snowmelt-driven streamflows in the Western United States since 1950 are detectably different from natural variability (significant at the $p < 0.05$ level).

- The signal from the Columbia River Basin dominates the analysis, and it is the only basin that showed a detectable signal when the analysis was performed on individual basins.

2008, Bonfils et al., "Detection and Attribution of Temperature Changes in the Mountainous Western United States"

Study Purpose

This article reports on a rigorous detection and attribution analysis that was performed to determine the causes of the late winter/early spring changes in hydrologically relevant temperature variables over mountain ranges of the Western United States during 1950–1999.

Method Highlights

- The study used three climate models and all GCM output was downscaled to 1/8° latitude/longitude using two techniques and compared to historical observations.

- The GCM ouput were from the Community Climate System Model version 3.0, Finite Volume (CCSM3-FV; Collins et al., 2007; Bala et al., 2008), Parallel Climate Model version 2.1 (PCM; Washington et al., 2000), and MIROC model (Hasumi and Emori, 2004; Nozawa et al., 2007).

- GCM temperature output was downscaled to 1/8° latitude/longitude using the method of constructed analogues (Hidalgo et al., 2008) and the method of Bias Correction and Spatial Disaggregation (Wood et al., 2004).

- Maximum and minimum temperature data for the period 1950–99 from the University of Washington Land Surface Hydrology Research were interpolated into a 1/8° latitude/longitude grid.

- The evaluation was performed on nine subregions: the Washington Cascades, the northern Rockies, the Oregon Cascades, the Blue Mountains, the northern Sierras, the southern Sierras, the Great Basin, the Wasatch area, and the Colorado Rockies.

- January–March minimum temperatures, the number of frost days, and the degree-days above freezing were evaluated.

- Sensitivity analyses were performed on the results.

Key Findings

- In most of the regions examined, observed changes in hydrologically related temperature variables are inconsistent with natural internal variability alone and consistent with the response to anthropogenic forcings.

- The authors found that the overall interregional anthropogenic fingerprint can be positively identified in all four observed temperature indices evaluated irrespective of the model used, the downscaling method, or the end points values.

- Natural variability in the western climate system was ruled out by the analysis as the major cause of observed changes.

- Solar variability and volcanic forcings were also ruled out by the analysis.

- In the 48 scenarios evaluated, the detection time for an anthropogenic fingerprint occurs as early as 1986 and no later than 1994.

2008, Pierce et al., "Attribution of Declining Western U.S. Snowpack to Human Effects"

Study Purpose

This article reports on a formal model-based detection and attribution analysis of changes in Western U.S. snowpack conditions based the ratio of April 1 SWE to October–March precipitation.

Method Highlights

- The study compared 1950–1999 observed SWE and precipitation data to hydrologic modeling output. GCM output was input to the hydrologic model. The intent was to isolate the signature of anthropogenically forced changes in SWE to precipitation ratio from historical model runs, determine how similar the observed changes are to the fingerprint, and

calculate the likelihood a signal of the observed strength could have occurred by chance in the control run.

- Ouput from two climate models was downscaled to 1/8° latitude/longitude using two techniques and input to the VIC hydrologic model.

- The GCMs used were the Community Climate System Model version 3.0, (CCSM3; Bala et al., 2008) and Parallel Climate Model version 2.1 (PCM; Washington et al., 2000. Multiple anthropogenic scenario runs were compared to 1,600 years of control run data.

- GCM output was downscaled to 1/8° latitude/longitude using the method of constructed analogues (Hidalgo et al., 2008) and the method of Bias Correction and Spatial Disaggregation (Wood et al., 2004).

- Historic snowpack observations included snow course data from the National Waterand Climate Center and data from the California Cooperative Snow Surveys obtained from the California Data Exchange Center for a total of 661 stations.

- Historic precipitation observations consisted of the gridded (1/8° latitude/longitude) daily precipitation dataset of Hamlet and Lettenmaier (2005), which was adjusted for gauge undercatch.

Key Findings

- The mean model estimate is that approximately half of the observed changes in snowpack over the Western United States during the period 1950–1999 arise from climate responses to anthropogenic forcings.

- The authors report the above finding did not depend on whether the snow course stations were grouped geographically (by mountain range across the West) or in equally weighted or area-weighted elevation bands.

- The signal indicating decreasing ratios of SWE to precipitation caused by anthropogenic forcing is detectable at the 95% significance level by the early 1990s: a record length of about 40 years.

- Only elevations below approximately 2,000 meters (6,560 feet) have statistically significant trends of decreasing ratios of SWE to precipitation.

2007, Hamlet et al., "20th Century Trends In Runoff, Evapotranspiration, And Soil Moisture in the Western United States"

Study Purpose

The VIC model is used to produce a long time series of key hydrologic variables (evapotranspiration, runoff, soil moisture) across the Western United States. The objective was to quantify hydrologic trends from simulations forced by observed temperature and precipitation over two time periods: the entire period of record (1916–2003) and a period that covers one full cycle of the Pacific decadal oscillation (1947–2003).

Method Highlights

- VIC was applied to the area west of the U.S. Continental Divide using a 1/8º spatial resolution.
- A gridded daily time step precipitation and temperature dataset from 1915–2003 used to drive the model.
- The first 9 months of VIC simulation were used as a simulation spin-up period (January to September 1915) to remove the effects of initial system conditions.

Key Findings

- VIC-simulated snowpack agreed well with snowpack derived using statistical approaches.
- A relationship was found between midwinter temperatures and the simulated seasonal snowmelt cycles.
- The model produced high quality streamflow simulations capturing hydrologic variability associated with different climate regimes.
- The model was well suited for identifying long-term trends in the streamflow seasonality.
- The model reproduced well the seasonal soil moisture and evapotranspiration dynamics.

2006, Mote, "Climate-driven Variability and Trends in Mountain Snowpack in Western North America"

Study Purpose

Multiple linear regression techniques are used to evaluate the sensitivity to temperature and precipitation of April 1 SWE using nearly 1,000 locations in the Western United States. This analysis allows the separation of the temperature and precipitation influences on the observed trends.

Method Highlights

- Snow course data through 2002 was obtained. In some instances, manual snow courses have been replaced with automated snow telemetry equipment. Both manual and telemetered data were used.
- A total of 995 snow records were obtained and used representing the time period 1960–2002.
- For each snow course location, reference time series temperature and precipitation data were developed by combining observations of the five nearest climate stations during November through March.
- A regression model of April 1 SWE values was developed as a function of seasonal mean temperature and precipitation during November through March.

Key Findings

- For most snow courses, the regression approach suggests that the long-term April 1 SWE variations can be reasonably explained by antecedent seasonal climate summaries at nearby locations.
- The study found general agreement between observed and climate derived SWE.
- Findings imply that other sources of long-term trends are secondary.
- Since mid-century, general winter and spring warming has caused a reduced snow pack at most locations. This has been offset by precipitation increases in the southern Sierra Nevada of California resulting in a net increase in SWE.
- Some of the trends might be explained by variations in North Pacific climate, which was shown to explain approximately 50% of the SWE variability through regression modeling.

2005, Hamlet et al. "Effects of Temperature and Precipitation Variability on Snowpack Trends in the Western United States"

Study Purpose

In this study, the authors developed simulations of spring SWE conditions throughout the Western United States based on observed climate data from 1916–2003 and evaluated the simulated conditions. Linear SWE trends were analyzed in an attempt to identify the influence of temperature and precipitation separately and to differentiate effects due to climate change versus those associated with the PDO.

Method Highlights

- 1915–2003 daily temperature and precipitation data from National Weather Service Observer stations were interpolated using the Symap algorithm to obtain $1/8^{o}$ latitude-longitude grid values for the Western United States and southern British Columbia.

- In the interpolation, temperatures were lapsed by 6.1 °C per kilometer, and precipitation was scaled for topographic effects using monthly precipitation maps produced by PRISM.

- VIC (version 4.0.5) model was used to develop 1916–2003 daily SWE values for the $1/8^{o}$ grid under three scenarios (base run, fixed precipitation, and fixed temperature) using the interpolated climate data.

- In the base run, unperturbed interpolated climate data were input to VIC, and the resulting SWE trends were the result of both temperature and precipitation.

- In the fixed precipitation run, the precipitation data were fixed (for each month) at the climatological value for each grid cell, and daily temperature was allowed to vary as in the base run with resulting SWE trends due to temperature only.

- In the fixed temperature run, the temperature data were fixed (for each month) at the climatological value for each grid cell and daily precipitation was allowed to vary as in the base run with resulting SWE trends due to precipitation only.

- March 1, April 1, and May 1 SWE values and trends were evaluated for the following time periods: 1916–2003 (full period); 1925–1976 (warm PDO to cool PDO); 1947–2003 (cool PDO to warm PDO); and 1925–1946 concatenated with 1977–2003 (warm PDO to warm PDO).

- The date of peak SWE and the days associated with 10% of peak accumulation and 90% melt were evaluated for each scenario and time period.

Key Findings

- Overall, the results show that March 1, April 1, and May 1 SWE trends are affected more by temperature and strongly suggest global warming is apparent in the observations evaluated in the study. Precipitation variability appears most strongly associated with decadal variability rather than long-term trends.

- The model shows that the widespread warming that has occurred in the Western United States during 1916 to 2003 has resulted in downward spring SWE over large areas.

- Model results for certain high-elevation areas with upward precipitation trends show upward SWE trends.

- The period from 1925 to 1976 was characterized by widespread increases in precipitation, which apparently dominated temperature trends to produce widespread upward trends in SWE.

- From 1947 to 2003, the model indicates regionally specific precipitation trends associated with decadal variability combined with strong downward trends in SWE due to widespread warming.

- The model results for the 1925–1946 concatenated with 1977–2003 period (warm PDO to warm PDO) combined with the 1916–2003 results strongly suggest that widespread regional warming trends are not well explained by PDO, but that decadal variability doe affect trends in winter precipitation that are apparent over shorter periods of the record.

- The trend for modeled dates of peak snow accumulation and 90% melt are generally earlier.

- The trend for modeled date of 10% peak SWE is also generally earlier, but appears to be due to trends in fall precipitation.

2005, Regonda et al., "Seasonal Cycle Shifts in Hydroclimatology Over the Western United States"

Study Purpose

The purpose of this study was to examine the relationship between the timing of snowmelt in the mountain basins of the Western United States relative to trends in temperature, precipitation and snow pack conditions.

Method Highlights

- The analysis considered data during 1950–1999 from 89 stream gauges in Western U.S. river basins having a significant snowmelt season.
- Stream gauge data were analyzed for runoff timing trends.
- Trend analyses were performed on March, April, and May SWE data from Western U.S. snow-course surveys and on winter precipitation and spring temperature.

Key Findings

- Peak runoff occurred earlier at most stations during the period and significant trends toward earlier runoff were found in the Pacific Northwest.
- Significant trends toward increasing spring temperature were found throughout the region, with larger trends found in the Pacific Northwest and Rocky Mountain regions.
- Increasing winter precipitation trends were identified for much of the study area; however, the fact that the data did not show a significant increase in total spring runoff suggests as total winter precipitation increases, more of it is coming in the form of rain.
- Significant decreasing trends in spring snow water equivalent were found at approximately 50% of the sites.

2004, Stewart et al., "Changes in Snowmelt Runoff Timing in Western North America Under a 'Business as Usual' Climate Change Scenario"

Study Purpose

The purpose of this study was to evaluate trends in western North America snowmelt-runoff relative and to predict future trends based on the output of a global climate model.

Method Highlights

- The analysis considered data from 279 stream gauges on North American river basins having a significant snowmelt season.
- Trends were evaluated for runoff CT defined as the "day of water year" (i.e., October through September) when 50% of the given water year's annual runoff has passed the reporting gauge.

- Average monthly temperature and precipitation anomaly trends from 1951–1980 observations were computed at each location in a 5° spatial grid, and then correlated to runoff CT data.

- PCM results for 1995–2099 under a business-as-usual greenhouse gas emissions scenario were used to predict future runoff CT conditions.

- The results of the statistical runoff CT model were compared to detailed, physically based hydrologic models under the same climatic conditions for several rivers where such models and simulations were available.

Key Findings

- 1995–2099 runoff CT trends are predicted to be earlier at most locations and especially so in the Pacific Northwest, Sierra Nevada, and Rocky Mountains.

- Projected CT runoff changes are consistent with observed rates and directions of change during the past five decades.

- Predicted responses of CT to the simultaneous effects of projected temperature and precipitation trends are dominated by the temperature changes.

Historical Trends (Rio Grande Basin)

2004, Passell et al., "Hydrological and Geochemical Trends and Patterns in the Upper Rio Grande, 1975 to 1999"

Study Purpose

The purpose of this study was to identify and analyze hydrological and geochemical spatial patterns and temporal trends in the Upper Rio Grande basin (above Bernardo, New Mexico).

Method Highlights

- Data from six stations for the 1975–1999 were analyzed for discharge, specific conductivity, pH, total dissolved solids and major cations and anions.

- Discharge data from the Otowi station for 1895–1905, 1910–1915, and 1919–1999 (105-year record) were evaluated for long-term trends.

- Air temperature data for Alamosa County, Colorado, for 1948–1999 were evaluated.

- Linear regression, Kendall's S and Seasonal Kendall's S methods were used for trend analyses.

Key Findings

- Trends of increasing discharge were identified for the months of January, February, and March in the 1975–1999 records.

- Significant trends were not identified in the analysis of peak runoff during the 105-year record or the 1975–1999 record.

- Analysis of individual monthly and average temperatures for January, February, and March 1948–1999 did not reveal significant trends.

2002, Lewis and Hathaway, "New Mexico Climate and Hydrology: Is the Historic Record Valid for Predictive Modeling?"

Study Purpose

The purposes of this study were to determine if 1950–1998 Middle Rio Grande observed hydrologic conditions are representative of the long-term Paleoclimate record and create a 40-year sequence representative of a broad range of climatic conditions.

Method Highlights

- The analysis considered a 1,370-year reconstruction (662–1992) of Palmer Drought Severity Index (PDSI) June values based on tree ring data from El Malpais National Monument.

- The analysis also considered PDO Index values from sea surface temperatures for 1900 to present and 1660–1899 PDO values reconstructed from Southern and Baja California tree ring data.

- Statistics were analyzed in the reconstructed PDSI and PDO time series and compared against those from the 1919–1998 continuous Rio Grande at Otowi, New Mexico, stream gauge record-based Otowi Index flow.

- The tree ring based PDSI values and measured PDSI values for northwestern New Mexico were used to develop a synthetic 40-year sequence of "typical" river flows.

Key Findings

- A correlation of $r = 0.56$ was found between the reconstructed 1919–1992 PDSI values and the observation based Otowi Index values.

- The PDSI data indicate that during 1700–1992, 83 years were drought years (below 22nd percentile), 77 years were wet period years (above 38th percentile), and 133 years were average (between 22nd and 38th percentiles).

- Relative to the 1,370-year reconstruction period, the 1950–1998 observed record includes a severe drought and a very wet period and is lacking average years.

- Relative to the 1,370-year reconstruction period, the 1918–1998 observed record includes a significantly higher percentage of wet periods.

- Strong correlations were found between observed flows and El Niño and La Niña events and PDO indices.

Projected Hydrologic, Ecosystem, and Water Demand Impacts (Upper Colorado River Basin)

2008, Barnett and Pierce, "When Will Lake Mead Go Dry?"

Study Purpose

The purpose of this study was to evaluate the potential effects of climate change on the Colorado River reservoir system, specifically Lake Powell and Lake Mead. Results include estimates of when reservoir storage may be depleted and when hydroelectric power production may cease as a function of climate change.

Method Highlights

- The water storage conditions for the combined Lake Powell and Lake Mead system were evaluated for the period 2008–2060 using a water budget method.

- A *simple* flow analysis was done without accounting for natural flow variability and assuming 10- to 30% percent reductions to the 1906–2004 annual average runoff amount of 15-MAF flow passing Lees Ferry.

- A *variable* flow analysis was also done which included natural flow variability at Lees Ferry developed from statistically modeled simulations based on 1906–2004 observations and flow estimates from approximately 1,250 years of tree ring data.

- The modeled annual flow reductions are assumed to occur incrementally beginning in 2007 and increasing linearly.

- System water supplies: Inflow is based on flow passing Lees Ferry and does not account for intervening inflows between Lake Powell and Lake Mead.

- System loss assumptions included: net annual evaporation/infiltration is assumed to be constant in all analyses at -1.7 MAF, and annual delivery to Mexico is constant at 1.5 MAF.

- System demand assumptions: Upper and Lower Basin total scheduled depletion is consistent with values assumed in the Shortage Guidelines FEIS.

- System initial conditions: reservoir system at 50% capacity.

- Drying metric determined by which year 50% of the 10,000 simulations went dry (deplete active storage) at least once since 2008. That is, recovery from a drying period was not considered in their risk analysis.

Key Findings[3]

- In the simple flow analysis (no natural flow variability), storage is depleted in 2030 and 2047, respectively, for the 30- and 10% flow reduction scenarios. The results also showed a 50% chance hydroelectric power generation would not be possible by 2021 due to low reservoir levels.

- In the variable flow analysis, the results indicate that, even without climate change, there is 50% chance the system will go dry by 2037. With a 20% reduction in flows, results indicate a 50% chance of the system going dry by 2028 and power production ceasing by 2017.

- Analyses results indicate that 10 and 20% reductions in future depletions would postpone system dry-up by 6 and 10 years, respectively, under the climate change flow reduction scenario, although this result appears to be sensitive to their treatment of several supply and demand assumptions, which differs from how they're treated in LC studies involving the Colorado River Basin.

[3] Assumptions are inconsistent with those in Reclamation modeling studies of the Colorado River Basin. Specifically, those in question are Lower Basin water supply (i.e., intervening inflows between Lake Powell and Lake Mead), reservoir evaporation, and reservoir management responses that would occur if low inflows were to persist for long periods of time.

2007, McCabe and Wolock, "Warming May Create Substantial Water Supply Shortages in the Colorado River Basin"

Study Purpose

The purpose of this study was to evaluate the potential effects of increasing air temperatures on the annual flow volume of the Colorado River. Impacts are presented in terms of percentage flow reductions and the frequency at which Colorado Compact flow allocations would not be met.

Method Highlights

- A water balance method was used under two temperature increase scenarios using 1490–1998 tree ring based reconstructed Colorado River flows as a baseline.
- Hydrologic unit temperature and precipitation values were input to the water balance model for estimation of inflows and depletions.
- Water balance model parameters were adjusted for calibration, and correlation between estimated and measured flow for the period 1906–2004 was 0.93.
- Changes in precipitation, reservoir evaporative losses and consumptive demands due to population increases were not included in the water balance analysis .
- Temperature increase scenarios included increasing 1901–2000 measured values uniformly by 0.86 and 2 °C.
- The water balance estimated flow values were input to a flow/surplus water supply model that simulated storage and consumption conditions.
- The simple flow/suplus model was developed by the authors and then evaluated by comparing estimated 1985–2000 storage in Lake Powell with measured storage data obtained from the Bureau of Reclamation, and the root-mean-squared error of the estimates was 16.8% of mean measured storage.
- The flow values for the driest 100-year period occurring in the 1490–1998 reconstructed period were adjusted using reduction factors from the temperature increase scenarios and these flows were also input to the flow/surplus model to evaluate worst case scenarios.
- The flow/surplus model output was used to calculate the fraction of time flow failed to meet the Colorado Compact allocations (failure rate).

Key Findings

- Under the 0.86-°C temperature increase scenario, 1901–2000 mean annual flow is reduced by 8% which is near the lower quartile level of the 1490–1998 reconstructed flows.

- Under the 2-°C temperature increase scenario, 1901–2000 mean annual flow is reduced by 17% to a level which is unprecedented in 1490–1998 reconstructed flows period.

- Under the 0.86-°C temperature increase scenario, the calculated Colorado Compact failure rate increased from 0.07 to 0.22.

- Under the 2-°C temperature increase scenario, the calculated Colorado Compact failure rate increased from 0.07 to 0.37.

- The Colorado Compact failure rates calculated for the driest 100-year period occurring in the 1490–1998 reconstructed period increased from 0.30 to 0.50 and 0.77 with the increased temperature scenarios flow reduction factors applied.

2003, Reiner et al., "Natural Ecosystems I: The Rocky Mountains"

Study Purpose

This peer reviewed assessment of climate-change effects on Rocky Mountain and Great Basin terrestrial ecosystems is based on research efforts discussed at a series of workshops conducted as part of the U.S. Global Change Research Program.

Method Highlights

- The ecosystem analysis was based on two climate change scenarios for each of two subregions. The subregions are defined as 1) Northern, North-central and West-central Rockies; and 2) East-central and Southern Rockies.

- The subregion climate change scenarios included the same seasonal temperature changes, but with differing precipitation and snowpack conditions.

- Under Scenario 1 for the East-central and Southern Rockies subregion, there is increased winter precipitation and decreased growing-season precipitation; and under Scenario 2, increased precipitation only in the summer.

- Under Scenario 1 for the Northern, North-central and West-central Rockies subregion, there is significantly increased winter precipitation; and under Scenario 2, increased precipitation predominantly in the spring and summer.

- The results of several cases studies are presented.

Key Findings

- General vegetation-related predictions include: where vegetation zones have the same character (e.g., alpine zone), their boundaries will move down in elevation with increasing latitude; the effect of slope-aspect will increase with latitude; and the nature of the zones themselves change with latitude through the addition and loss of dominant species.

- Under Scenario 1 for the East-central and Southern Rockies subregion, significant decreases in plant productivity, losses of area in forested ecosystems, and some local losses of native species are predicted. Under Scenario 2, less impact is predicted.

- Under Scenario 1 for the Northern, North-central and West-central Rockies subregion, relatively more drought-tolerant species such as Douglas fir might expand into higher elevations while maintaining populations in their current elevation zone and early season crops in intermountain basins could benefit. Under Scenario 2, vegetation in the Northern Rockies would experience more favorable conditions for growth in general due to more moisture and longer growing season.

- It is discussed that all of the scenarios would increase forest fires in that warmer temperatures help to produce more fuel in wet periods and to dry fuels in dry periods.

- There is evidence that pest infestations and diseases such as white pine blister rust may be exacerbated by warming temperatures, but many other factors must be considered.

- The authors discuss that animal species may appear in new locations and become extinct in others and the ability to adapt to heat and water stress are difficult to predict.

2003, Covich et al., "Natural Ecosystems II: Aquatic Ecosystems"

Study Purpose

This peer reviewed assessment of climate-change effects on Rocky Mountain and Great Basin aquatic ecosystems is based on research efforts discussed at a series of workshops conducted as part of the U.S. Global Change Research Program.

Method Highlights

- The goals of this effort were to 1) summarize important points needed to understand ways in which large-scale, long-term dynamics of climate would affect inland aquatic ecosystems, 2) provide examples and case studies that illustrate general relationships of how climate change has already affected aquatic species and ecosystems in the Rocky Mountain/Great Basin (RMGB) region, and 3) identify gaps in current understanding that need more study in order to improve future forecasts regarding the expected consequences of climate change on freshwater ecosystems.

- Past and current climate variability, as well as spatial variability of impacts, is discussed.

- The RMGB region was divided into northern and southern subregions for future climate change impacts assessments. The Southern Subregion includes the southern halves of Utah and Colorado, and the northern New Mexico portions of the RMGB region. The Northern Subregion includes virtually all of the Great Basin, and those portions of the Rocky Mountain system north of central Utah and central Colorado.

- The climate change scenario considered for the Northern Region consists of warmer fall, winter, and spring temperatures and increased winter precipitation. The climate change scenario considered for the Southern Region consists of warmer winter and late summer temperatures, reduced winter rain, and increased summer rain.

Key Findings

- The authors report climate change will almost certainly alter the aquatic ecosystems of the RMGB region, and some changes can be anticipated, especially for the Southern Subregion.

- Warmer spring temperatures are expected to extend the growing seasons of some species of fishes and invertebrates and alter food-web dynamics.

- Warmer surface waters (epilimnion) and slightly warmer bottom waters (hypolimnion) of stratified lakes and reservoirs will likely alter phytoplankton and zooplankton community structure and productivity by increasing metabolic rates and shifting competitive and feeding relationships.

- Higher water temperatures may well shift the distributions of cold-water species northward and to higher elevations, and favor some nonnative species which are likely to compete more stringently with species that are now threatened or endangered.

- Warmer and more nutrient-rich waters (from various human effluents) will likely modify many different types of aquatic ecosystems by accelerating nutrient cycling and increasing primary and secondary productivity while at the same time impacting individual species.

- Firm quantitative predictions await the development of coupled hydrologic and ecosystem models, and increased information on many aspects of the RMGB aquatic ecosystems.

Projected Hydrologic, Ecosystem, and Water Demand Impacts (Rio Grande Basin)

1996, Ramirez and Finnerty, "CO_2 and Temperature Effects on Evapotranspiration and Irrigated Agriculture"

Study Purpose

The purpose of this study was to assess climate change impacts on an irrigated potato crop in the San Luis Valley, Colorado, by estimating changes in ET rates due to changes in CO_2, temperature, precipitation, and water table conditions.

Method Highlights

- Changes in potato crop potential ET under six changed $C0_2$ and air temperature scenarios were evaluated using the modified Penman-Monteith equation.

- Scenarios included plus and minus 3-°C temperature changes with no change in CO_2, 50 and 100% CO_2 increases with no change in temperature, and combined CO_2 increases and 3-°C temperature increase and decrease.

- A root zone soil water balance was done with a soil-crop-climate model using the estimated potential ET rates to analyze soil moisture sensitivity, actual ET, and the effects of CO_2 fertilization on plant photosynthesis and crop production.

- Additive crop yield and optimal irrigation scheduling models were used to perform benefit-cost analyses.

Key Findings

- Under all potential ET scenarios, except for the 3-°C temperature increase only scenario, potential ET decreased significantly (14–39%) relative to the baseline.

- CO_2 induced effects on potential ET are greater than temperature-induced effects.

- Crop yield decreased under the temperature increase only scenario and increased under the increased temperature only scenario.

- Crop yield increased under both increased CO_2 only scenarios.

- Crop yield increased under all increased CO_2 combined with temperature change scenarios.

- Increasing available irrigation reduces the impacts of temperature and CO_2 changes.

- CO_2 fertilization will significantly increase crop production.

1989, Marinec and Rango, "Effects of Climate Change on Snowmelt Runoff Patterns"

Study Purpose

The purpose of this study was to evaluate potential changes to snowmelt runoff volumes and timing in three mountainous river basins based on general circulation model predicted temperature increases and changes in precipitation due to doubling of CO_2 levels within the next century.

Method Highlights

- The river basins studied include the Rio Grande, the Illecillewaet basin (Canada), and the Felsberg basin (Switzerland).

- A snowmelt runoff model was used with temperature, precipitation, and snow covered area variables.

- Observed conditions for a given year were modeled to provide a baseline, and then runs were made with a 3-°C temperature increase only and a 3-°C temperature increase with -5%, +5%, and +10% precipitation changes.

- The baseline scenario for the Rio Grande basin was from 1983 observed conditions.

Key Findings

- In the modeled basins, total seasonal runoff volume increases from 8 to 16% due to earlier snowmelt during a time when basin losses to runoff are less than the baseline scenario.

- The results are primarily temperature increase driven with minimal precipitation change effects.

- Results on Rio Grande basin total runoff ranged from 15 to 18% increase among the various scenarios.

- Results on Rio Grande basin April and May runoff showed expected increases of 158 and 89%, respectively. Results showed decreases in all other months.

Projected Operations Impacts (Upper Colorado River Basin)

2007, Christensen and Lettenmaier, "A Multimodel Ensemble Approach to Assessment of Climate Change Impacts on the Hydrology and Water Resources of the Colorado River Basin"

Study Purpose

This study predicts climate change impacts to the Colorado River Basin reservoir system based on climate projections included in the 2007 IPCC Fourth Assessment. It essentially an application of the approach demonstrated in Christensen et al., 2004 (see below), but featuring a larger ensemble of climate models and their respective climate projections.

Method Highlights

- The authors used output from 11 major climate models and two different future emissions scenarios and evaluated maximum, minimum and average projections relative to current conditions.

- The GCM results were input to the VIC hydrologic model and river inflow values from VIC were input to the CRRM to predict reservoir effects.

- VIC was calibrated to 1950–1999 data and generated a less than 1% under-prediction of streamflow at Imperial Dam, and +3% and -9% errors at Green River and Cisco, respectively, based on reconstructed natural flow at these points.

- CRRM was modified from the version used by Christensen et al. (2004) to reflect the Basin States' then current proposal with regard to how Lower Basin shortages should be tied to Lake Mead Levels and the model calculates shortages when necessary to all major Lower Basin entities.

- The emissions scenarios used are A2, a relatively high scenario with 2100 CO_2 levels of 850 ppm and B1, a relatively low level scenario with 2100 CO_2 levels of 550 ppm.

- Results were presented relative to historical conditions for three periods: (1) 2010–2039; (2) 2040–2069; and (3) 2070–2099.

Key Findings

- Temperatures increases (ºC) for the B1 runs during periods 1–3, shown as "average (minimum, maximum)," were 1.28 (0.53, 1.83), 2.05 (1.13, 2.99), and 2.74 (1.13, 2.99), respectively.

- For the A2 runs during the same periods, the temperature increases (ºC) by 1.23 (0.63, 1.82), 2.56 (1.61, 3.65), and 4.35 (2.77, 6.06).

- Annual precipitation percent change for the B1 runs during periods 1–3 were +1% (-8, 11), -1% (-11, 9), -1% (-11, 19), respectively.

- For the A2 runs and same periods, percent precipitation changes were -1% (-9, 7), -2% (-21, 13) and -2% (-16, 13), respectively.

- October to March average precipitation increased by +5%, +1%, and +2% for B1 and by +6%, +5% and +4% for the A2 scenario.

- April 1 SWE change for the B1 runs was -15% (-41, 0), -25% (-48, -1), and -29% (-53, -18) and for the A2 runs, SWE change was -13% (-36, 1), -21% (-52, 6) and -38% (-66, -15).

- Changes in mean-annual runoff during periods 1–3 were 0% (-23, 17), -7% (-27, 12) and -8% (-30, 29) for the B1 runs, respectively, and by 0% (-16, 14), -6% (-39, 18), and -11% (-37, 11) for the A2 runs.

- A decrease of 10% in average streamflow is magnified into a 20% change of the same sign in Lake Mead reservoir storage and a 20% inflow change results in a 40% storage impact.

- The authors state that because of the large ratio of storage to inflow in the basin, neither increase in storage nor change in operating rules will likely change the storage impacts under declining inflows.

2004, Christensen, et al., "The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin"

Study Purpose

This study predicts climate change impacts to the Colorado River Basin reservoir system based on output from the National Center for Atmospheric Research PCM.

Method Highlights

- Three PCM runs for the 21st century were used with slightly different initial atmospheric conditions and a 50-year control climate run starting in 1995 with greenhouse gas emissions fixed at the 1995 level was also completed.

- The PCM results were downscaled to 1/8° daily data and input to the VIC hydrologic model, and river inflow values from VIC were input to the monthly CRRM to predict reservoir effects.

- VIC was calibrated to 1950–1989 data and generated a less than 1% error of streamflow at Imperial Dam, and +3% and -9% errors at Green River and Cisco, respectively, based on reconstructed natural flow at these points.

- The CRRM was based roughly on Reclamation's Colorado River Simulation System model.

- PCM 21st century results averaged over the three runs were compared to the control run and to historical observed data or calculated natural flow in the historical period.

- Results were presented relative to historical conditions for three periods: (1) 2010–2039; (2) 2040–2069; and (3) 2070–2099.

Key Findings

- The control run showed warming of about 0.5 ºC (0.9 ºF) which is in rough agreement with what many believe to be 'committed warming'

should greenhouse gas emissions stop immediately. The three 21st century runs showed average increases of approximately 3 ºC (5.4 ºF) over the observed average temperature of 10 ºC (18 ºF). In general, the warming was concentrated in spring and summer.

- Average annual precipitation in the control run was 1% less than historical, and in the three 21st century runs was 3, 6, and 3% lower in periods 1, 2, and 3, respectively. The seasonal precipitation pattern in the control run was very similar to the historical observed, and the 21st century runs showed a similar pattern but with less precipitation in the spring.

- April 1 SWE in the control run was only 86% of the observed historical SWE, while SWE was 76, 71, and 70% in periods 1–3, respectively. Southern Colorado suffered the highest reductions and those occurred in periods 2 and 3.

- Runoff was reduced by 10% in the control run, and by 14, 18, and 17 in periods 1–3, respectively, in the 21st century runs. Peak runoff advanced from June in the historical data to May in the latter parts of the control and 21st century runs.

- Reservoir storage in the control run dropped by 7%, and periods 1–3 showed reductions of 36, 32, and 40%, respectively, relative to simulated historical conditions.

- Deliveries from Lake Powell were met 92% of the time in the historical data, and 72% in the control run and 59, 73, and 77% in periods 1–3, respectively.

Projected Operations Impacts (Rio Grande Basin)

2007, Hurd and Coonrod, "Climate Change and Its Implications for New Mexico's Water Resources and Economic Opportunities"

Study Purpose

The purpose of this study was to evaluate hydrologic responses and water demands associated climate change predictions within a framework that optimizes water use allocations for the greatest economic benefit. The framework is designed to reveal potential changes in future water resource management.

Method Highlights

- Output from three GCM run under the SRES A1B emissions scenario (as defined by the Intergovernmental Panel on Climate Change) was translated into weather inputs for a hydrologic model.
- Results from hydrologic model were translated into inputs for hydroeconomic model.
- The GCM results were from the Hadley Centre for Climate Prediction and Research Met Office, Atmospheric Research Australia, and U.S. Department of Commerce Geophysical Fluid Dynamics Laboratory models and meant to represent respective wet, middle, and dry climate scenarios.
- The hydrologic WATBAL model was used to simulate changes in soil moisture and runoff as a function of temperature and precipitation.
- The hydroeconomic model (RBHE) of the Rio Grande watershed was used to simulate management of the water resources system.
- Hydrologic and hydroeconomic model runs were made for 2030 and 2080 baseline conditions and wet, middle, and dry climate change runs were made for these time periods.
- Key changes in hydroeconomic model input parameters include changes in runoff and streamflow, reservoir evaporation and water use (shift from agricultural to urban).

Key Findings

- New Mexico’s social, economic, and environmental systems are very susceptible to water resources impacts due to climate change.
- Reduced snow pack, earlier runoff, and higher evaporative demands will affect vegetative cover and species’ habitat.
- Direct economic losses of up to $100 million are estimated under climate changes by 2080, with an additional estimated $200 million in indirect economic losses.
- Agricultural economies will be impacted most.
- Other costs and values lost that were identified but not quantified include water transfer transaction costs, ecological and social values that agriculture provides, ecological and environmental benefits associated

with flowing water in riparian systems, and erosion and loss of cultural values and services from historical acequias and community irrigation systems.

2006, D'Antonio, "The Impact of Climate Change on New Mexico's Water Supply and Ability to Manage Water Resources"

Study Purpose

- The purpose of this effort was to research the impact of climate change on the State of New Mexico's water supply and identify measures to improve its ability to manage its water resources under future conditions.

Method Highlights

- Research was led by the State Engineer's Office with assistance from other State agencies, local and Federal agencies, and State research institutions.
- Predicted climate change impacts to New Mexico were projected from global climate model results.
- Strategies, policies and tools needed to manage water resources in the context of climate change were identified.

Key Findings

- General recommendations include incorporating climate change scenarios into strategic planning, improving adaptive management capacity at the watershed scale, making infrastructure improvements, and addressing statutory, regulatory and institutional barriers.
- In northern New Mexico, recent annual average temperatures have been more than 2 ºF (1.1 ºC) above mid-20th century values.
- The projected statewide New Mexico 100-year average temperature increase, based on the average of 18 GCM results, is greater than 5 ºF (2.8 ºC).
- Effects of increasing temperature identified include reduced snow pack, changes in runoff, ecological impacts, and increased consumptive use of water.
- The authors also report that Rio Grande spring peak flows would be expected to increase significantly and that flood events would be expected to occur earlier and with relatively greater volumes due to climate change.

A.5 Great Plains Region

This attachment summarizes each article surveyed as part of this synthesis of climate change literature for Great Plains (GP) Region. The survey is representative of articles published through early 2008, but is not exhaustive. The intent for each article summary is to give the reader a quick sense for study purpose, method highlights, and key findings. Study details are kept to a minimum; and it is suggested those readers interested in more detail should refer to the articles themselves.

Article summaries are organized in this attachment under the themes of: Historic Trends; Projected Hydrologic, Ecosystems, and Water Demands Impacts; and Projected Operations Impacts. Under each theme, the articles are organized chronologically (most recent year first), then by author.

Historical Trends

2008, Bonfils et al., "Detection and Attribution of Temperature Changes in the Mountainous Western United States"

Study Purpose

This article reports on a rigorous detection and attribution analysis that was performed to determine the causes of the late winter / early spring changes in hydrologically relevant temperature variables over mountain ranges of the Western United States during 1950–1999.

Method Highlights

- The study used three climate models and all GCM output was downscaled to 1/8° latitude/longitude using two techniques and compared to historical observations.

- The GCM ouput were from the Community Climate System Model version 3.0, Finite Volume (CCSM3-FV; Collins et al., 2007; Bala et al., 2008), Parallel Climate Model version 2.1 (PCM; Washington et al., 2000), and MIROC model (Hasumi and Emori, 2004; Nozawa et al., 2007).

- GCM temperature output was downscaled to 1/8° latitude/longitude using the method of constructed analogues (Hidalgo et al., 2008) and the method of Bias Correction and Spatial Disaggregation (Wood et al., 2004).

- Maximum and minimum temperature data for the period 1950–99 from the University of Washington Land Surface Hydrology Research were interpolated into a 1/8° latitude/longitude grid.

- The evaluation was performed on nine subregions: the Washington Cascades, the northern Rockies, the Oregon Cascades, the Blue Mountains, the northern Sierras, the southern Sierras, the Great Basin, the Wasatch area, and the Colorado Rockies.

- January–March minimum temperatures, the number of frost days, and the degree-days above freezing were evaluated.

- Sensitivity analyses were performed on the results.

Key Findings

- In most of the regions examined, observed changes in hydrologically related temperature variables are inconsistent with natural internal variability alone and consistent with the response to anthropogenic forcings.

- The authors found that the overall interregional anthropogenic fingerprint can be positively identified in all four observed temperature indices evaluated irrespective of the model used, the downscaling method, or the end points values.

- Natural variability in the western climate system was ruled out by the analysis as the major cause of observed changes.

- Solar variability and volcanic forcings were also ruled out by the analysis.

- In the 48 scenarios evaluated, the detection time for an anthropogenic fingerprint occurs as early as 1986 and no later than 1994.

2008, Pierce et al., "Attribution of Declining Western U.S. Snowpack to Human Effects"

Study Purpose

This article reports on a formal model-based detection and attribution analysis of changes in Western U.S. snowpack conditions based the ratio of April 1 SWE to October–March precipitation.

Method Highlights

- The study compared 1950–1999 observed SWE and precipitation data to hydrologic modeling output. GCM output was input to the hydrologic

model. The intent was to isolate the signature of anthropogenically forced changes in SWE to precipitation ratio from historical model runs, determine how similar the observed changes are to the fingerprint, and calculate the likelihood a signal of the observed strength could have occurred by chance in the control run.

- Ouput from two climate models was downscaled to 1/8° latitude/longitude using two techniques and input to the VIC hydrologic model.

- The GCMs used were the Community Climate System Model version 3.0, (CCSM3; Bala et al., 2008) and Parallel Climate Model version 2.1 (PCM; Washington et al., 2000. Multiple anthropogenic scenario runs were compared to 1,600 years of control run data.

- GCM output was downscaled to 1/8° latitude/longitude using the method of constructed analogues (Hidalgo et al., 2008) and the method of Bias Correction and Spatial Disaggregation (Wood et al., 2004).

- Historic snowpack observations included snow course data from the National Water and Climate Center and data from the California Cooperative Snow Surveys obtained from the California Data Exchange Center for a total of 661 stations.

- Historic precipitation observations consisted of the gridded (1/8° latitude/longitude) daily precipitation dataset of Hamlet and Lettenmaier (2005), which was adjusted for gauge undercatch.

Key Findings

- The mean model estimate is that approximately half of the observed changes in snowpack over the Western United States during the period 1950–1999 arise from climate responses to anthropogenic forcings.

- The authors report the above finding did not depend on whether the snow course stations were grouped geographically (by mountain range across the West) or in equally weighted or area-weighted elevation bands.

- The signal indicating decreasing ratios of SWE to precipitation caused by anthropogenic forcing is detectable at the 95% significance level by the early 1990s: a record length of about 40 years.

- Only elevations below approximately 2,000 meters (6,560 feet) have statistically significant trends of decreasing ratios of SWE to precipitation.

2007, Knowles et al., "Trends in Snowfall Versus Rainfall for the Western United States, 1949–2001"

Study Purpose

The purpose of this study was to examine whether a trend is occurring in the ratio of snowfall to total winter precipitation in the Western United States.

Method Highlights

- The analysis considered daily snowfall depth, precipitation, and maximum and minimum temperature data from Western U.S. climate stations for 1948 to 2001.
- The analysis also considered temperature data from 647 stations and precipitation data from 173 stations.
- The liquid water equivalent of snowfall was calculated as the total precipitation measured on a day when snowfall was reported.
- Winter and monthly ratios of snowfall water equivalent to total precipitation were then calculated.
- Trend analyses were performed on both sets of these ratios (winter and monthly for 1948–2001).

Key Findings

- Pronounced trends were found toward reduced winter period ratios of snowfall to total winter precipitation in the Sierra Nevada and Pacific Northwest. Results were less clear for the Rocky Mountain region.
- Where found, the trends toward reduced ratios of snowfall to total winter precipitation correspond with a warming trend in the Western United States.
- Winter period ratio trends correspond to reduced snow water equivalent values rather than to changes in overall precipitation, with the exception of the Southern Rocky Mountain region where both snowfall and precipitation have increased.
- Focusing on the months of January and March, trends toward reduced ratio of snowfall water equivalent to precipitation are most pronounced in March, throughout the Western United States, and in January near the west coast. The geographic constraint on the latter trend may be related to the decreasing trend in mean temperature found during January was found at higher elevations, potentially restricting the trends toward reduced ratio

of January snowfall water equivalent to precipitation to occur in the lower elevations near the west coast. In contrast, March trends toward increasing air temperature were found throughout the region, which corresponded to the March reductions in ratio of snow water equivalent to total precipitation.

2005, Regonda et al., "Seasonal Cycle Shifts in Hydroclimatology Over the Western United States"

Study Purpose

The purpose of this study was to examine the relationship between the timing of snowmelt in the mountain basins of the Western United States relative to trends in temperature, precipitation and snow pack conditions.

Method Highlights

- The analysis considered data during 1950–1999 from 89 stream gauges in Western U.S. river basins having a significant snowmelt season.
- Stream gauge data were analyzed for runoff timing trends.
- Trend analyses were performed on March, April and May SWE data from Western U.S. snow-course surveys, and on winter precipitation and spring temperature.

Key Findings

- Peak runoff occurred earlier at most stations during the period and significant trends toward earlier runoff were found in the Pacific Northwest.
- Significant trends toward increasing spring temperature were found throughout the region, with larger trends found in the Pacific Northwest and Rocky Mountain regions.
- Increasing winter precipitation trends were identified for much of the study area; however, the fact that the data did not show a significant increase in total spring runoff suggests as total winter precipitation increases, more of it is coming in the form of rain.

2001, Cayan et al., "Changes in the Onset of Spring in the Western United States"

Study Purpose

The purpose of this study was to evaluate the affects of spring climate conditions in the Western United States on blooming plants and the timing of snowmelt-runoff pulses. Statistical methods were used to determine whether correlations exist between spring temperatures, first bloom dates and runoff timing.

Method Highlights

- Statistical methods were used to determine whether correlations exist between spring temperatures, first bloom dates, and runoff timing.
- The analysis considered data from 105 lilac observation stations with 20 years or more of data during 1957–94, and from 87 honeysuckle stations with 15 or more years of data during 1968–94.
- These plant observation stations were located throughout the Western United States at elevations ranging from 15 to 2,927 meters.
- The analysis also considered streamflow records from 110 Western U.S. rivers for periods beginning in 1948 and ending between 1988 and 1995, focusing on the annual date of first major pulse of spring runoff (defined as the day when the cumulative departure from that year's mean flow is most negative, equivalent to finding the day after which most flows are greater than average).
- Temperature and precipitation averages for regions corresponding to plant observation stations were used for correlation analyses.

Key Findings

- Lilac and honeysuckle first bloom dates are highly correlated with each other.
- The first bloom dates of both plants were found to positively correlate with initial runoff pulse dates and temperature anomaly.
- Authors suggested that earlier onset of spring is remarkable since the late 1970s, as spring temperatures were found to have increased from 1–3 ^{o}C (1.8–5.4 ºF) in western North America since the late 1970s.
- Earlier and warmer-than-normal spring temperatures were related to larger scale atmospheric conditions across North America and the North Pacific.

Projected Hydrologic, Ecosystem, and Water Demand Impacts

2007, Elgaali et al., "High Resolution Modeling of the Regional Impacts of Climate Change on Irrigation Water Demand"

Study Purpose

This study predicts future changes in ET and irrigation water demands for the Arkansas River Basin in eastern Colorado based on downscaled GCM output. ET and irrigation water demand predictions were developed using a model called Integrated Decision Support Consumptive Use (IDSCU) that was developed at Colorado State University.

Method Highlights

- Historical climate was based on weather station data during 1985–1990.
- Future climate was derived from two 1994–2099 GCM simulations were used, one produced by the Hadley Centre for Climate Prediction and Research (HAD) and the other by the Canadian Climate Centre (CCC). Each simulation was forced by increasing atmospheric CO_2 by 1% per year and was developed as part of the Vegetation-Ecosystem Modeling and Analysis Project (VEMAP) (Kittel et al., 1995). Simulation outputs were downscaled and topographically adjusted to 0.5° latitude/longitude resolution. The downscaling/adjusting process accounted for the effects of local topography on climate parameters.
- The downscaled/adjusted future climate results were input to the IDSCU model for calculation of ET and irrigation water demand predictions.
- IDSCU calculates ET at a daily time-step following a Penman-Monteith combination method algorithm (ASCE, 1990).
- Results are presented for the 21st century relative to the average seasonal ET estimated from the baseline 1960–1990 scenario.

Key Findings

- The predicted average departure of temperatures from the baseline ranges from 0-°C change in the 1990s up to 5-°C (9-°F) change in the 2090s for the growing season months (April–September).
- The projected mean precipitation increases gradually from the 2010s to 2030s with an average rate of increase of 1.4% per decade, decreases in the 2040s and 2050s with an average rate of decrease of 1.0% per decade,

and gradually increases from the 2060s to 2090s with an average rate of increase of 2.2% per decade.

- Based on the CCC output, the seasonal ET increases from values below the historical level and crosses the threshold of the historical level in the 2020s. These increases range from 5% above the historical level in the 2020s up to 22% in the 2090s with a rate of increase of 2.6% per decade.

- Based on the HAD output, it takes up to the 2040s for ET to cross the threshold of the historical level; ET gradually increases up to 10% above the baseline in the 2090s at a rate of 1% per decade.

- Changes in predicted monthly ET are more vigorous than those in seasonal ET, and predicted rates increase much more during the spring months and less during summer months.

- Irrigation water demand (ET minus effective precipitation) is also projected to increase gradually as a function of increasing temperatures.

2007, Hamlet and Lettenmaier, "Effects of 20th century warming and Climate Variability on Flood Risk in the Western United States"

Study Purpose

This study investigates changes in flood risk in the Western United States associated with century-wide warming and interannual climate variations. Additionally, implications of increases in precipitation variability since the mid 1970s are explored.

Method Highlights

- The VIC model with a spatial resolution of 1/8º was used.

- A daily time step streamflow routing model (described by Lohmann et al. (1998)) was used to postprocess the runoff generated by VIC.

- The driving meteorological data was the gridded 1/8º data set for the Western United States described by Hamlet and Lettenmaier (2005).

- 5-, 10-, 20-, 50-, and 100-year return flood periods were calculated for each model forcing data set.

Key Findings

- Simulations suggest that the warming over the 20th century has resulted in changes in flood risks in many parts of the region broadly characterized by midwinter temperatures.

- Colder, snowmelt basins typically show reductions in flood risks because of snowpack reductions.

- The precipitation data sets show clear increases in the variability of cool season precipitation.

2005, Johnson et al., "Vulnerability of Northern Prairie Wetlands to Climate Change"

Study Purpose

This study evaluated potential climate change impacts on North America's prairie pothole region (PPR) and how these impacts would affect waterfowl breeding conditions.

Method Highlights

- A wetland simulation model (WETSIM 3.1) was applied to simulate historic and future PPR wetland conditions using weather station data and three climate change scenarios. WETSIM 3.1 simulates water balance, wetland stage and vegetation dynamics as a function daily mean temperature and precipitation data.

- Weather data from 18 stations throughout the PPR with 95-year records were used to model historic conditions.

- WETSIM 3.1 was calibrated using wetland condition data from a site in North Dakota where data has been collected continuously since 1979, and its mobility was tested using data from another long-term wetland monitoring site.

- The climate change scenarios included: (1) a 3-^{o}C (5.4-^{o}F) temperature increase and no change in precipitation; (2) a 3-^{o}C (5.4-^{o}F) temperature increase and 20% increase in precipitation; and (3) a 3-^{o}C (5.4-^{o}F) temperature increase and 20% decrease in precipitation. These changes were applied uniformly to all PPR weather station data all the results were compared relative to simulated historic conditions.

Key Findings

- WETSIM 3.1 accurately simulated the spring rise, summer drawdown, and interannual variability of the wetland site it was calibrated to.

- Simulation results for future climate change scenario 1 (temperature increase only) and scenario 3 (temperature increase and precipitation decrease) showed significant negative impacts overall.

- Water balance effects of temperature and precipitation increases offset each other in scenario 2 with positive impacts due to increased vegetation.

- A temperature increase only (scenario 1) indicates more dense vegetation at the relatively wet sites in the eastern PPR.

- Increased temperature and decreased precipitation (scenario 3) showed the greatest effects with most sites becoming dominated by dry marsh conditions due to more frequent and longer drought.

- Under warmer and drier future climate conditions, the most productive waterfowl areas of the PPR would shift from its central region to the eastern, wetter areas.

2003, Reiner et al., "Natural Ecosystems I: The Rocky Mountains"

Study Purpose

This peer reviewed assessment of climate-change effects on Rocky Mountain and Great Basin terrestrial ecosystems is based on research efforts discussed at a series of workshops conducted as part of the U.S. Global Change Research Program.

Method Highlights

- The ecosystem analysis was based on two climate change scenarios for each of two subregions. The subregions are defined as 1) Northern, North-central and West-central Rockies; and 2) East-central and Southern Rockies.

- The subregion climate change scenarios included the same seasonal temperature changes, but with differing precipitation and snowpack conditions.

- Under Scenario 1 for the East-central and Southern Rockies subregion, there is increased winter precipitation and decreased growing-season precipitation; and under Scenario 2, increased precipitation only in the summer.

- Under Scenario 1 for the Northern, North-central and West-central Rockies subregion, there is significantly increased winter precipitation; and under Scenario 2, increased precipitation predominantly in the spring and summer.

- The results of several cases studies are presented.

Key Findings

- General vegetation-related predictions include: where vegetation zones have the same character (e.g., alpine zone), their boundaries will move down in elevation with increasing latitude; the effect of slope-aspect will increase with latitude; and the nature of the zones themselves change with latitude through the addition and loss of dominant species.

- Under Scenario 1 for the East-central and Southern Rockies subregion, significant decreases in plant productivity, losses of area in forested ecosystems, and some local losses of native species are predicted. Under Scenario 2, less impact is predicted.

- Under Scenario 1 for the Northern, North-central and West-central Rockies subregion, relatively more drought-tolerant species such as Douglas fir might expand into higher elevations while maintaining populations in their current elevation zone and early season crops in intermountain basins could benefit. Under Scenario 2, vegetation in the Northern Rockies would experience more favorable conditions for growth in general due to more moisture and longer growing season.

- It is discussed that all of the scenarios would increase forest fires in that warmer temperatures help to produce more fuel in wet periods and to dry fuels in dry periods.

- There is evidence that pest infestations and diseases such as white pine blister rust may be exacerbated by warming temperatures, but many other factors must be considered.

- The authors discuss that animal species may appear in new locations and become extinct in others and the ability to adapt to heat and water stress are difficult to predict.

2003, Covich et al., "Natural Ecosystems II: Aquatic Ecosystems"

Study Purpose

This peer reviewed assessment of climate-change effects on Rocky Mountain and Great Basin aquatic ecosystems is based on research efforts discussed at a series of workshops conducted as part of the U.S. Global Change Research Program.

Method Highlights

- The goals of this effort were to 1) summarize important points needed to understand ways in which large-scale, long-term dynamics of climate would affect inland aquatic ecosystems, 2) provide examples and case

studies that illustrate general relationships of how climate change has already affected aquatic species and ecosystems in the Rocky Mountain/Great Basin (RMGB) region, and 3) identify gaps in current understanding that need more study in order to improve future forecasts regarding the expected consequences of climate change on freshwater ecosystems.

- Past and current climate variability, as well as spatial variability of impacts, is discussed.

- The RMGB region was divided into northern and southern subregions for future climate change impacts assessments. The Southern Subregion includes the southern halves of Utah and Colorado, and the northern New Mexico portions of the RMGB region. The Northern Subregion includes virtually all of the Great Basin, and those portions of the Rocky Mountain system north of central Utah and central Colorado.

- The climate change scenario considered for the Northern Region consists of warmer fall, winter and spring temperatures and increased winter precipitation. The climate change scenario considered for the Southern Region consists of warmer winter and late summer temperatures, reduced winter rain and increased summer rain.

Key Findings

- The authors report climate change will almost certainly alter the aquatic ecosystems of the RMGB region, and some changes can be anticipated, especially for the Southern Subregion.

- Warmer spring temperatures are expected to extend the growing seasons of some species of fishes and invertebrates and alter food-web dynamics.

- Warmer surface waters (epilimnion) and slightly warmer bottom waters (hypolimnion) of stratified lakes and reservoirs will likely alter phytoplankton and zooplankton community structure and productivity by increasing metabolic rates and shifting competitive and feeding relationships.

- Higher water temperatures may well shift the distributions of cold-water species northward and to higher elevations, and favor some nonnative species which are likely to compete more stringently with species that are now threatened or endangered.

- Warmer and more nutrient-rich waters (from various human effluents) will likely modify many different types of aquatic ecosystems by accelerating

nutrient cycling and increasing primary and secondary productivity while at the same time impacting individual species.

- Firm quantitative predictions await the development of coupled hydrologic and ecosystem models, and increased information on many aspects of the RMGB aquatic ecosystems.

2001, Conly and van der Kamp, "Monitoring the Hydrology of Canadian Prairie Wetlands to Detect the Effects of Climate Change and Land Use Changes"

Study Purpose

Prairie Pothole areas of North America are primary breeding habitat for more than half of North American ducks. These small wetlands are very sensitive to climate and land use changes. Currently monitoring is based on statistical analysis of general surveys. This large-scale and nonsite-specific information does not lend itself well to estimates of effects that can be expected related to continued changes in land use and climate. Since the 1960s, a few sites have been intensively monitored. At each site, 30 to 100 wetlands have been studied to determine a quantitative background for identifying the effects of climate variability. This paper summarizes the present status of the monitoring program and how the data have been used to date.

Method Highlights

- Watershed and climate monitoring data, of differing qualities and scales, are used to evaluate patterns in wetland water levels

- In one instance (St. Denis National Wildlife Area) 1968–1997 wetland water level data coupled with meteorological data in the SLURP model to simulate water level changes in the wetland

Key Findings

- Modeling success is tied to availability and quality of long-term water level data, land use data, and onsite meteorological data

- Wetland numbers can be tied to climate indices. The warmer/dryer the climate could indicate a reduction in the number of prairie wetlands. Because of the effects of other parameters, it is unlikely that this type of analysis will be helpful for early detection of climate effects.

- Effective monitoring of wetlands should include intensive (10 square kilometers) hydrologic data collection and extensive (regional) hydrologic data collection (with fewer parameters and reduced sampling frequency)

1999, Lettenmaier, et al. "Water Resources Implications of Global Warming: A U.S. Regional Perspective"

Study Purpose

This paper summarizes six studies on the sensitivity of water resources to climate change. Of the six, the Missouri system applies to the GP region. The studies were conducted under contemporary climate predictions, included investigation of water resources management effects (not just the sensitivity of the hydrologic system), and used models and methods of analysis that are somewhat standard.

Method Highlights

- Climate change scenarios were produced using three coupled ocean-atmosphere GCMs (GFDL89, ECHAM1-A, UKMO) forced first by current CO_2 conditions (base run) and then again by annually increasing CO_2 concentrations and a doubled CO_2 evaluation.

- Five analyses were based on emission scenarios resembling forcing used in the IPCC Is92a scenario, with years corresponding to 2005–2050 and monthly precipitation, temperature, and solar radiation changes.

- Basin approach was consistent for each site: 1) downscaling of GCM precipitation, temperature and solar radiation; 2) hydrologic models used to generate streamflow parameters; 3) streamflows used in water resource management models of the systems to model system performance under each scenario.

- Climate change effects were, when available, compared against other, nonclimate, system impacts.

Key Findings

- The Missouri River site was the most sensitive to global warming of all sites studied

- Snow accumulation plays a modest role in total Missouri runoff. Temperature increases affect snowpack but not total runoff.

- Reduced precipitation combined with increasing potential evapotranspiration led to substantial decreases in Missouri River runoff for two scenarios (MPTR, HCTR); favoring flood control but impacting supply, navigation, and hydropower.

- Doubling CO_2 (GFDL $2XCO_2$) tended to increase runoff for the Missouri.

1999, Ojima et al. "Potential Climate Change Impacts on Water Resources in the Great Plains"

Study Purpose

The study explores potential climate change impacts on water resources (aquatic ecosystems, agricultural demands, water management) in the Great Plains.

Method Highlights

- Climate change scenarios were developed by referencing simulations from two (CCC - Canadian Center for Climate Prediction and HAD - Hadley Center for Climate Prediction and Research) GCMs.

- Water demand response was simulated using the SCS-Blaney Criddle consumptive use model for three crop types, (grass, alfalfa, and corn).

Key Findings

- Results from GCM's indicate average temperature and precipitation will increase over the region but seasonal patterns may not be uniform.

- Under CCC: perennial crops, grass and alfalfa pasture would experience a 50- to 60-percent increase in consumptive demand toward the end of the 21st century across the region.

- Under HAD for the same period: grass pasture would experience a 50-percent increase in consumptive use; alfalfa pasture would experience a 30-percent increase in consumptive demand, while consumptive demand for corn is unchanged.

1999, Rosenberg et al., "Possible Impacts of Global Warming on the Hydrology of the Ogallala Aquifer Region"

Study Purpose

The study explores climate change impacts on surface water runoff and associated water supplies in the Ogallala Aquifer region. The study considered various temperature increases and effects on hydrology, and also various changes in atmospheric CO_2 and associated impacts on photosynthesis and evapotranspiration.

Method Highlights

- Climate change scenarios were developed based on evaluation of climate projections from three GCMs (GISS, UKTR, and BMRC) with an effective doubling of atmospheric CO_2 concentration.

- Derived scenarios (+1.0, 2.5 and 5.0 ºC) represent a range of mild to severe warming associated with assumed future emissions.

- The different global mean temperature (GMT) levels above were used as a surrogate for time, the higher temperatures simulating times later in the century when global temperatures are expected to be substantially higher than now.

- The study also considered CO_2 fertilization effect for C3 and C4 class plants by running each scenario at 365-, 560-, and 750-ppm CO_2 levels.

- Surface water response was simulated using the Hydrologic Unit Model of the United States (HUMUS) with:

    - Actual soil and deep groundwater conditions were estimated using Soil Water Assessment Tool (SWAT).

    - Potential and actual evapotranspiration modeled using Penman-Monteith method.

    - CO_2 fertilization effects simulated with algorithms of Stoekle et al.

Key Findings

- The three climate projections referenced all indicated increases in temperature. However, they differed substantially with regard to projected precipitation, ranging from 20- to 60-percent spring increases in the Missouri Basin and little change to 60-percent decreases in late summer. For the Arkansas-White-Red River Basins, precipitation differences are dramatically different.

- Water yield was found to increase in the Missouri Basin under the wetter scenarios (GISS and UKTR).

- Water yield was found to decrease sharply under the drier BMRC scenario. The amount of yield reduction grew larger for scenarios with increasing temperature.

- Elevated CO_2 levels cause even more water yield increases because of reduced water demand by all irrigated plants. This increase does not offset the water yield decreases in the BMRC scenarios.

- Water yield in the Arkansas-White-Red River Basin decreased under all three GCM scenarios. Little or no CO_2 fertilization was seen in this basin.

- Aquifer recharge is reduced under all GCM, GMT, and CO_2 scenarios in both the Missouri River and Arkansas-White-Red Rivers Basins.

1997, Covich, et al. "Potential Effects of Climate Change on Aquatic Ecosystems of the Great Plains of North America"

Study Purpose

This study summarizes available information on patterns of spatial climate variability and identifies subregions of importance to ecological processes.

Method Highlights

- The Great Plains were divided into four unique hydrologic areas: glaciated prairie, high plains, eastern plains, and Ozark plateau.

- The study considered long-term water level data available for streams and some pothole wetlands. Additionally, the study considered tree ring data records during the past 300 years.

Key Findings

- Climate sensitive areas of the Great Plains range from cold-water systems (springs, and spring fed streams) to warmer, temporary systems (intermittent streams, ponds, pothole wetlands, playas).

- Regional climate is generally continental with steep spatial gradients in temperature and precipitation.

- Climate history can be deduced from pollen studies documenting plant community types and populations for about 12,000 years.

- Past climate change evidence in the Great Plains suggests that climate has changed rapidly several times in the past 10,000 years.

- Trends in climate variables are influence by ENSO teleconnections.

- Studies to address effects of 21st century warming on prairie wetlands are few. Prairie wetlands provide breeding ground for 50–80% of North American waterfowl. Habitat loss currently is high due to competing agricultural practices.

- A coordinated research program focused on broad-scale comparisons of matched catchments with different land use.

1993, Poiani and Johnson, "Potential Effects of Climate Change on a Semi-Permanent Prairie Wetland"

Study Purpose

This study assessed the potential effects of climate change on the hydrology and vegetation of a semipermanent prairie wetland using a calibrated wetland simulation model.

Method Highlights

- The hydrology and vegetation conditions at a North Dakota wetland were modeled under 11 climate change scenarios.
- A spatially defined, rule-based simulation model was used that consists of interacting hydrology and vegetation components.
- The model was calibrated and validated to actual wetland conditions observed during 1979–1989.
- One climate change scenario was based Goddard Institute for Space Studies GCM output under a doubling of current atmospheric CO_2.
- Others scenarios included combinations of 2-°C and 4-°C temperature increases with -20, -10, 0, +10, and +20% precipitation changes relative to the observed 1979–1989 conditions.

Key Findings

- Under the doubling of current CO_2 scenario, the GCM output monthly temperatures were 3- to 6-°C higher than the observed 1979–1989 monthly mean temperatures and precipitation increased slightly.
- The wetland simulation model predicted significant impacts under all climate change scenarios; including reduction of open water area, reduced water level fluctuation, and loss of wetland vegetation.
- Under the doubling of current CO_2 scenario, it was predicted the wetland would dry up during the summer periods in every year except for one beginning in the fourth year of the modeled period.
- Under the 2-°C temperature increase scenarios, it was predicted the wetland would dry up during the summer periods beginning in the 3rd to 6th years for all except the 20% precipitation increase scenario.
- It was predicted the wetland would eventually dry up during the summer periods under all five 4-°C temperature increase scenarios.

Projected Operations Impacts

2000, Hotchkiss et al., "Regulated River Modeling for Climate Change Impact Assessment: The Missouri River"

Study Purpose

This study demonstrated the ability to incorporate complex operation rules for multiple reservoirs into a hydrologic model capable of assessing climate change impacts on water resources of large, completely managed, river basins. The study stems from the MINK project on assessing economic impacts of climate change in Missouri, Iowa, Nebraska, and Kansas.

Method Highlights

- The SWAT was used to simulate surface water hydrology (soil moisture, evapotranspiration, snow, snowmelt, overland flow, ground water, channel routing) as well as the transpiration suppression effects of CO_2 enrichment.

- Climate input included daily precipitation and temperature, and monthly average wind speed and direction.

- Four simulations were run on the calibrated model: 1) a 10% increase in basin-wide precipitation over the entire watershed for 25 years, 2) zero precipitation basin-wide over the same 25-year period, 3) historic precipitation in the same period (with cumulative reservoir storage initially set to zero), and 4) a short (2-year) intense (zero precipitation) drought.

Key Findings

- Reservoir modeling:

    - For regions with a large snowmelt component two shortcomings in SWAT modeling were apparent.

    - Snowmelt algorithms are too simple and underestimate snowmelt; thus, inflow to upper reservoirs is under predicted.

    - Historic snowpack data cannot be used to simulate precipitation increases. Thus, reservoir inflow will be lower.

- Climate simulation:

    - The reservoir model simulations, some with extreme bounds, indicated modeling subroutines worked well for many ranges of input.

2000, Loáiciga et al., "Climate-Change Impacts in a Regional Karst Aquifer, Texas, USA"

Study Purpose

This study attempted to determine the impacts of climate change scenarios on management of the Edwards aquifer system.

Method Highlights

- Climate change scenario was defined based on one GCM (GFDL E30) simulated under a 2X CO_2 scenario.
- The Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) provided an observed temperature and precipitation dataset for study. This dataset was used with the GCM climate projections to scale historic time series and simulate climate projections.
- Surface water recharge was calculated using methods developed by Puente and used by the U.S. Geological Survey to determine monthly recharge to the Edwards Aquifer.
- A two-dimensional, finite-difference model (GWSIM IV) was used to simulate ground water and spring flows.
- Ground water pumping rates were developed for the model grid based on data from 1934–1996. Groundwater pumping forecasts (developed by others) were applied to the 2x CO_2 climate scenario.
- Two historic periods used: 1947–1959, 1978–1989, are representative of critically dry and average climate conditions respectively.
- A second modeling effort, linking a lumped parameter ground water model and a rainfall/runoff model included six alternative CGMs in a study of Edwards Aquifer response to warming.
- Historic precipitation and temperature from 1975–1990 were used in the second modeling effort.

Key Findings

- GWSIM aquifer modeling:
    - Edwards Aquifer appears to be very vulnerable to warming trends based on current levels of extraction and projected future pumping rates.

  - Under average recharge conditions and a 2x CO_2 concentration, the aquifer could sustain a pumping rate of approximately 400,000 acre-feet per year and preserve minimum flows at key springs.
  - A maximum pumping rate if 140,000 acre-feet per year is indicated in a critically dry recharge period under 2X CO_2 concentrations.

- Lumped parameter ground water model:
  - Given the 2X CO_2 concentration simulations, negative environmental impacts associated with declining spring flows are indicated for withdrawals of 440,000 acre-feet per year.
  - Greater impacts are sown for 550,000 acre-feet per year withdrawals.

- Given predictions of growth and water demand, the Edwards Aquifer groundwater resources are threatened under 2X CO_2 concentration scenarios.

Appendix B. Graphical Resources – Downscaled Climate Changes Projected over Reclamation Regions

This appendix contains maps that that summarize an assessment of downscaled, current climate projections[1] for decadal moving changes in 30-year mean precipitation and temperature. The downscaled climate projections used in this assessment are described in the main report, chapter 4. Each map shows change by Reclamation region, climate variable, and projected future period relative to a given base period (periods are indicated in map title).

About the climate periods, projected future period varies from 1960–1989 to 2070–2099. Projected base period provides the reference for assessing climate change and is always "simulated historical" 1950–1979 period. Being simulated and not observed, the reference climate is unique for each projection. It is statistically close but not equal to the historically observed climate during 1950–1979. The reason for the latter relates to discussion in chapter 4 of the main report. The base period climates in these projections are generated using a given climate model forced by estimated historical time series atmospheric composition (1900–1999) and starting from a given estimate of the initial climate system condition in year 1900. Multiple initial condition estimates might be considered, leading to multiple historical "runs."[2] As discussed in chapter 4, the "simulated historical" climate of each projection has been bias-corrected to be statistically consistent with historically observed climate during 1950–1999. This bias-correction procedure does not constrain frequency characteristics to be the same (e.g., occurrence of drought and surplus spells). Thus, when these bias-corrected "simulated historical" climates are sampled for 30-year subperiods (e.g., 1950–1979, 1960–1989, 1970–1999) within the bias-correction period (1950–1999), it is possible that the sampled 30-year statistics will vary among projections and also vary relative to historically observed 30-year statistics.

On computing changes in period climate, period mean-annual changes were first computed for both climate variables for each projection and downscaling location. For temperature, the computed change is incremental of future period minus base period (degrees Fahrenheit [ºF]). For precipitation, the computed change is the quotient of "incremental change of future period minus base period" divided by

[1] Data source the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multimodel dataset (http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php). Finer-spatial resolution translations of these data were then obtained from the "Statistically Downscaled WCRP CMIP3 Climate Projections" archive at http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/.

[2] http://www-pcmdi.llnl.gov/ipcc/time_correspondence_summary.htm.

base period, expressed as a percent. At each downscaling location and for a given pair of periods (e.g., 2020–2049 relative to the base 1950–1979 period), these computations resulted in an ensemble of 112 projection-specific changes. From these results, the maps show ensemble-median change at each location. It is relevant to focus on the ensemble-median change given that the projections do not all start from the same climate-system state, and because natural multidecadal climate variability can affect period-specific climate statistics like 30-year means. Change values are indicated in two ways on the maps: (a) color shading as indicated by the color bar legend, and (b) contours with change values labeled (i.e., contours at 5 percent [%] intervals for precipitation change and at 0.5 ºF intervals for temperature change).

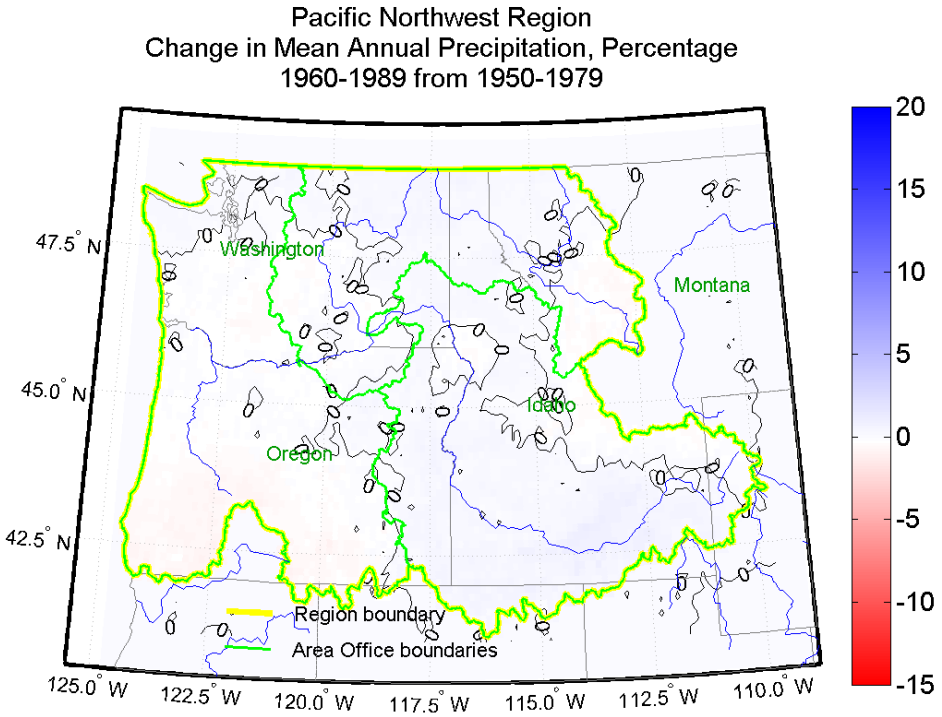
It is recommended that the maps be interpreted as follows:

- All of the downscaled climate projections that contributed to this assessment offer a plausible portrayal of how temperature and precipitation might have evolved during the past and could evolve into the future.

- At any projection time-stage, we can focus on the middle condition among all of the projections' conditions to get a sense about mean climate state in the context of this sequencing uncertainty (i.e., focus on the projection ensemble-median).

- If we apply this view to "change in period-mean climate" and track the middle change through time, we can evaluate the information for presence or absence of climate change trends.

Pacific Northwest Region – Precipitation Change


Pacific Northwest Region
Change in Mean Annual Precipitation, Percentage
1960-1989 from 1950-1979
Washington
Montana
Idaho
Oregon
Region boundary
Area Office boundaries
47.5° N
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42.5° N
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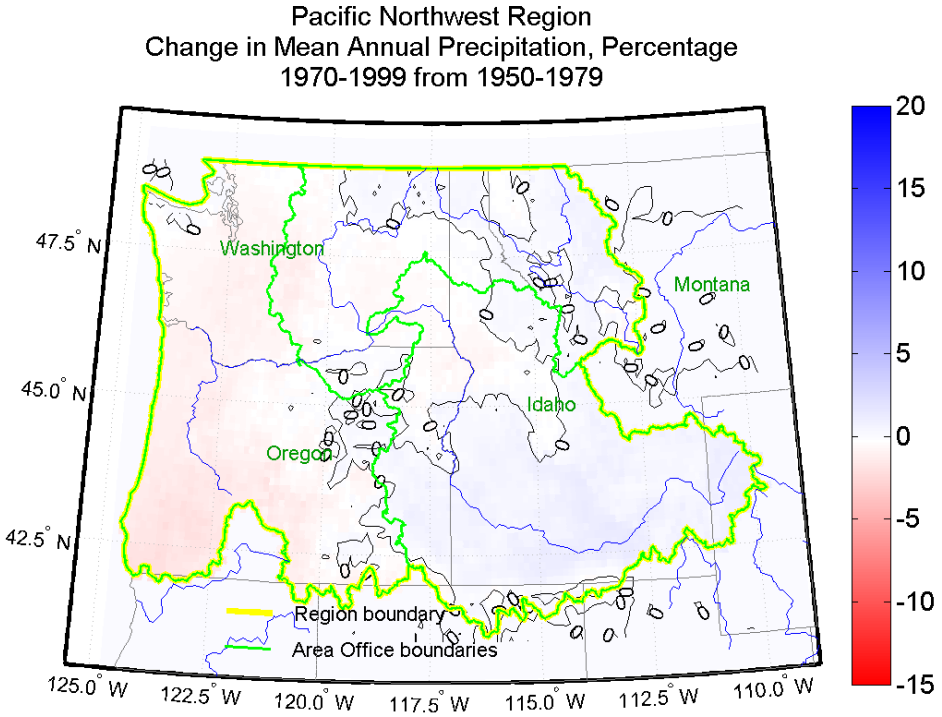
Pacific Northwest Region
Change in Mean Annual Precipitation, Percentage
1970-1999 from 1950-1979
Washington
Montana
Idaho
Oregon
Region boundary
Area Office boundaries
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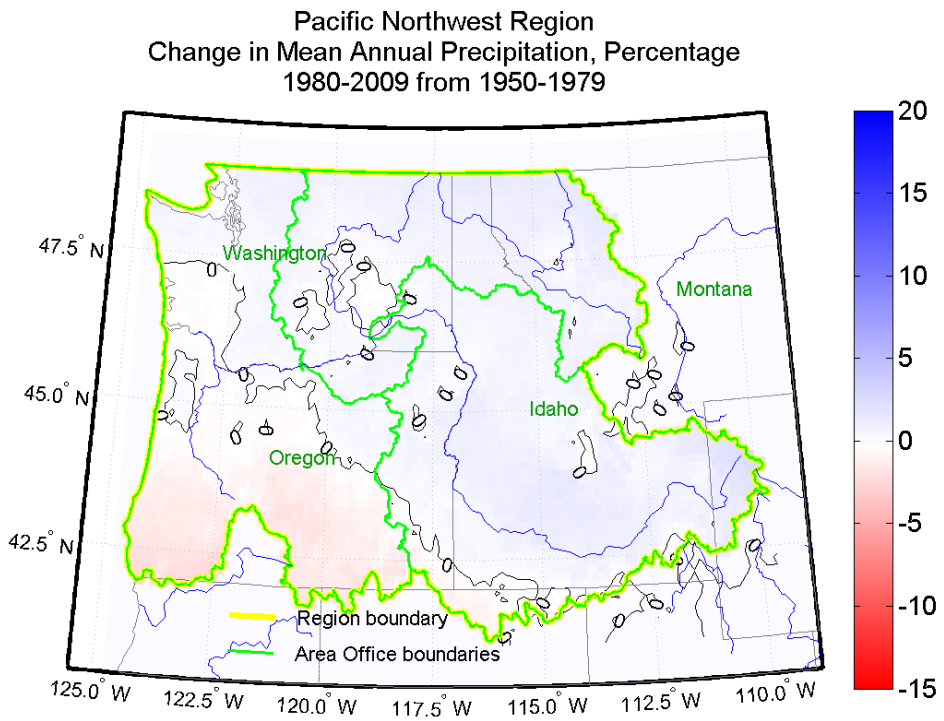
Pacific Northwest Region
Change in Mean Annual Precipitation, Percentage
1980-2009 from 1950-1979
Washington
Montana
Idaho
Oregon
Region boundary
Area Office boundaries
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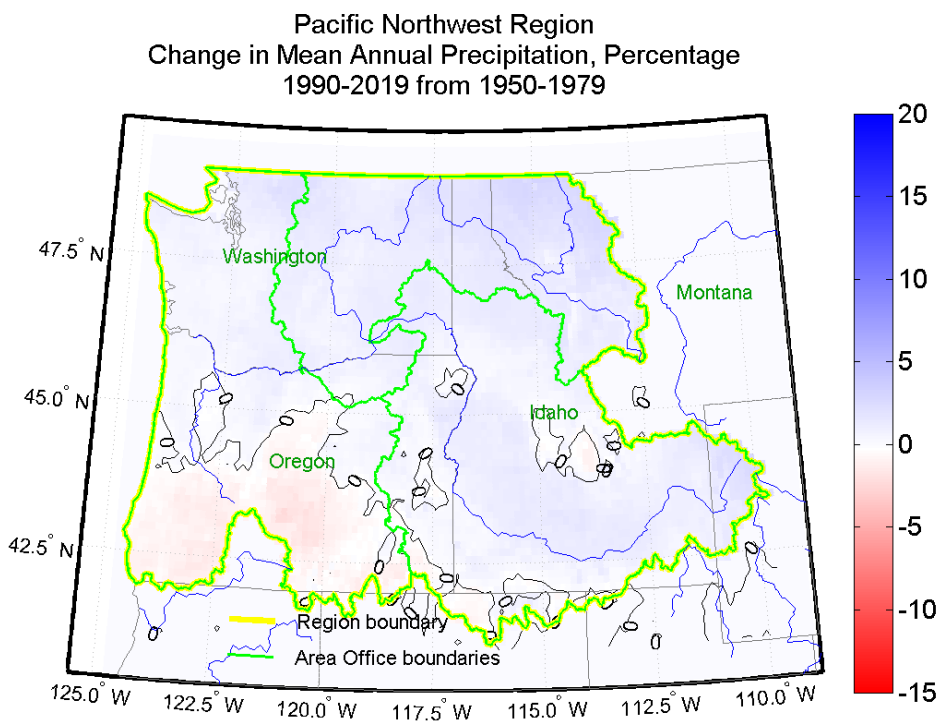
Pacific Northwest Region
Change in Mean Annual Precipitation, Percentage
1990-2019 from 1950-1979
Washington
Montana
Idaho
Oregon
Region boundary
Area Office boundaries
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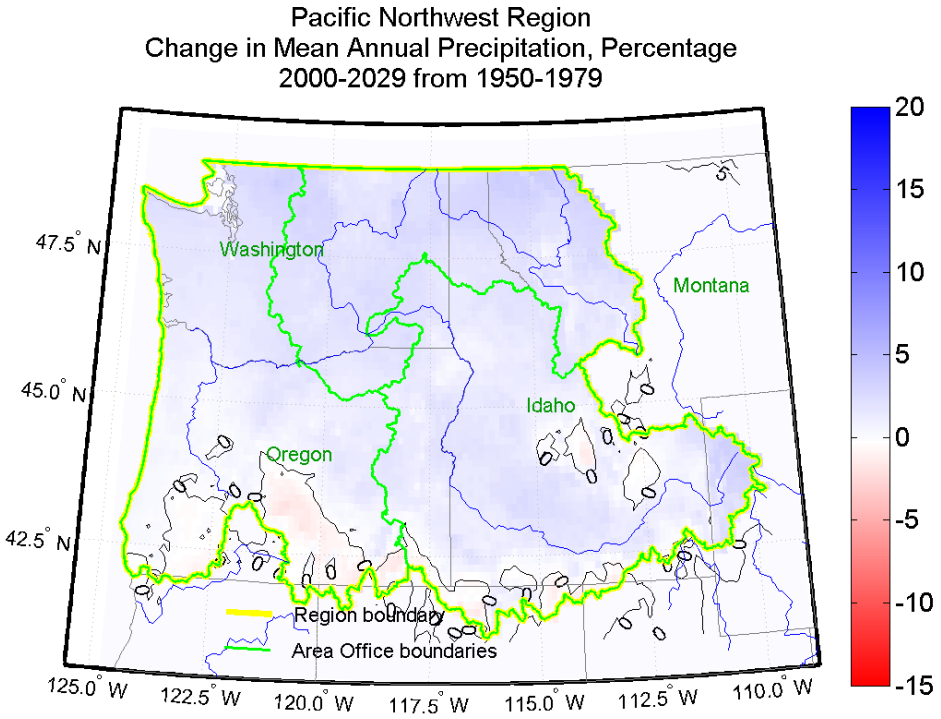
Pacific Northwest Region
Change in Mean Annual Precipitation, Percentage
2000-2029 from 1950-1979
Washington
Montana
Idaho
Oregon
Region boundary
Area Office boundaries
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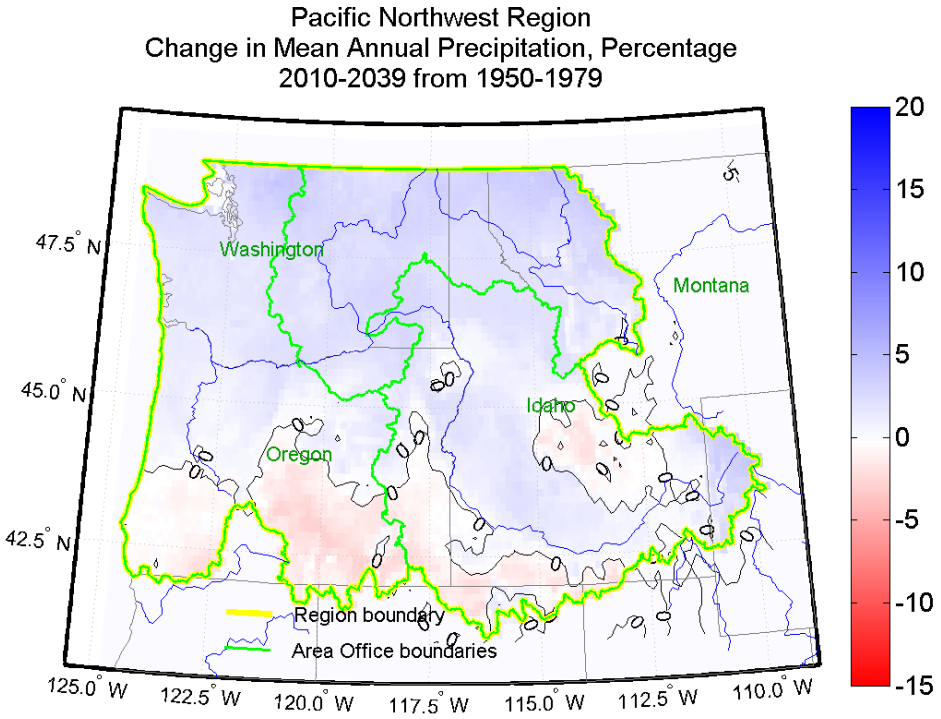
Pacific Northwest Region
Change in Mean Annual Precipitation, Percentage
2010-2039 from 1950-1979
Washington
Montana
Idaho
Oregon
Region boundary
Area Office boundaries
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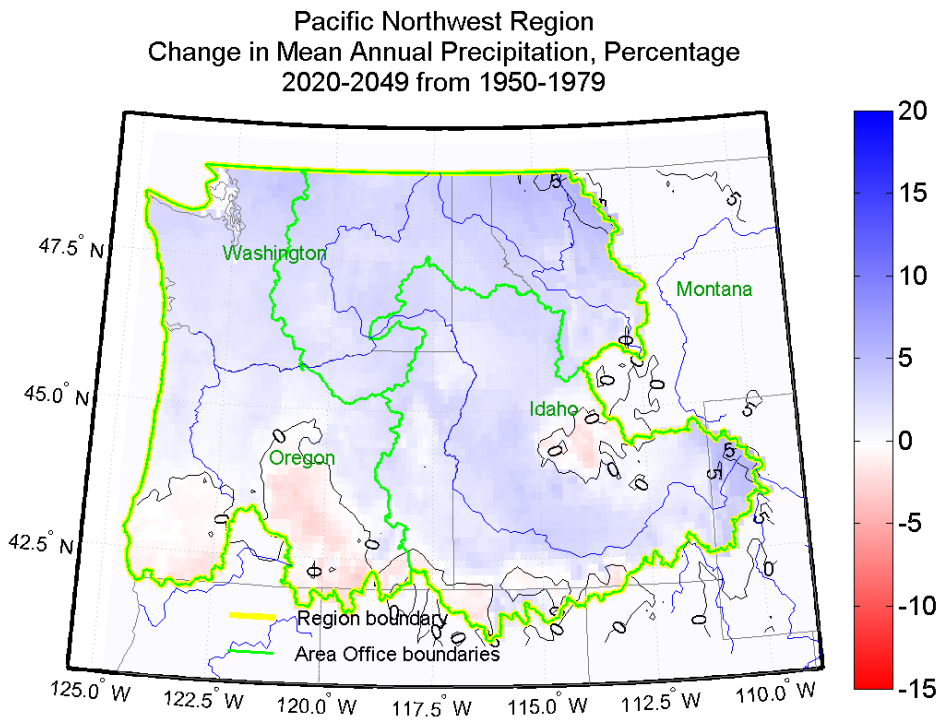
Pacific Northwest Region
Change in Mean Annual Precipitation, Percentage
2020-2049 from 1950-1979
Washington
Montana
Idaho
Oregon
Region boundary
Area Office boundaries
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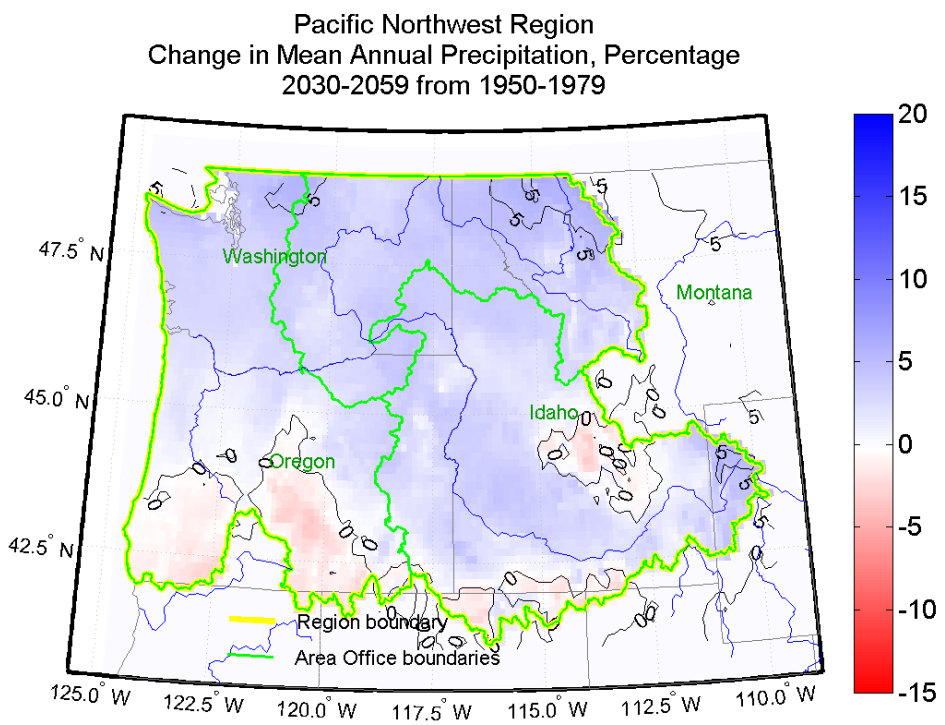
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Change in Mean Annual Precipitation, Percentage
2030-2059 from 1950-1979
Washington
Montana
Idaho
Oregon
Region boundary
Area Office boundaries
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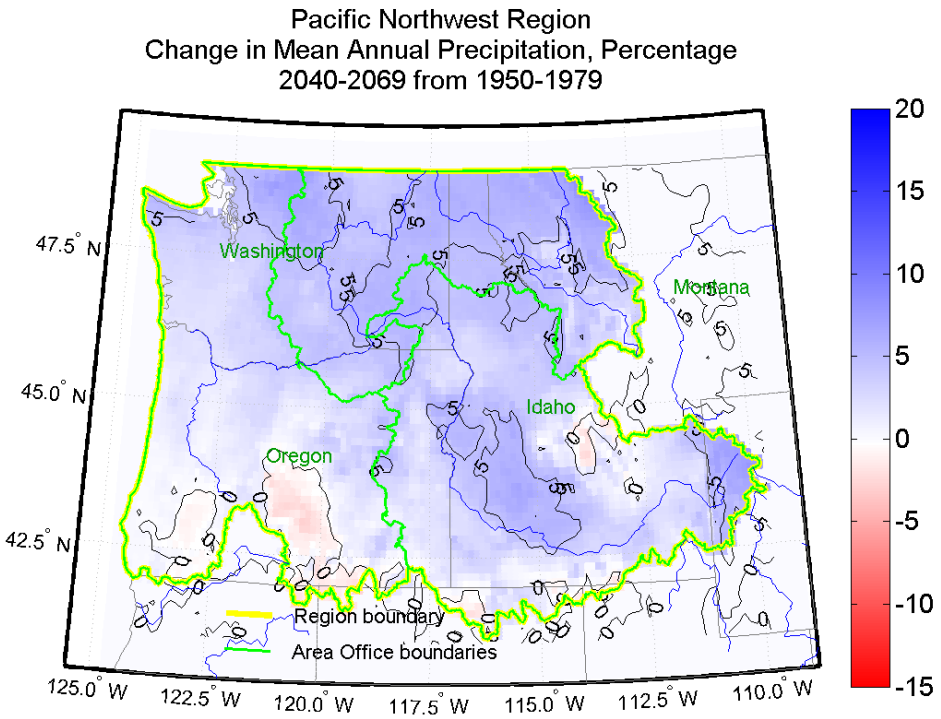
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Change in Mean Annual Precipitation, Percentage
2040-2069 from 1950-1979
Washington
Montana
Idaho
Oregon
Region boundary
Area Office boundaries
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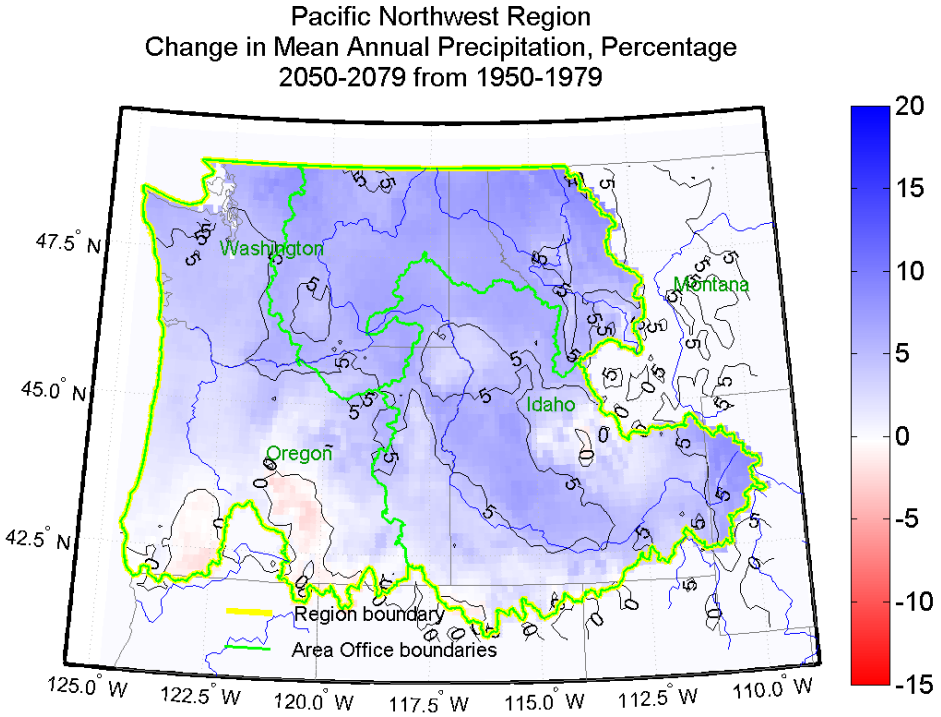
Pacific Northwest Region
Change in Mean Annual Precipitation, Percentage
2050-2079 from 1950-1979
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Montana
Idaho
Oregon
Region boundary
Area Office boundaries
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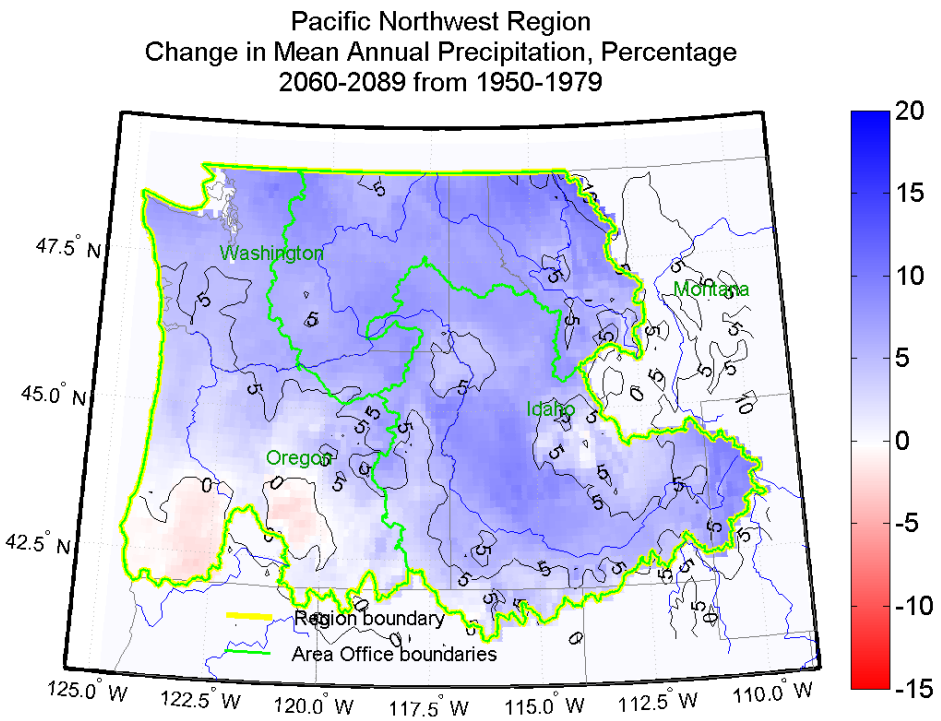
Pacific Northwest Region
Change in Mean Annual Precipitation, Percentage
2060-2089 from 1950-1979
Washington
Oregon
Idaho
Montana
Region boundary
Area Office boundaries
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42.5° N
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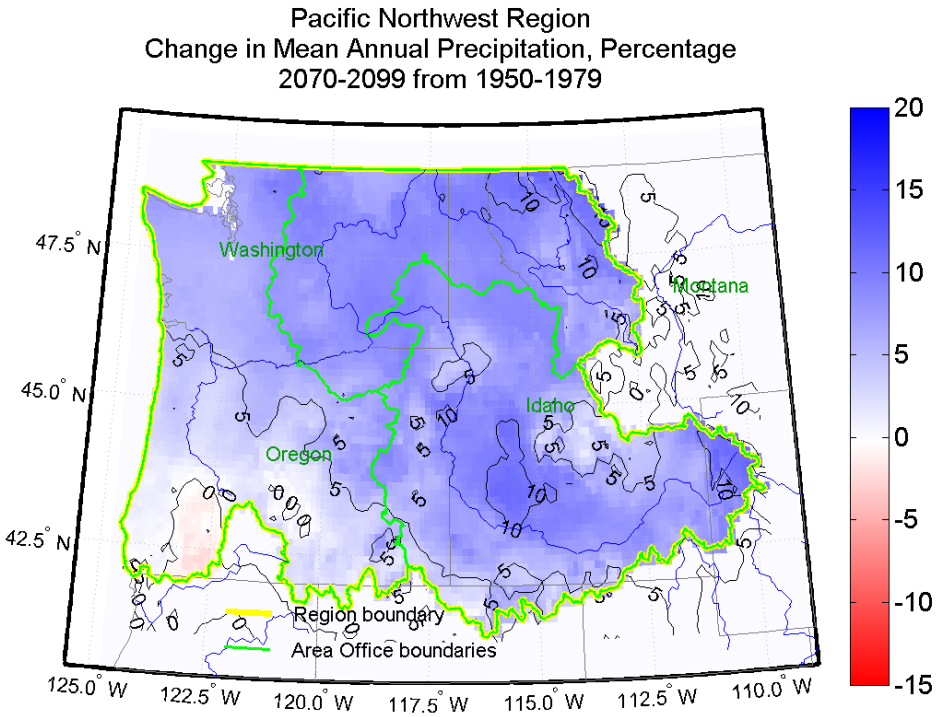
Pacific Northwest Region
Change in Mean Annual Precipitation, Percentage
2070-2099 from 1950-1979
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Oregon
Idaho
Montana
Region boundary
Area Office boundaries
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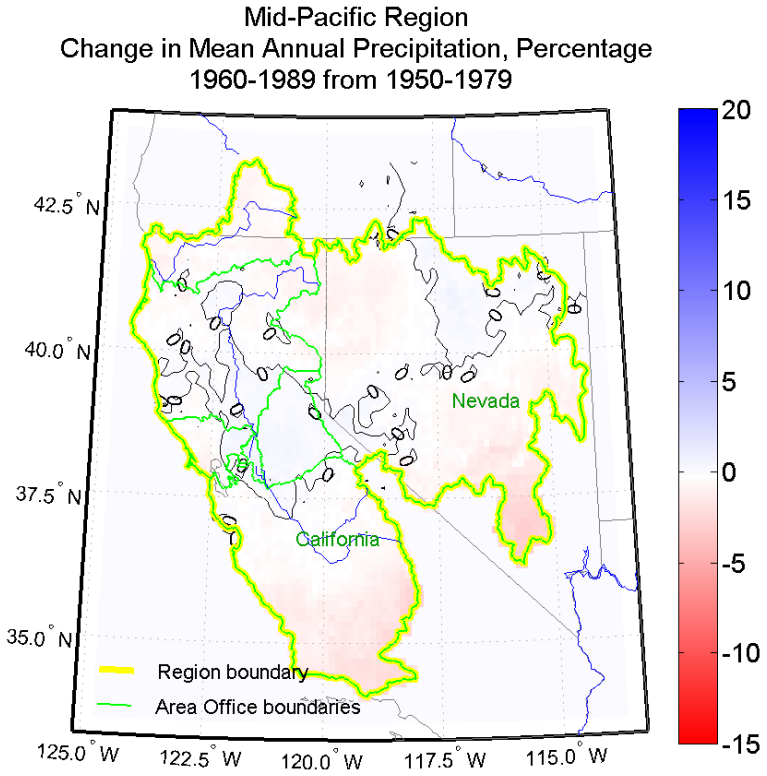
Mid-Pacific Region – Precipitation Change


Mid-Pacific Region
Change in Mean Annual Precipitation, Percentage
1960-1989 from 1950-1979
42.5° N
40.0° N
37.5° N
35.0° N
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120.0° W
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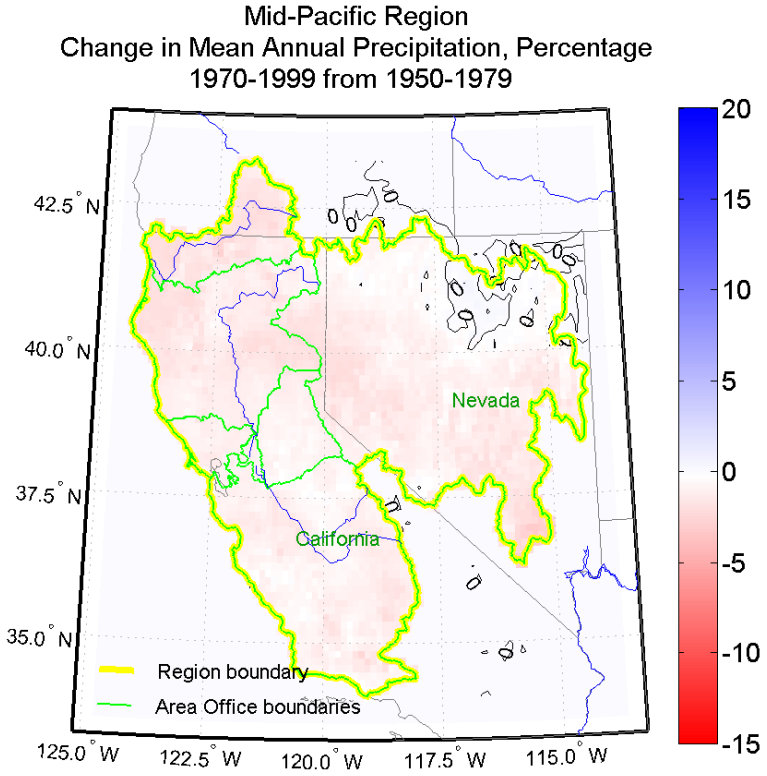
Mid-Pacific Region
Change in Mean Annual Precipitation, Percentage
1970-1999 from 1950-1979
42.5° N
40.0° N
37.5° N
35.0° N
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120.0° W
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Nevada
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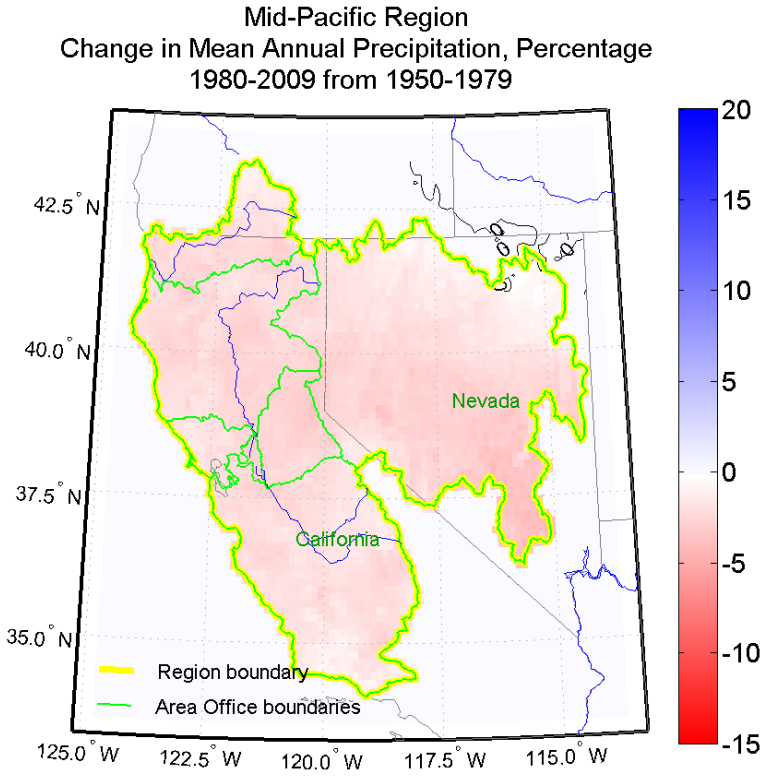
Mid-Pacific Region
Change in Mean Annual Precipitation, Percentage
1980-2009 from 1950-1979
42.5° N
40.0° N
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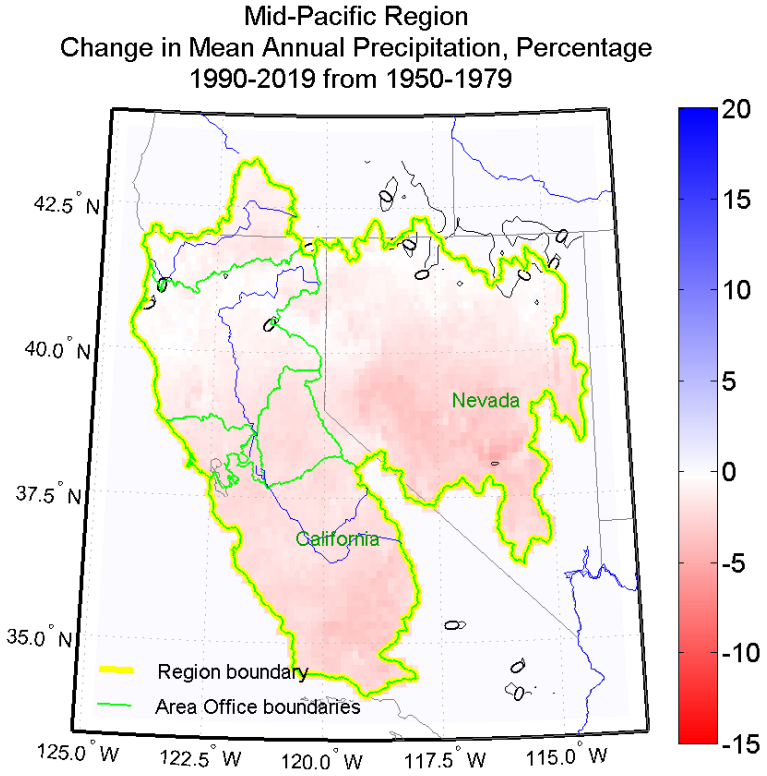
Mid-Pacific Region
Change in Mean Annual Precipitation, Percentage
1990-2019 from 1950-1979
42.5° N
40.0° N
37.5° N
35.0° N
125.0° W
122.5° W
120.0° W
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Nevada
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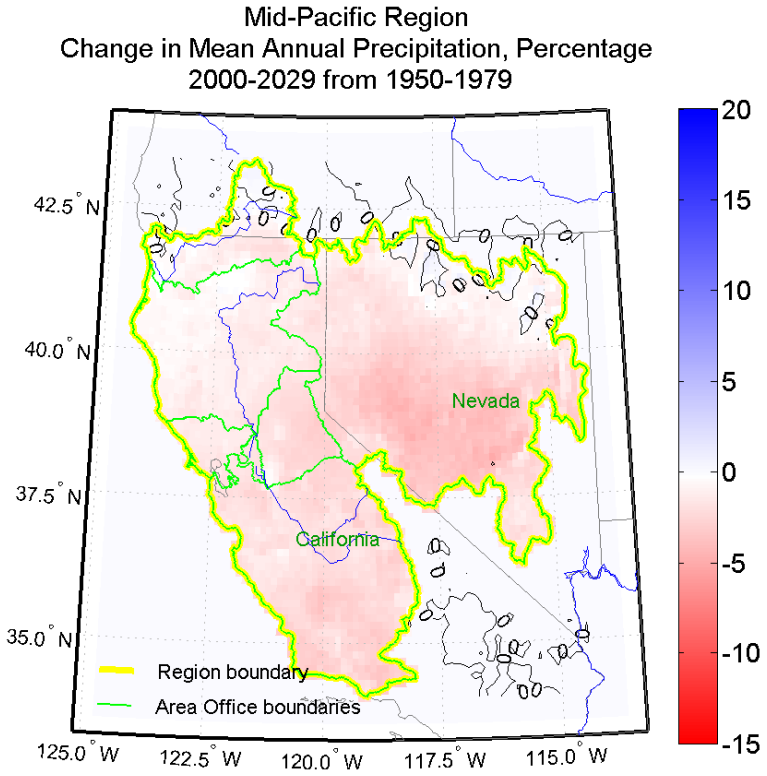
Mid-Pacific Region
Change in Mean Annual Precipitation, Percentage
2000-2029 from 1950-1979
42.5° N
40.0° N
37.5° N
35.0° N
125.0° W
122.5° W
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117.5° W
115.0° W
Nevada
California
Region boundary
Area Office boundaries
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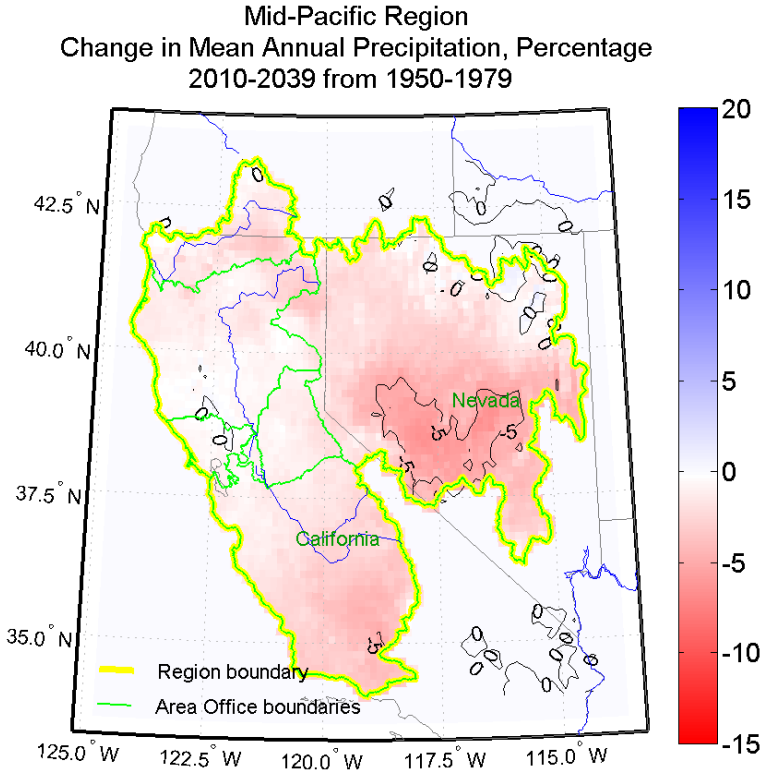
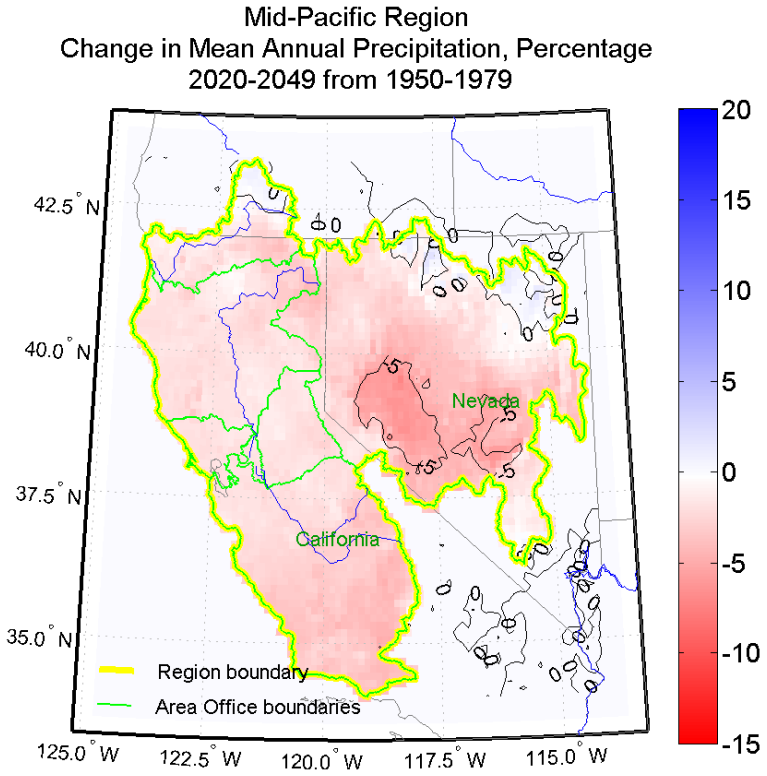

Mid-Pacific Region
Change in Mean Annual Precipitation, Percentage
2010-2039 from 1950-1979
42.5° N
40.0° N
37.5° N
35.0° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
Nevada
California
Region boundary
Area Office boundaries
20
15
10
5
0
-5
-10
-15


Mid-Pacific Region
Change in Mean Annual Precipitation, Percentage
2020-2049 from 1950-1979
42.5° N
40.0° N
37.5° N
35.0° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
Nevada
California
Region boundary
Area Office boundaries
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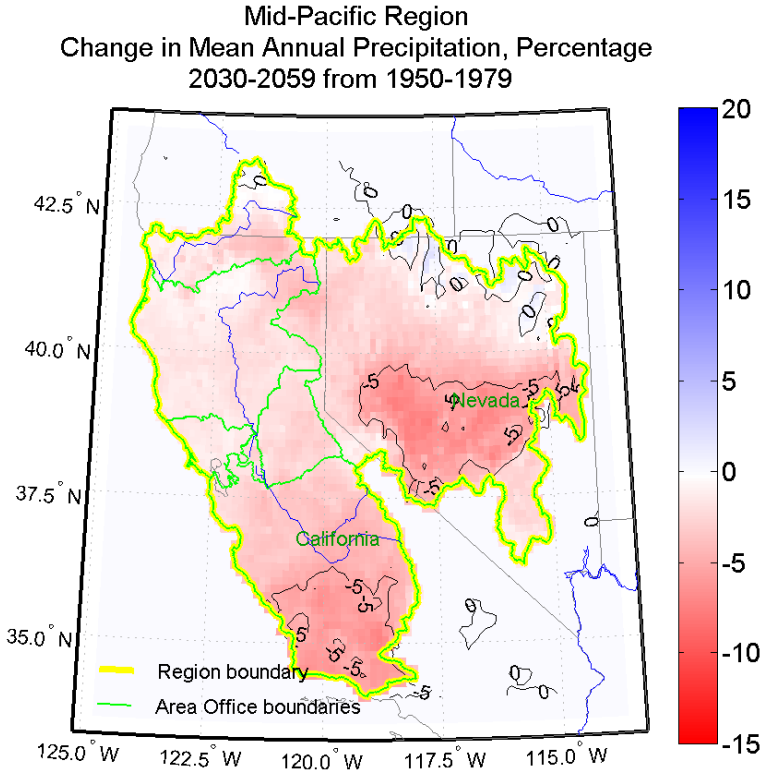
0
-5
-10
-15


Mid-Pacific Region
Change in Mean Annual Precipitation, Percentage
2030-2059 from 1950-1979
42.5° N
40.0° N
37.5° N
35.0° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
Nevada
California
Region boundary
Area Office boundaries
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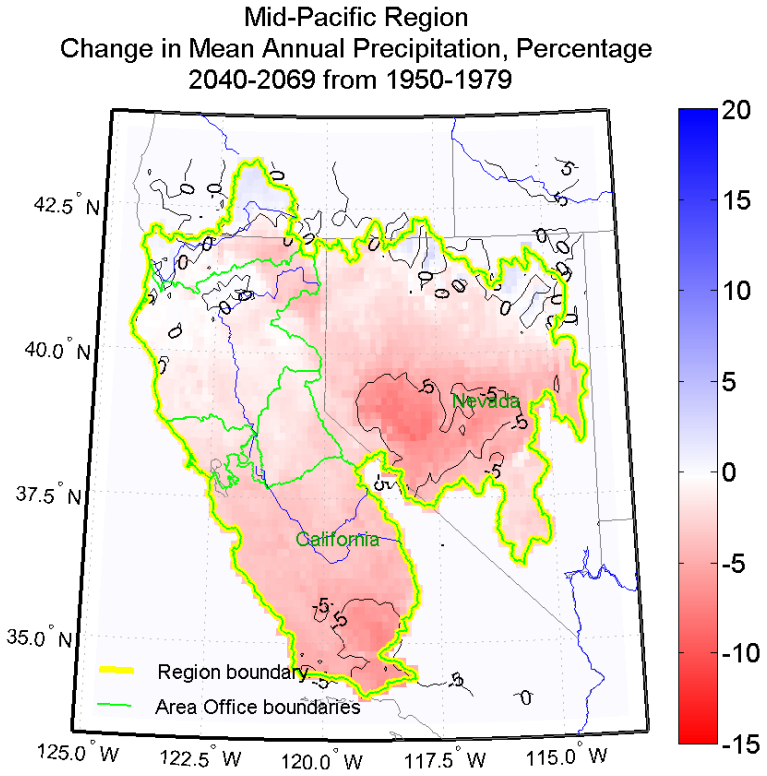
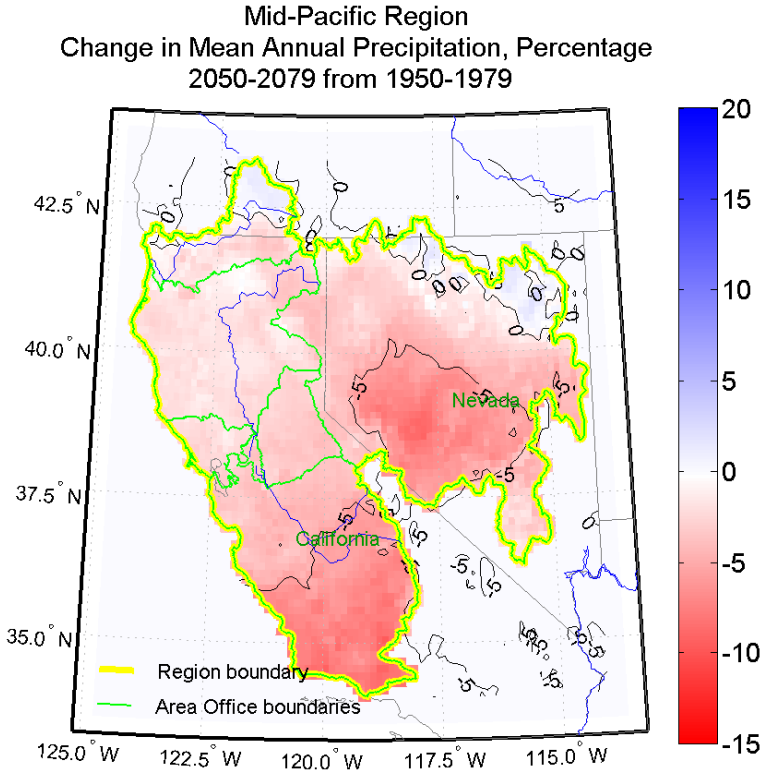
-5
-10
-15


Mid-Pacific Region
Change in Mean Annual Precipitation, Percentage
2040-2069 from 1950-1979
42.5° N
40.0° N
37.5° N
35.0° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
Nevada
California
Region boundary
Area Office boundaries
20
15
10
5
0
-5
-10
-15


Mid-Pacific Region
Change in Mean Annual Precipitation, Percentage
2050-2079 from 1950-1979
42.5° N
40.0° N
37.5° N
35.0° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
Nevada
California
Region boundary
Area Office boundaries
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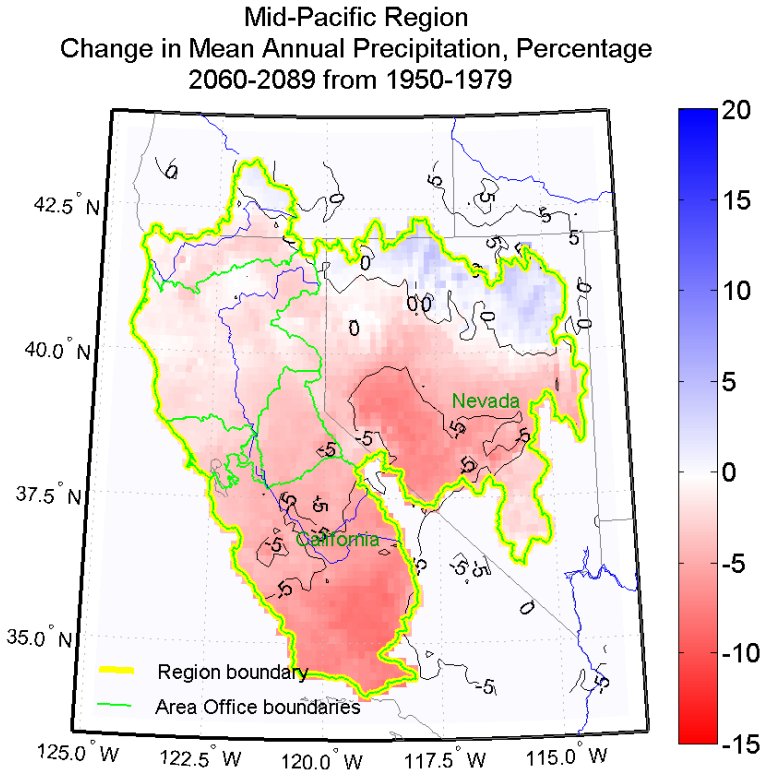
5
0
-5
-10
-15


Mid-Pacific Region
Change in Mean Annual Precipitation, Percentage
2060-2089 from 1950-1979
42.5° N
40.0° N
37.5° N
35.0° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
Nevada
California
Region boundary
Area Office boundaries
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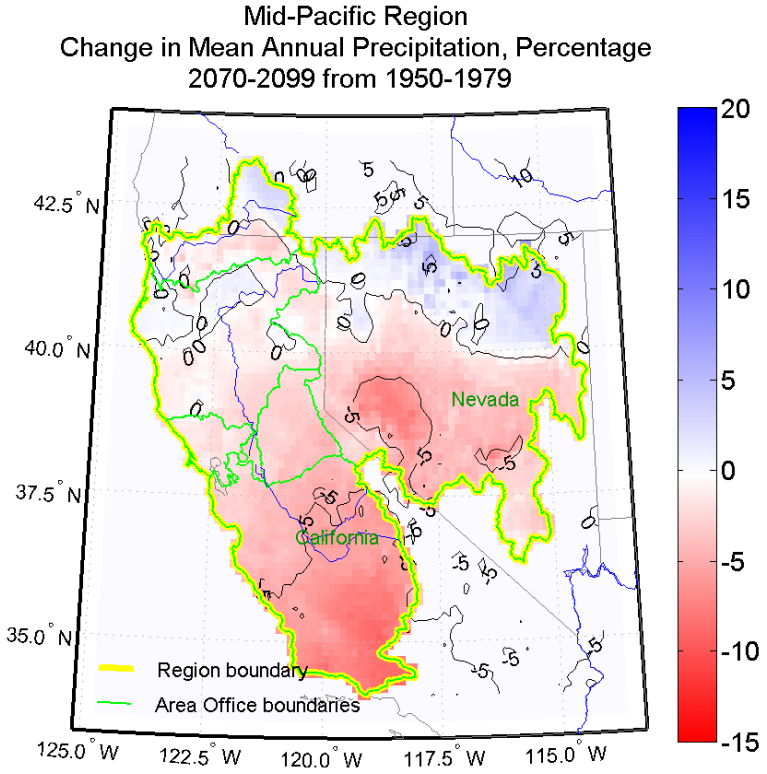
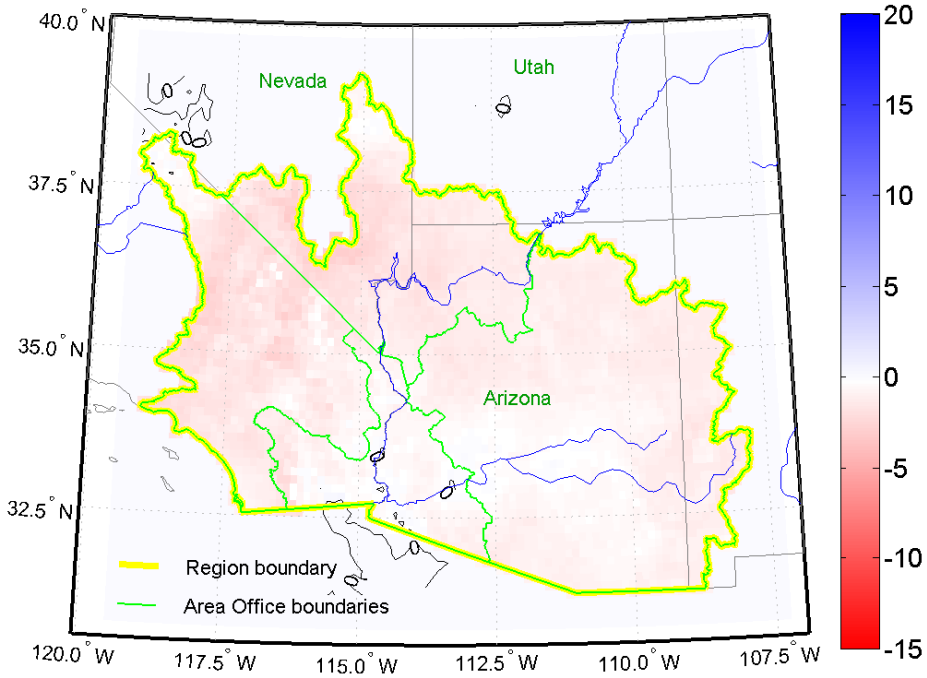
0
-5
-10
-15

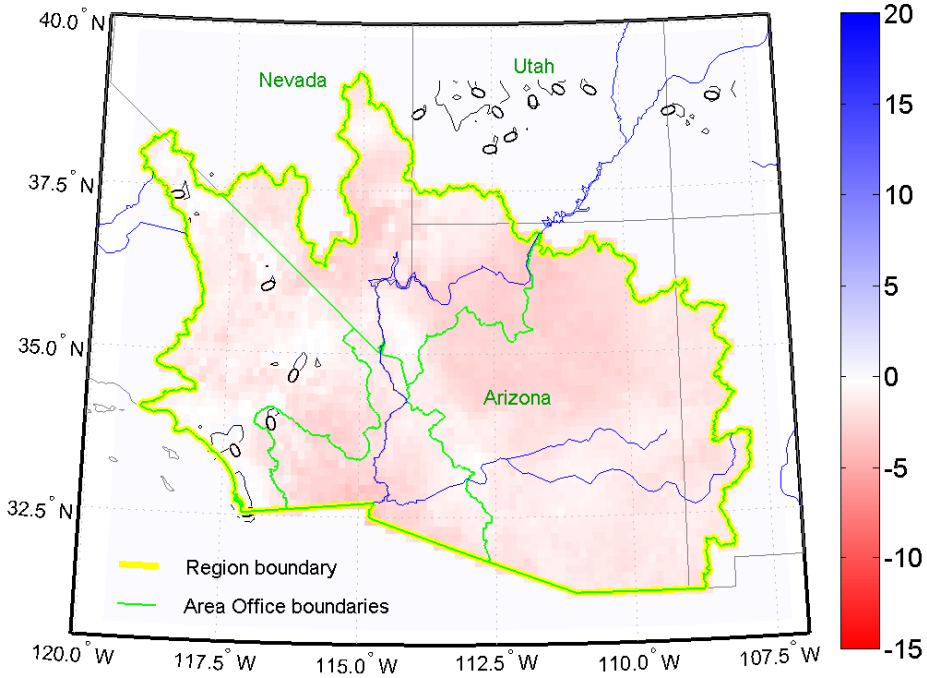

Mid-Pacific Region
Change in Mean Annual Precipitation, Percentage
2070-2099 from 1950-1979
42.5° N
40.0° N
37.5° N
35.0° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
Nevada
California
Region boundary
Area Office boundaries
20
15
10
5
0
-5
-10
-15

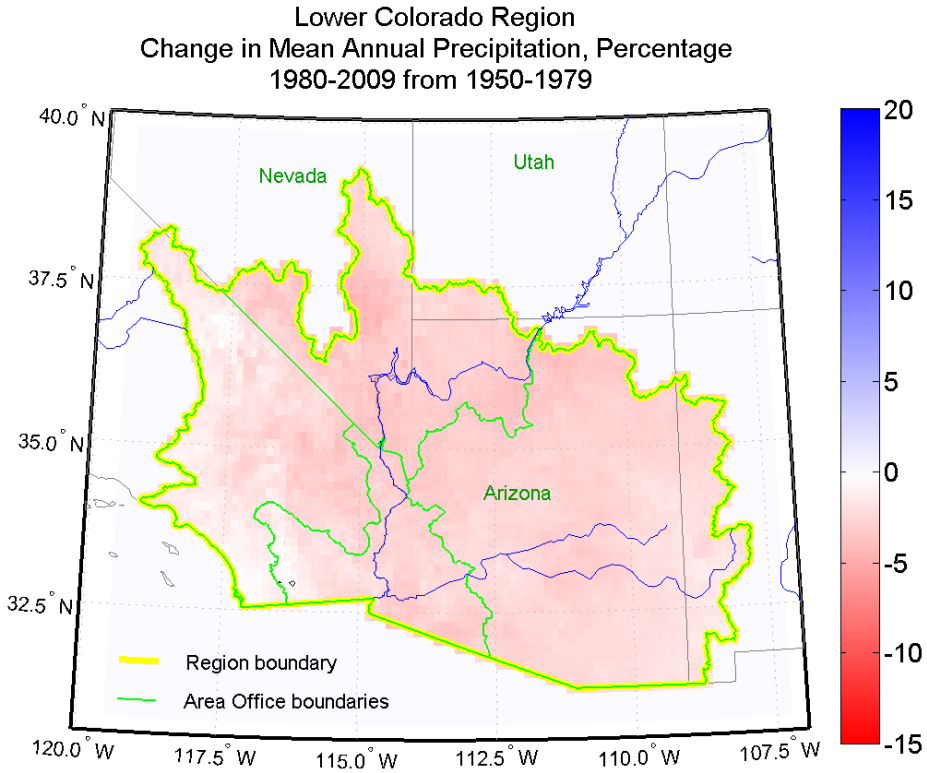
Lower Colorado Region – Precipitation Change

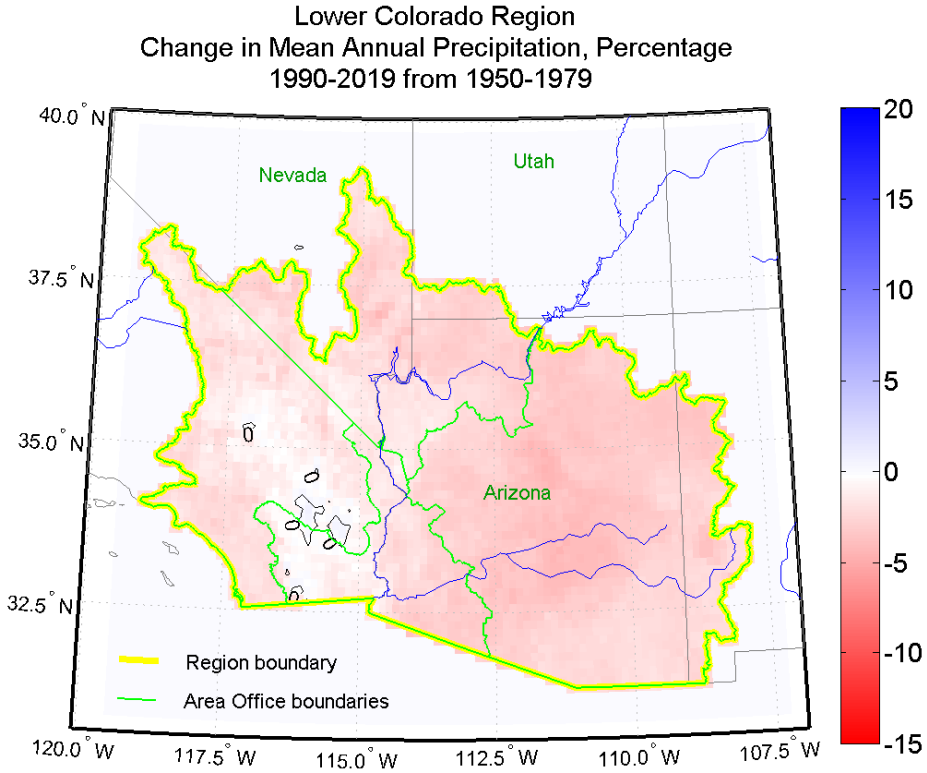
Lower Colorado Region
Change in Mean Annual Precipitation, Percentage
1960-1989 from 1950-1979



Lower Colorado Region
Change in Mean Annual Precipitation, Percentage
1970-1999 from 1950-1979




Lower Colorado Region
Change in Mean Annual Precipitation, Percentage
1980-2009 from 1950-1979
40.0° N
37.5° N
35.0° N
32.5° N
120.0° W
117.5° W
115.0° W
112.5° W
110.0° W
107.5° W
Nevada
Utah
Arizona
Region boundary
Area Office boundaries
20
15
10
5
0
-5
-10
-15


Lower Colorado Region
Change in Mean Annual Precipitation, Percentage
1990-2019 from 1950-1979
40.0° N
37.5° N
35.0° N
32.5° N
120.0° W
117.5° W
115.0° W
112.5° W
110.0° W
107.5° W
Nevada
Utah
Arizona
Region boundary
Area Office boundaries
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15
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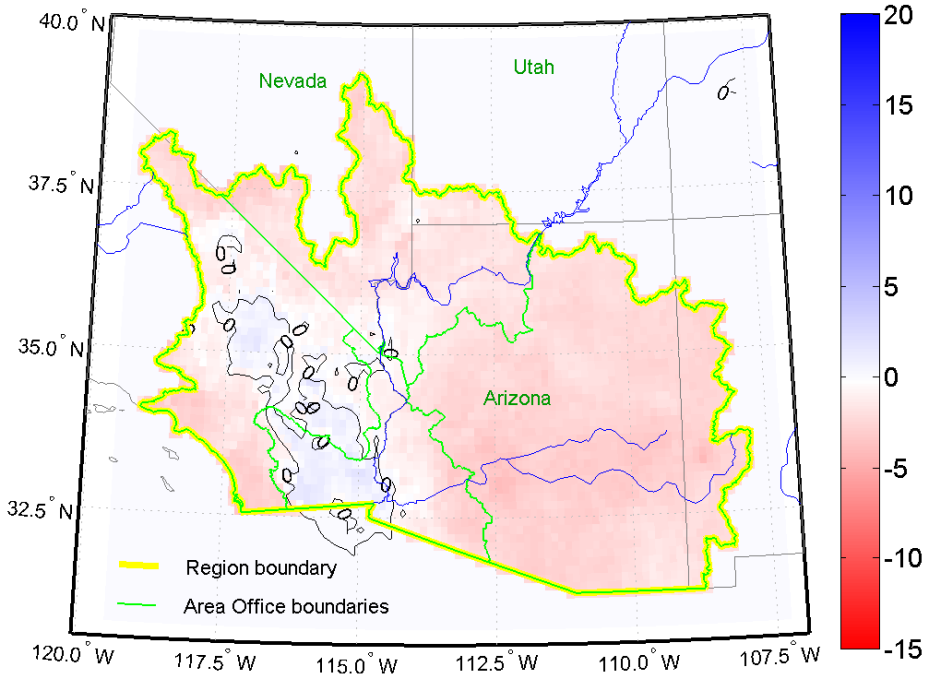
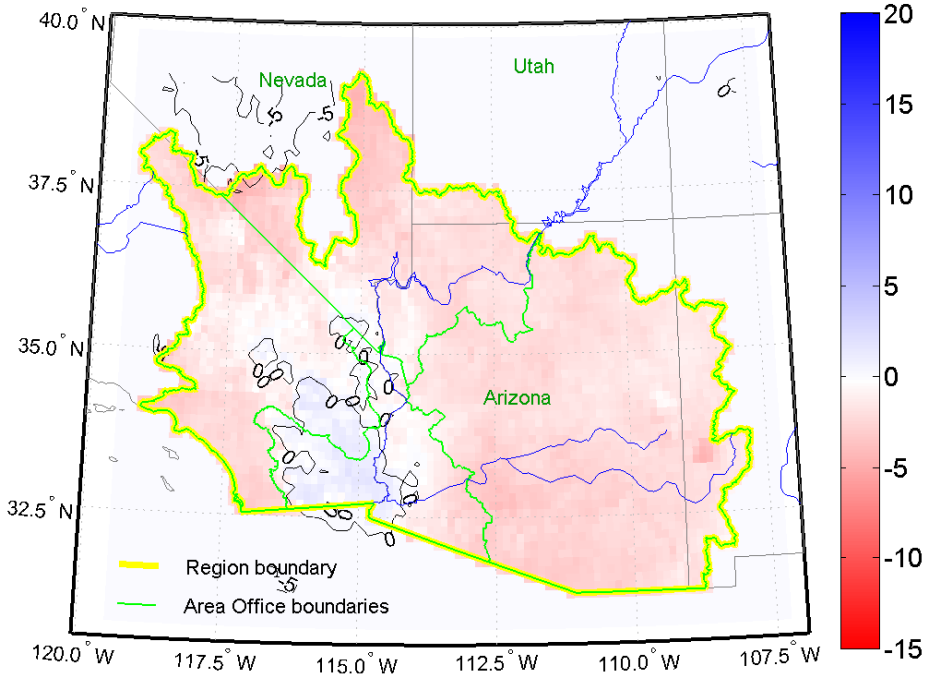
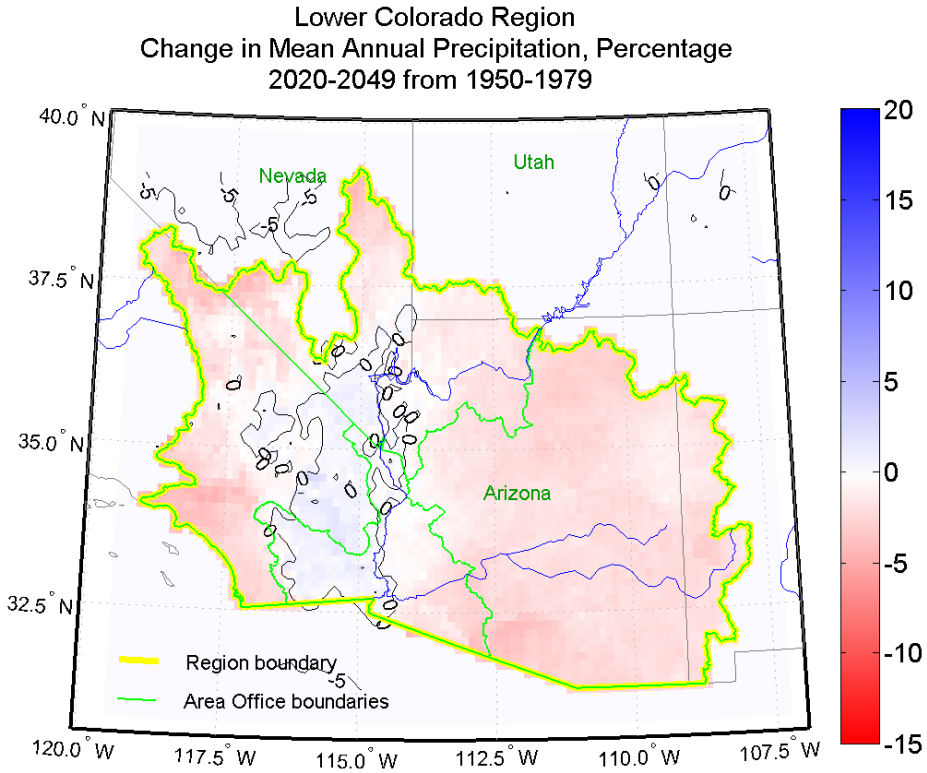
0
-5
-10
-15

Lower Colorado Region
Change in Mean Annual Precipitation, Percentage
2000-2029 from 1950-1979



Lower Colorado Region
Change in Mean Annual Precipitation, Percentage
2010-2039 from 1950-1979




Lower Colorado Region
Change in Mean Annual Precipitation, Percentage
2020-2049 from 1950-1979
Nevada
Utah
Arizona
Region boundary
Area Office boundaries
40.0° N
37.5° N
35.0° N
32.5° N
120.0° W
117.5° W
115.0° W
112.5° W
110.0° W
107.5° W
20
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-5
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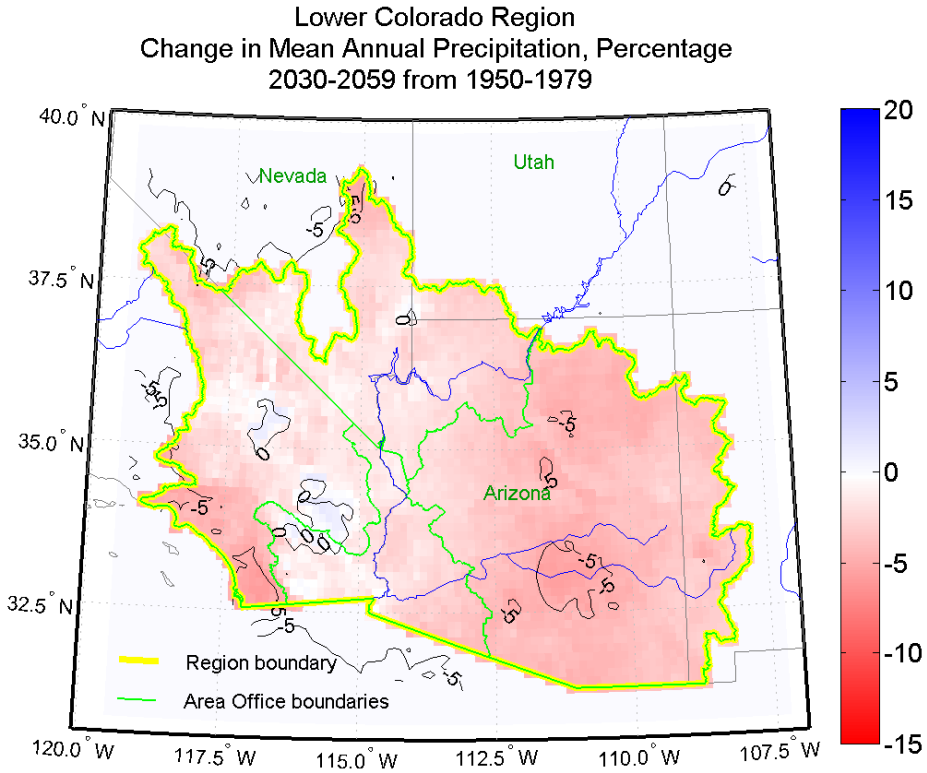
Lower Colorado Region
Change in Mean Annual Precipitation, Percentage
2030-2059 from 1950-1979
Nevada
Utah
Arizona
Region boundary
Area Office boundaries
40.0° N
37.5° N
35.0° N
32.5° N
120.0° W
117.5° W
115.0° W
112.5° W
110.0° W
107.5° W
20
15
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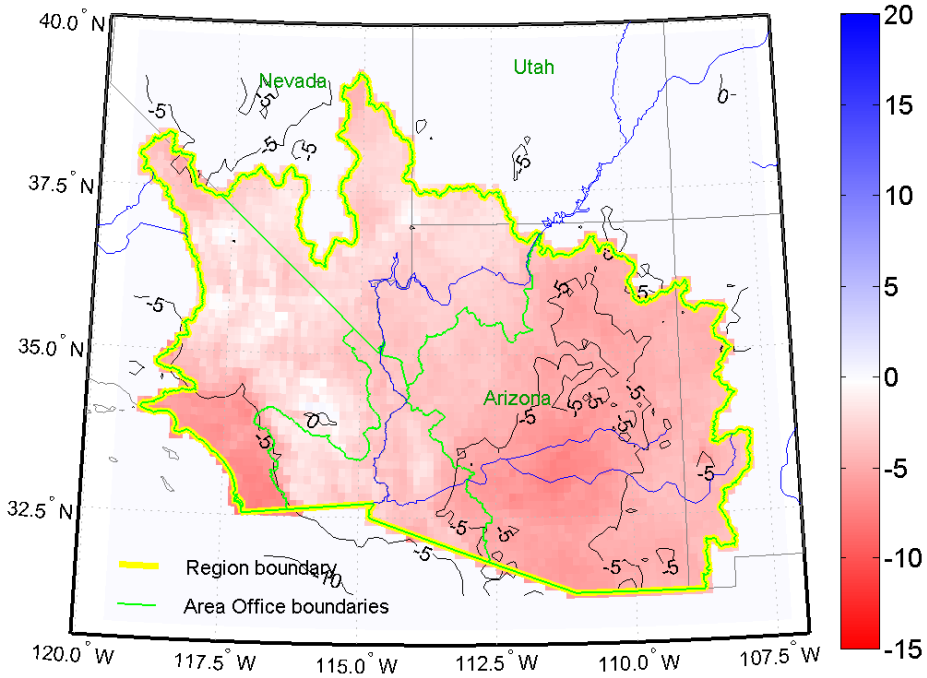
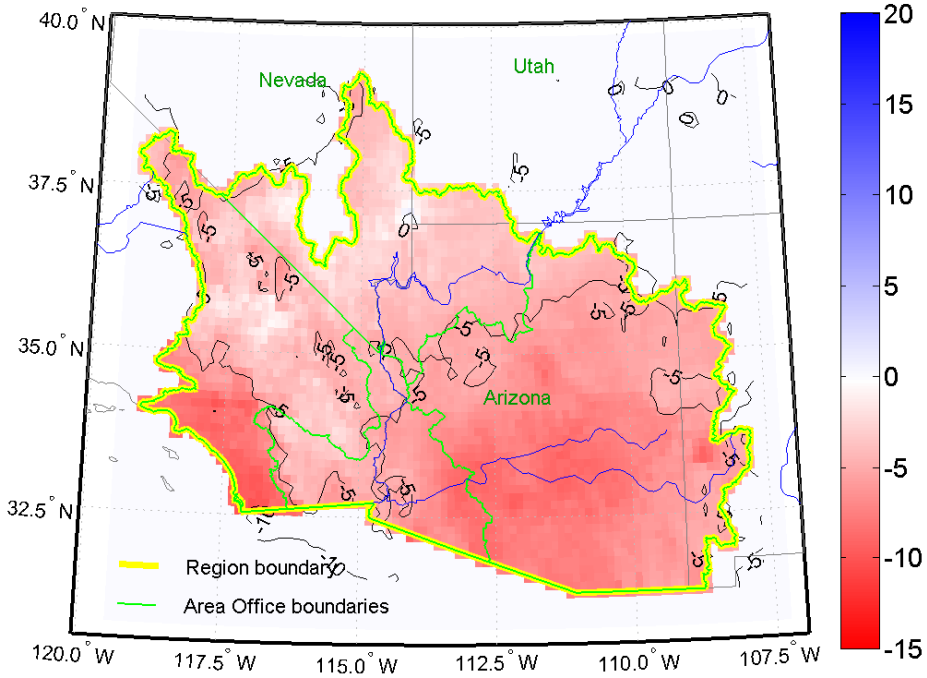
0
-5
-10
-15

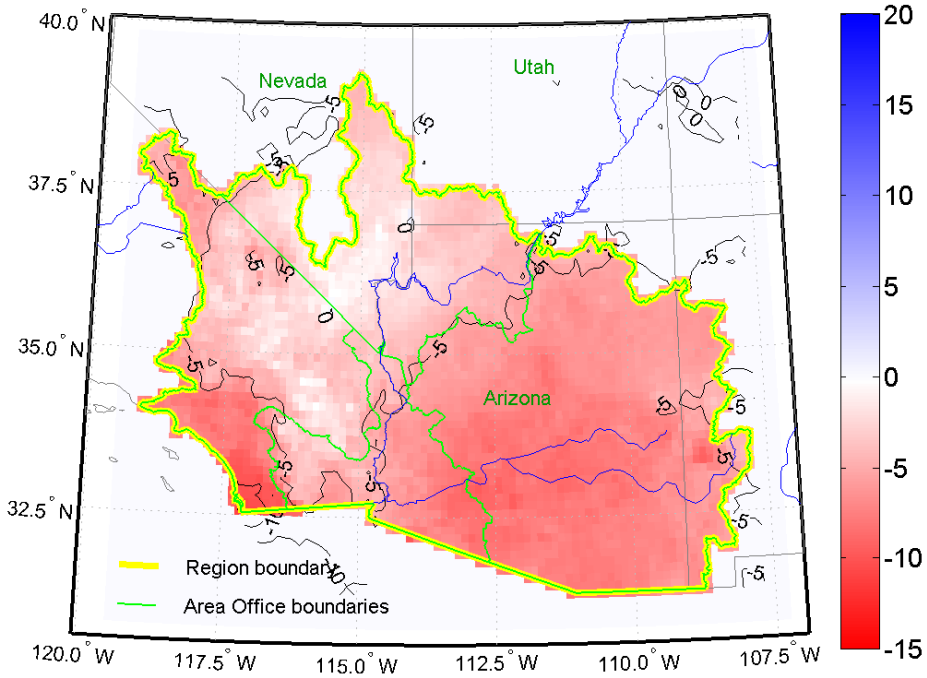
Lower Colorado Region
Change in Mean Annual Precipitation, Percentage
2040-2069 from 1950-1979



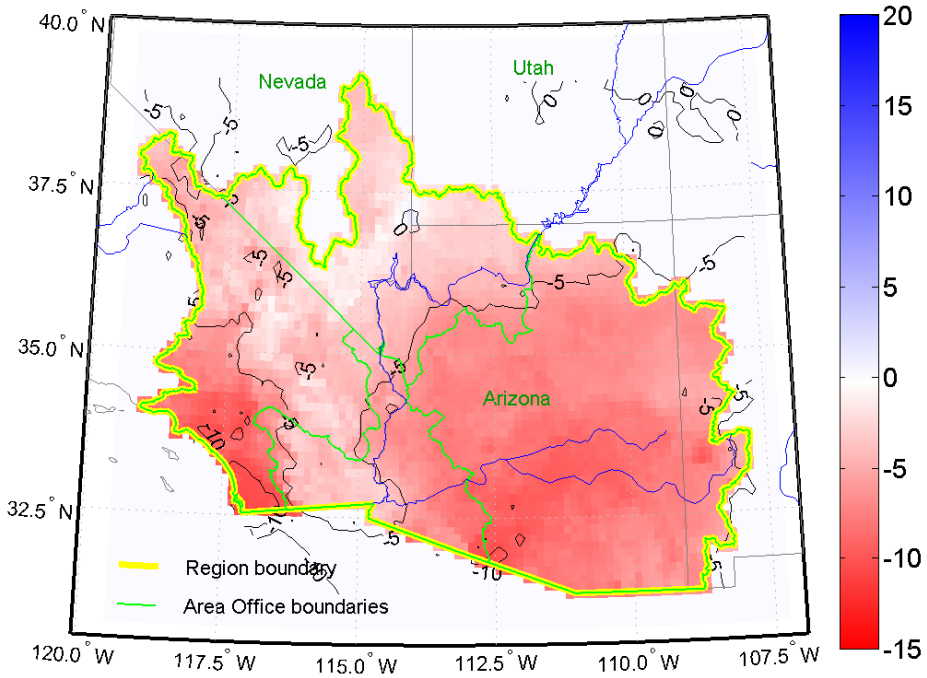
Lower Colorado Region
Change in Mean Annual Precipitation, Percentage
2050-2079 from 1950-1979



Lower Colorado Region
Change in Mean Annual Precipitation, Percentage
2060-2089 from 1950-1979

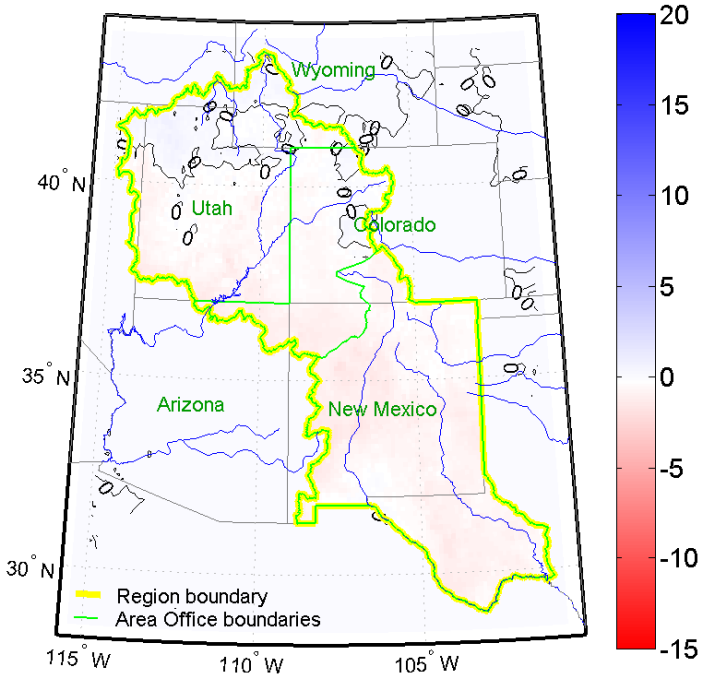


Lower Colorado Region
Change in Mean Annual Precipitation, Percentage
2070-2099 from 1950-1979

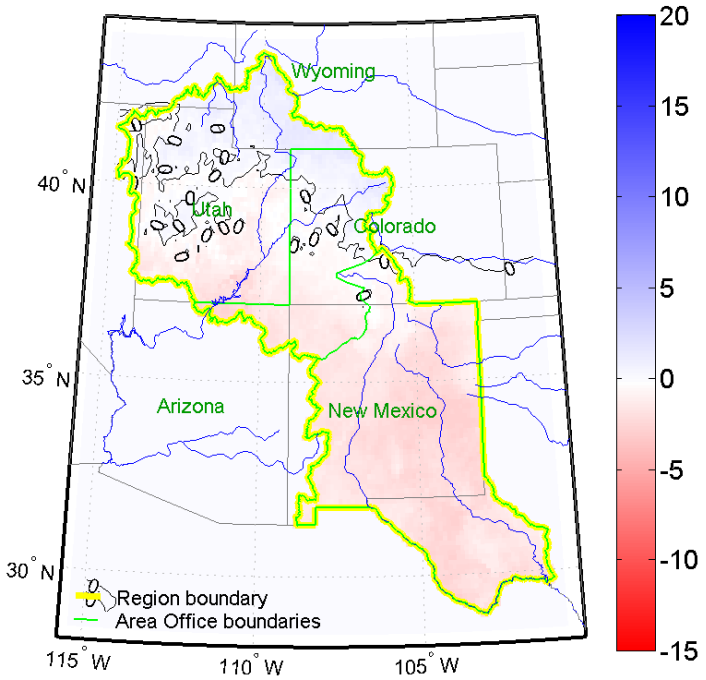


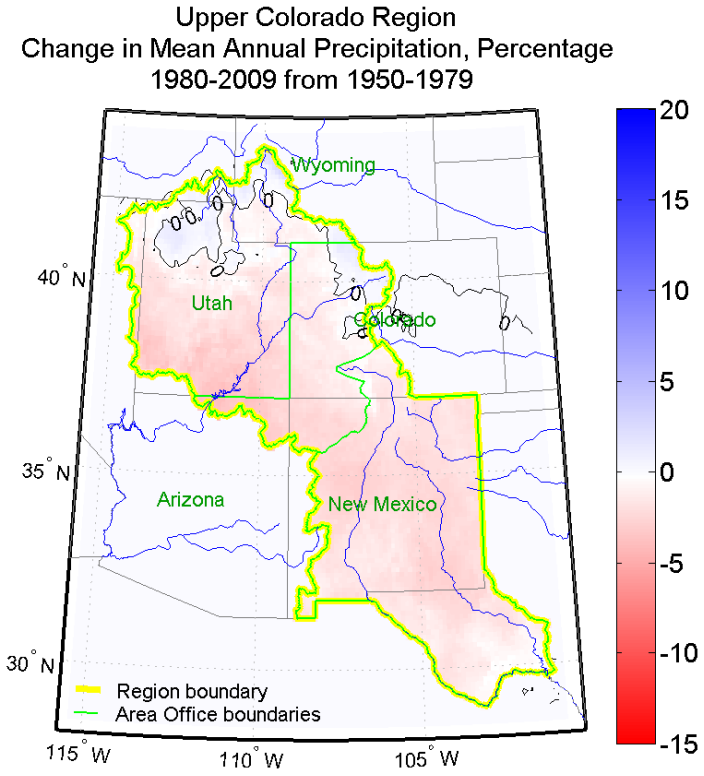
Upper Colorado Region – Precipitation Change

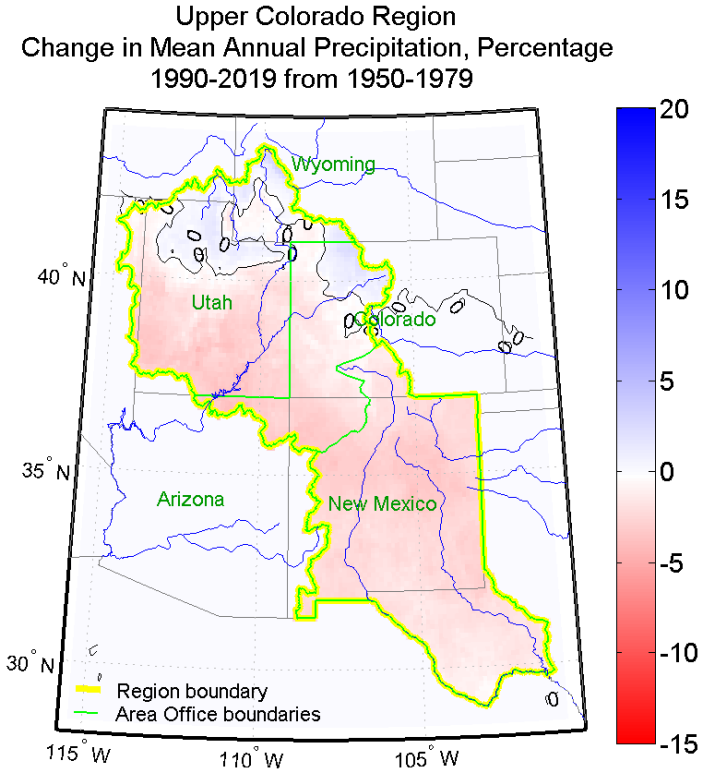
Upper Colorado Region
Change in Mean Annual Precipitation, Percentage
1960-1989 from 1950-1979



Upper Colorado Region
Change in Mean Annual Precipitation, Percentage
1970-1999 from 1950-1979




Upper Colorado Region
Change in Mean Annual Precipitation, Percentage
1980-2009 from 1950-1979
Wyoming
Utah
Colorado
Arizona
New Mexico
40° N
35° N
30° N
115° W
110° W
105° W
Region boundary
Area Office boundaries
20
15
10
5
0
-5
-10
-15


Upper Colorado Region
Change in Mean Annual Precipitation, Percentage
1990-2019 from 1950-1979
Wyoming
Utah
Colorado
Arizona
New Mexico
40° N
35° N
30° N
115° W
110° W
105° W
Region boundary
Area Office boundaries
20
15
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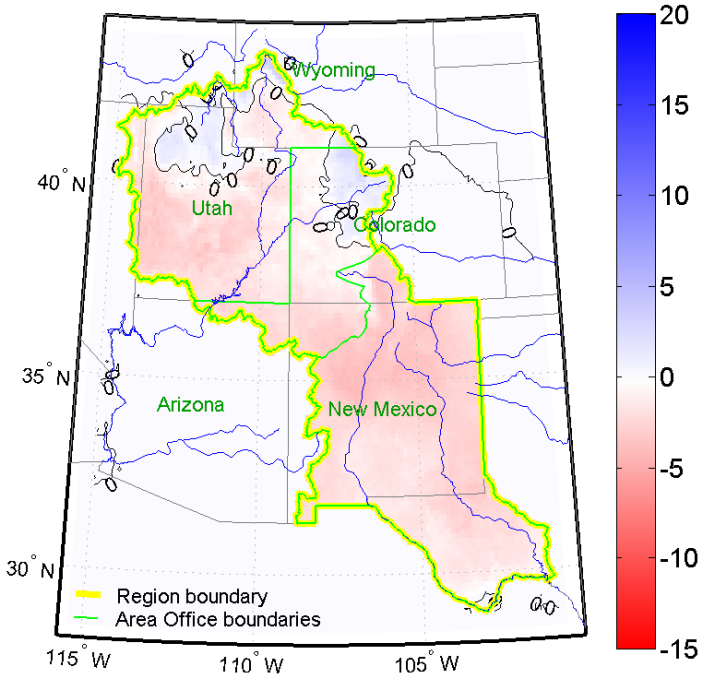
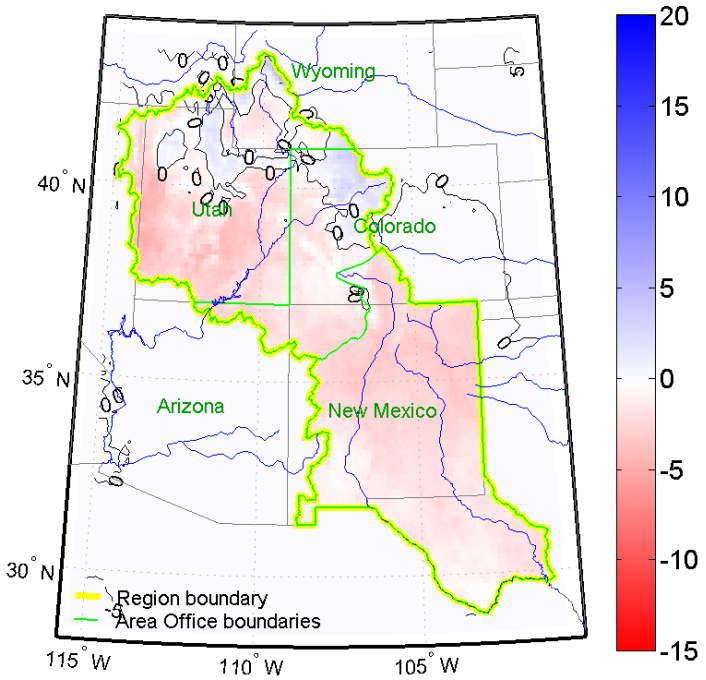
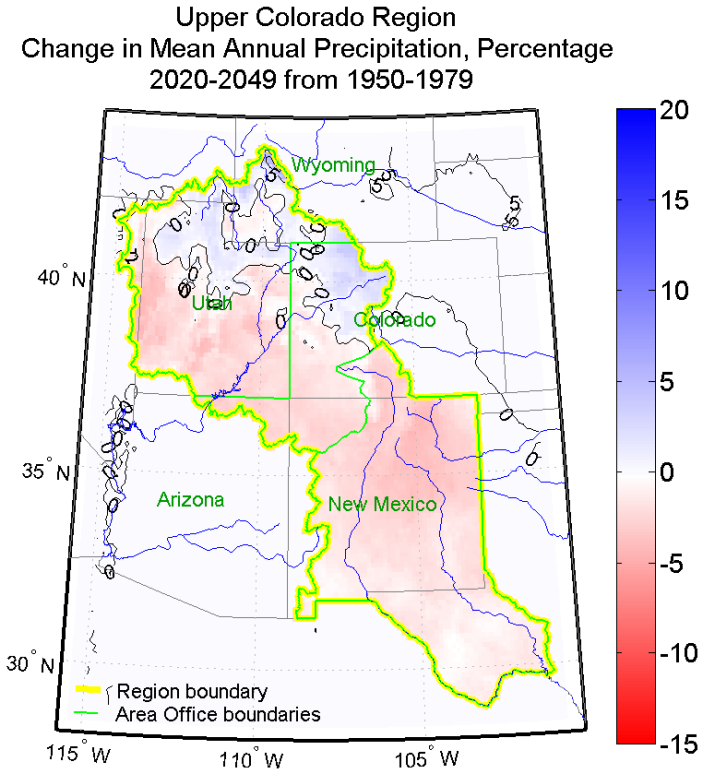
5
0
-5
-10
-15

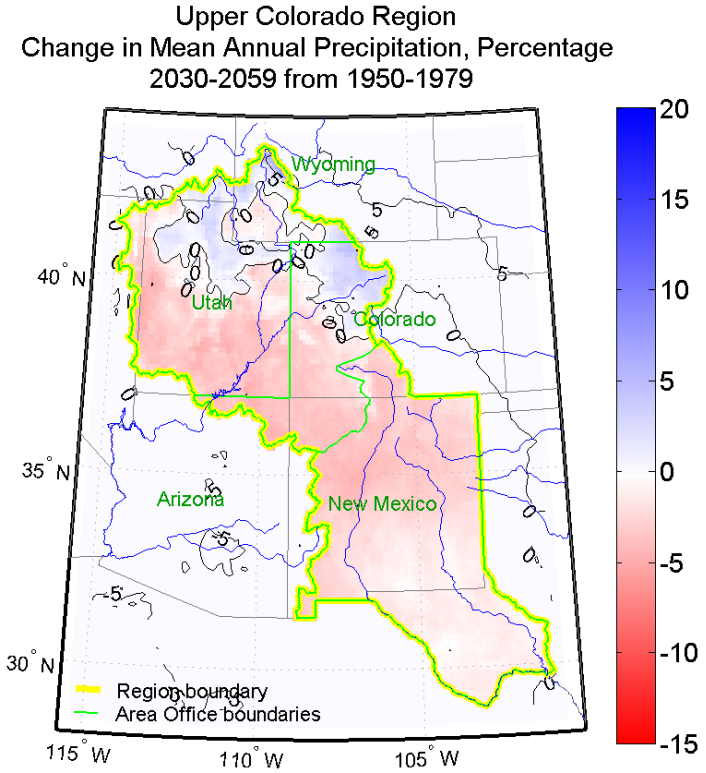
Upper Colorado Region
Change in Mean Annual Precipitation, Percentage
2000-2029 from 1950-1979



Upper Colorado Region
Change in Mean Annual Precipitation, Percentage
2010-2039 from 1950-1979




Upper Colorado Region
Change in Mean Annual Precipitation, Percentage
2020-2049 from 1950-1979
Wyoming
Utah
Colorado
Arizona
New Mexico
40° N
35° N
30° N
115° W
110° W
105° W
Region boundary
Area Office boundaries
20
15
10
5
0
-5
-10
-15


Upper Colorado Region
Change in Mean Annual Precipitation, Percentage
2030-2059 from 1950-1979
Wyoming
Utah
Colorado
Arizona
New Mexico
40° N
35° N
30° N
115° W
110° W
105° W
Region boundary
Area Office boundaries
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15
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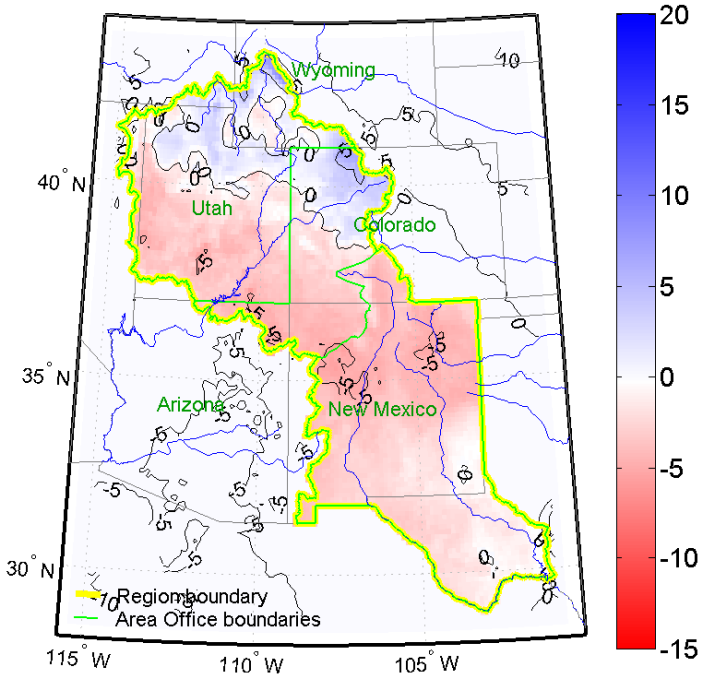
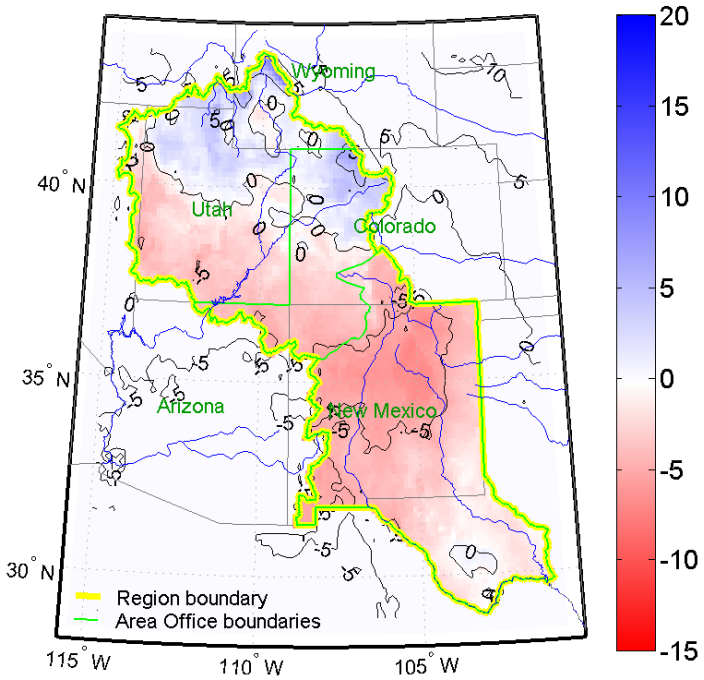
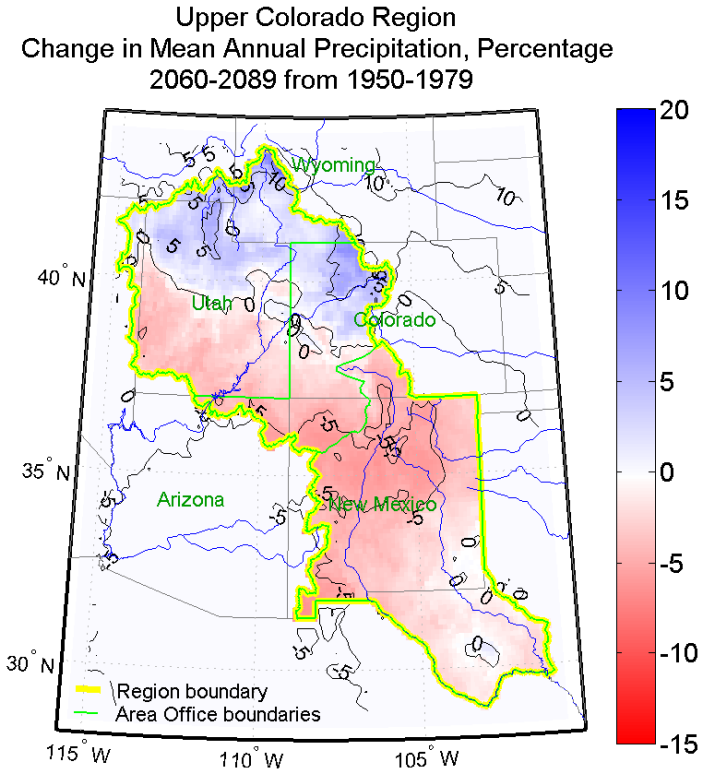
5
0
-5
-10
-15

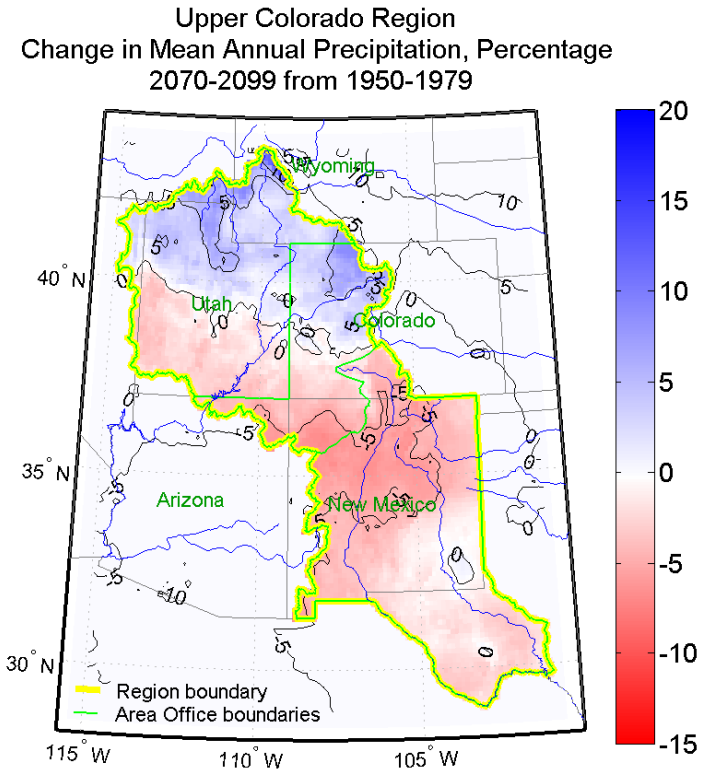
Upper Colorado Region
Change in Mean Annual Precipitation, Percentage
2040-2069 from 1950-1979



Upper Colorado Region
Change in Mean Annual Precipitation, Percentage
2050-2079 from 1950-1979

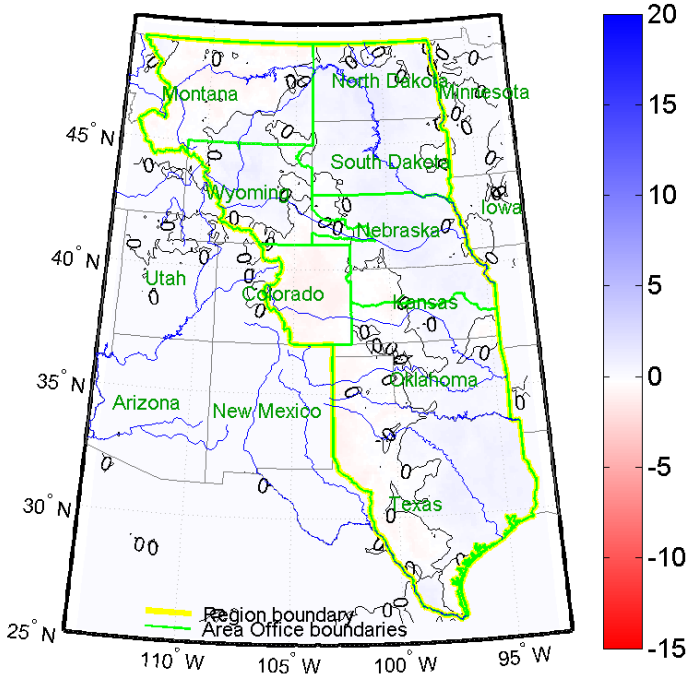



Upper Colorado Region
Change in Mean Annual Precipitation, Percentage
2060-2089 from 1950-1979
Wyoming
Utah
Colorado
Arizona
New Mexico
Region boundary
Area Office boundaries
40° N
35° N
30° N
115° W
110° W
105° W
20
15
10
5
0
-5
-10
-15

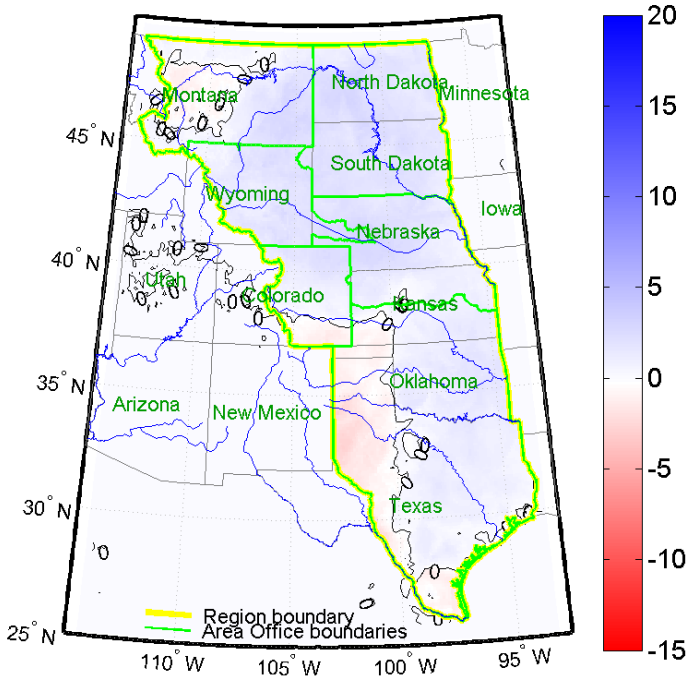

Upper Colorado Region
Change in Mean Annual Precipitation, Percentage
2070-2099 from 1950-1979
Wyoming
Utah
Colorado
Arizona
New Mexico
Region boundary
Area Office boundaries
40° N
35° N
30° N
115° W
110° W
105° W
20
15
10
5
0
-5
-10
-15

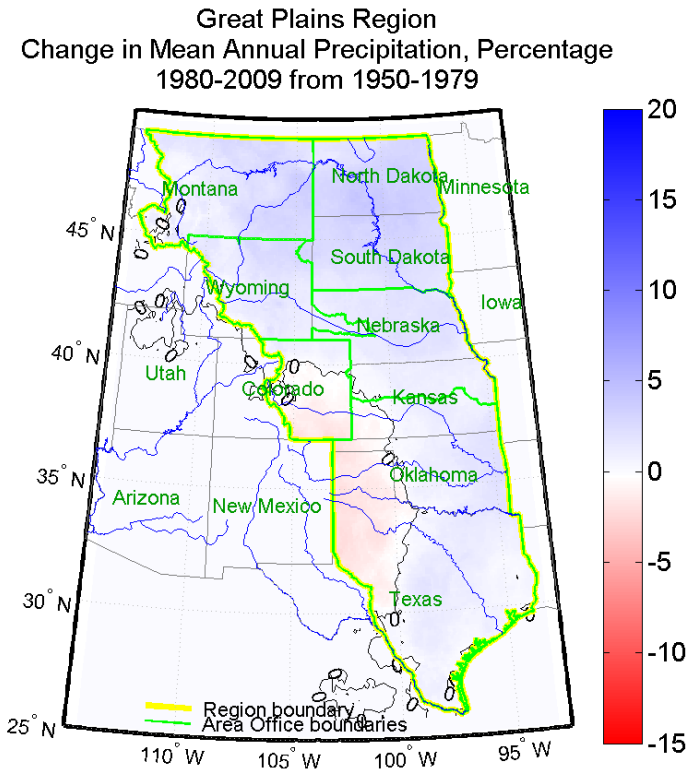
Great Plains Region – Precipitation Change

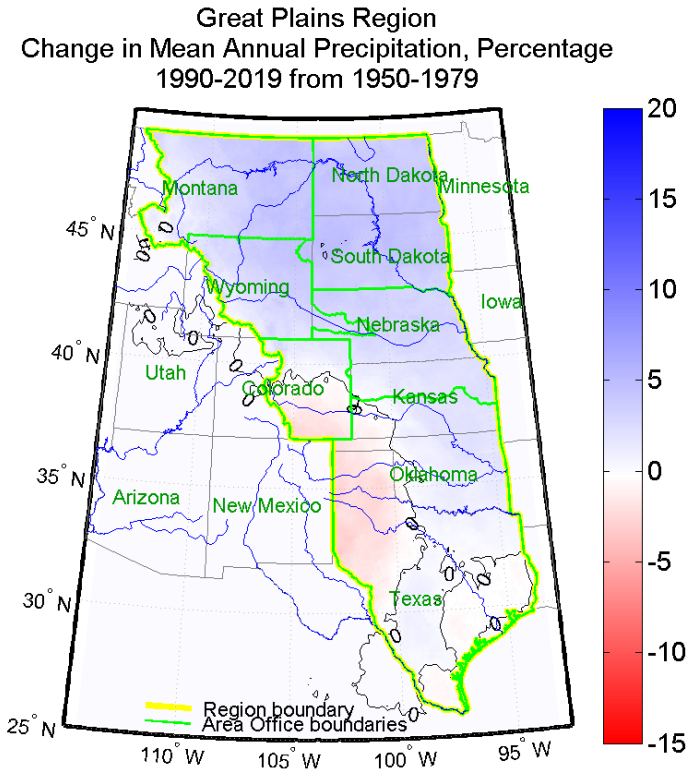
Great Plains Region
Change in Mean Annual Precipitation, Percentage
1960-1989 from 1950-1979



Great Plains Region
Change in Mean Annual Precipitation, Percentage
1970-1999 from 1950-1979




Great Plains Region
Change in Mean Annual Precipitation, Percentage
1980-2009 from 1950-1979
Montana
North Dakota
Minnesota
South Dakota
Wyoming
Iowa
Nebraska
Utah
Colorado
Kansas
Oklahoma
Arizona
New Mexico
Texas
Region boundary
Area Office boundaries
45° N
40° N
35° N
30° N
25° N
110° W
105° W
100° W
95° W
20
15
10
5
0
-5
-10
-15


Great Plains Region
Change in Mean Annual Precipitation, Percentage
1990-2019 from 1950-1979
Montana
North Dakota
Minnesota
South Dakota
Wyoming
Iowa
Nebraska
Utah
Colorado
Kansas
Oklahoma
Arizona
New Mexico
Texas
Region boundary
Area Office boundaries
45° N
40° N
35° N
30° N
25° N
110° W
105° W
100° W
95° W
20
15
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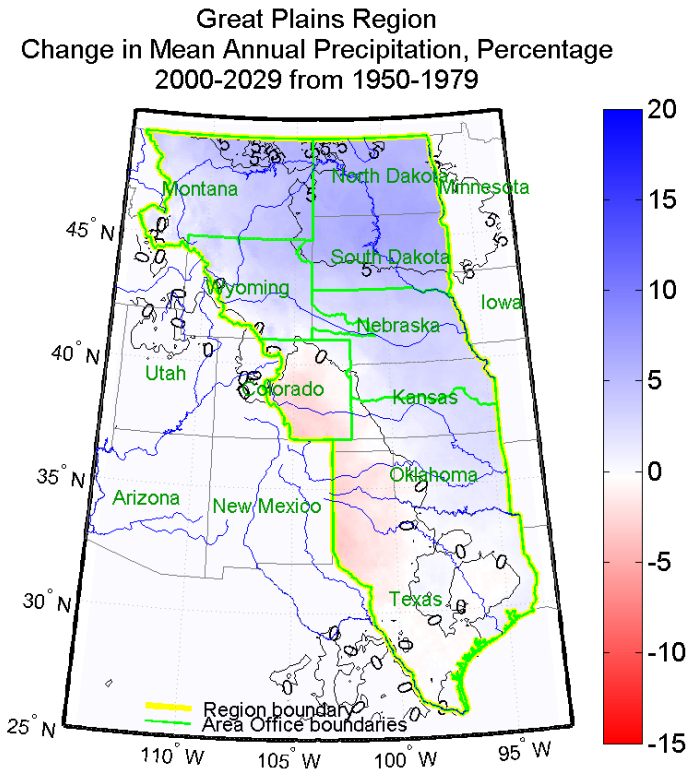
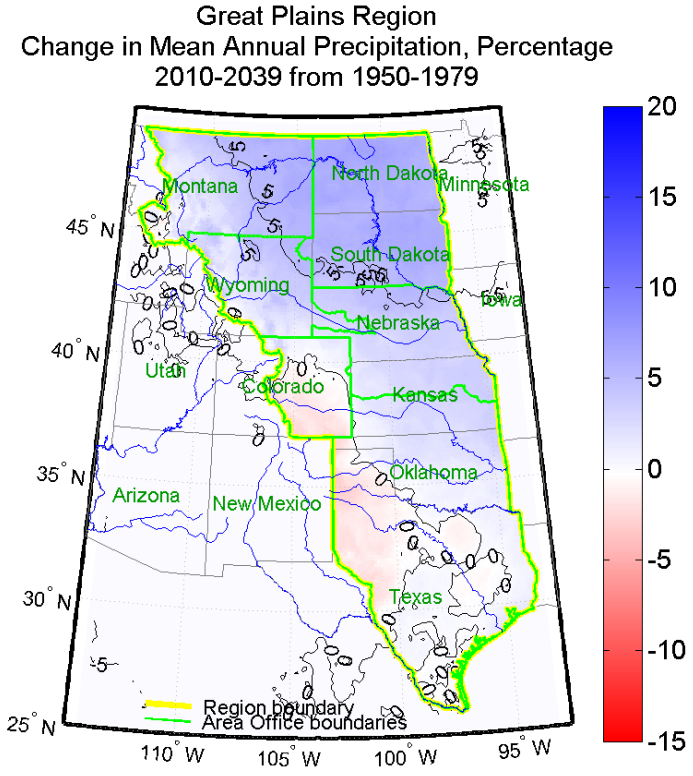
5
0
-5
-10
-15


Great Plains Region
Change in Mean Annual Precipitation, Percentage
2000-2029 from 1950-1979
Montana
North Dakota
Minnesota
South Dakota
Wyoming
Iowa
Nebraska
Utah
Colorado
Kansas
Oklahoma
Arizona
New Mexico
Texas
Region boundary
Area Office boundaries
45° N
40° N
35° N
30° N
25° N
110° W
105° W
100° W
95° W
20
15
10
5
0
-5
-10
-15


Great Plains Region
Change in Mean Annual Precipitation, Percentage
2010-2039 from 1950-1979
Montana
North Dakota
Minnesota
South Dakota
Wyoming
Iowa
Nebraska
Utah
Colorado
Kansas
Oklahoma
Arizona
New Mexico
Texas
Region boundary
Area Office boundaries
45° N
40° N
35° N
30° N
25° N
110° W
105° W
100° W
95° W
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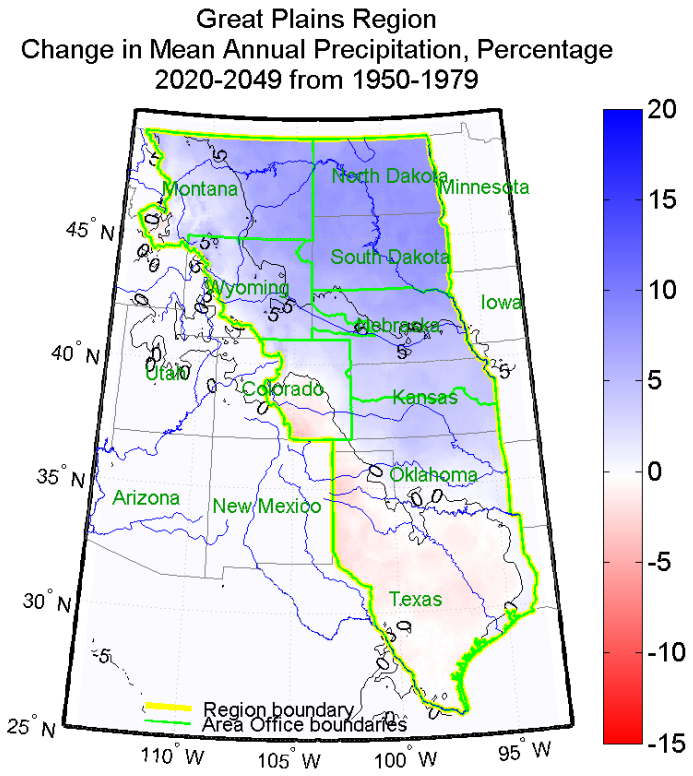
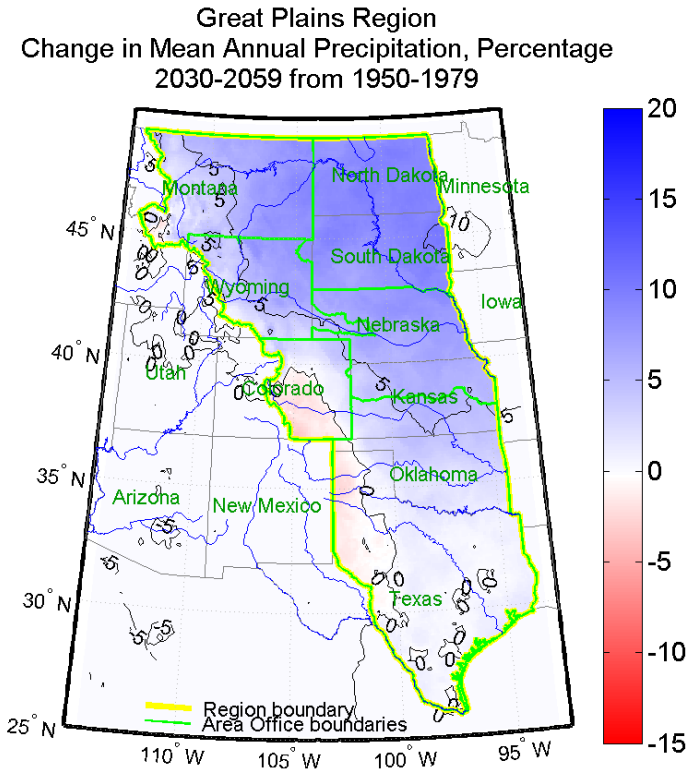
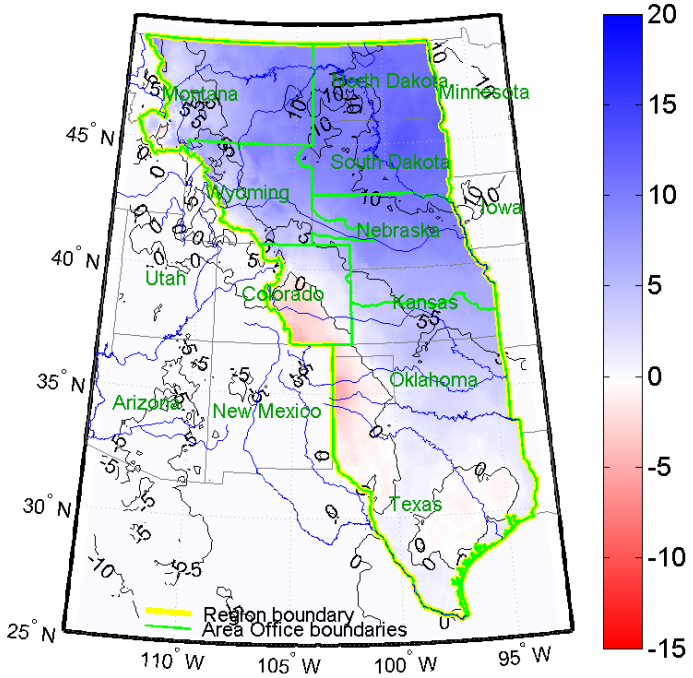
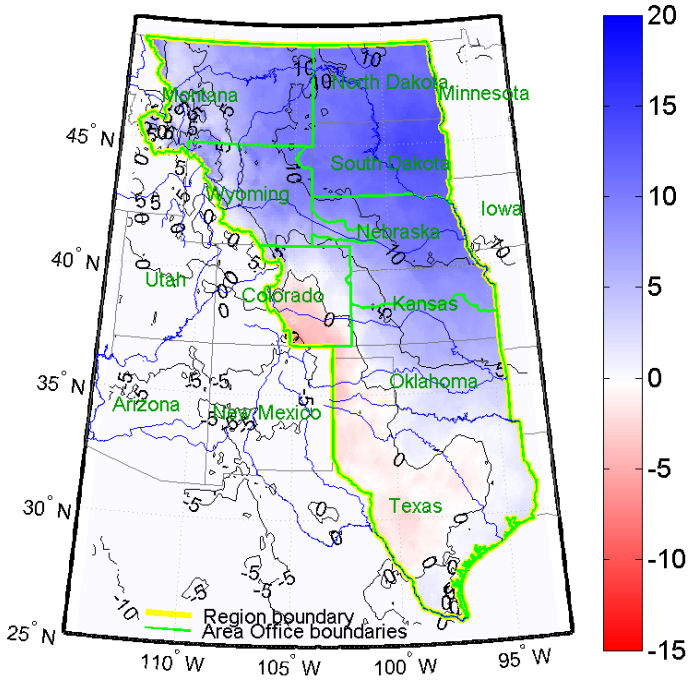

Great Plains Region
Change in Mean Annual Precipitation, Percentage
2020-2049 from 1950-1979
Montana
North Dakota
Minnesota
South Dakota
Wyoming
Iowa
Nebraska
Utah
Colorado
Kansas
Oklahoma
Arizona
New Mexico
Texas
Region boundary
Area Office boundaries
45° N
40° N
35° N
30° N
25° N
110° W
105° W
100° W
95° W
20
15
10
5
0
-5
-10
-15

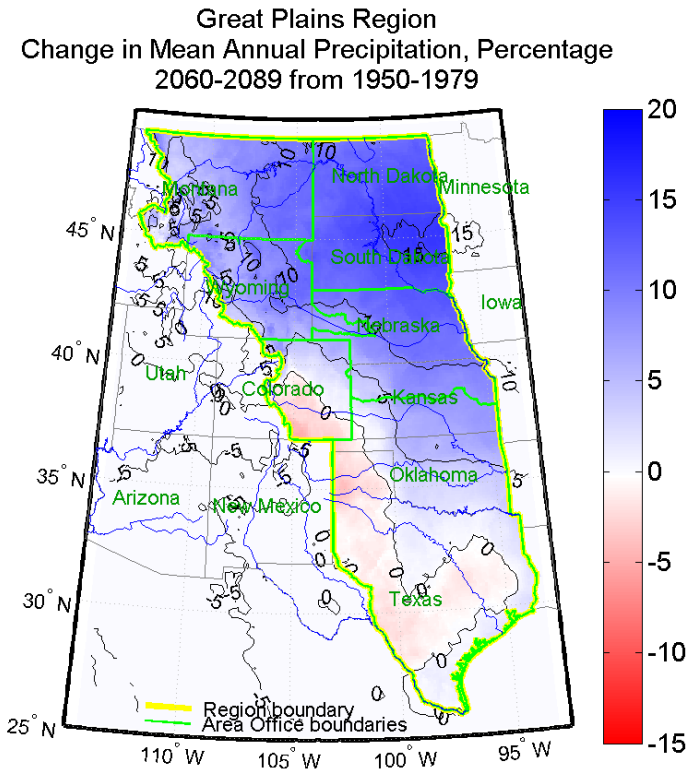

Great Plains Region
Change in Mean Annual Precipitation, Percentage
2030-2059 from 1950-1979
Montana
North Dakota
Minnesota
South Dakota
Wyoming
Iowa
Nebraska
Utah
Colorado
Kansas
Oklahoma
Arizona
New Mexico
Texas
Region boundary
Area Office boundaries
45° N
40° N
35° N
30° N
25° N
110° W
105° W
100° W
95° W
20
15
10
5
0
-5
-10
-15

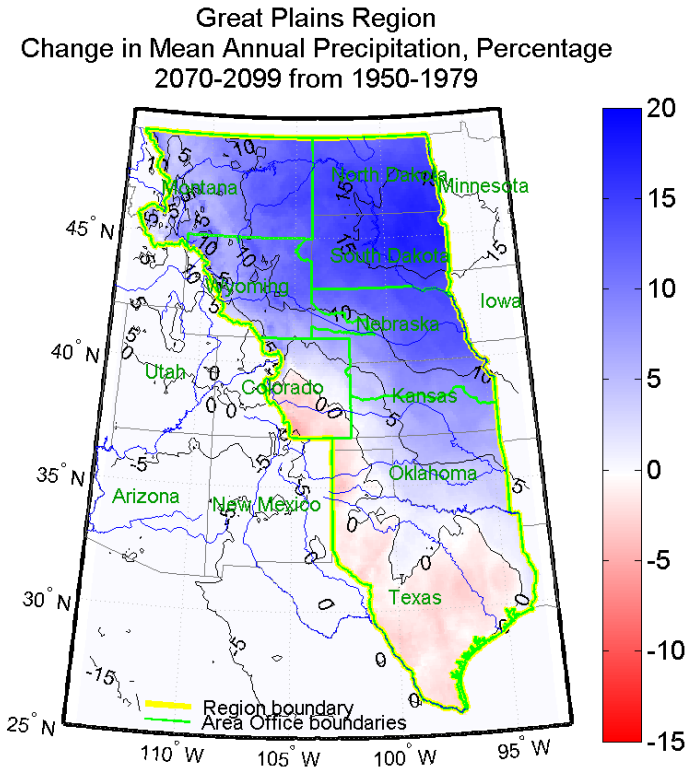
Great Plains Region
Change in Mean Annual Precipitation, Percentage
2040-2069 from 1950-1979



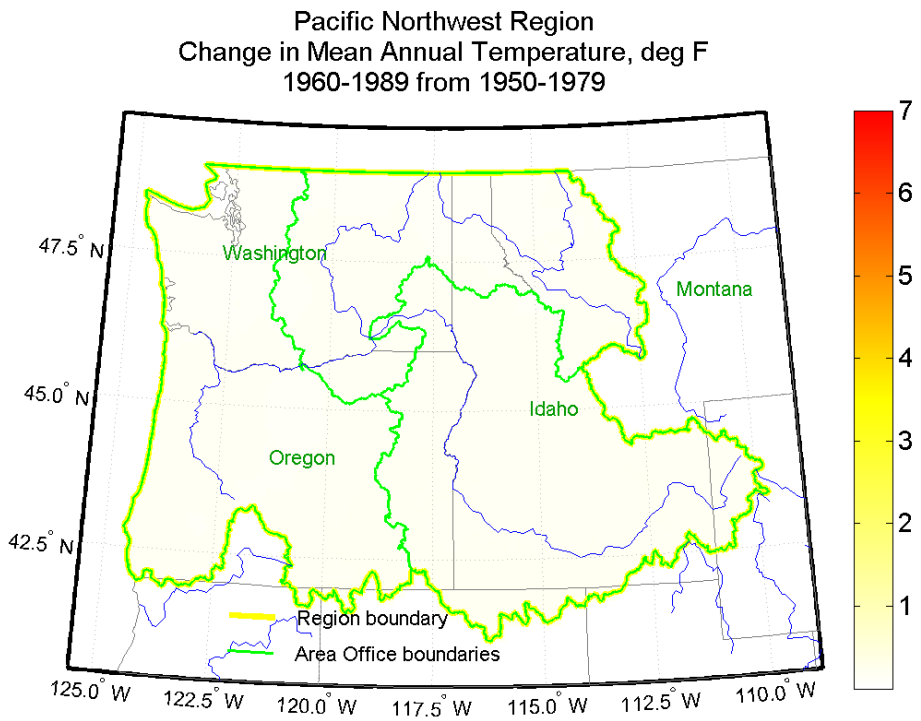
Great Plains Region
Change in Mean Annual Precipitation, Percentage
2050-2079 from 1950-1979

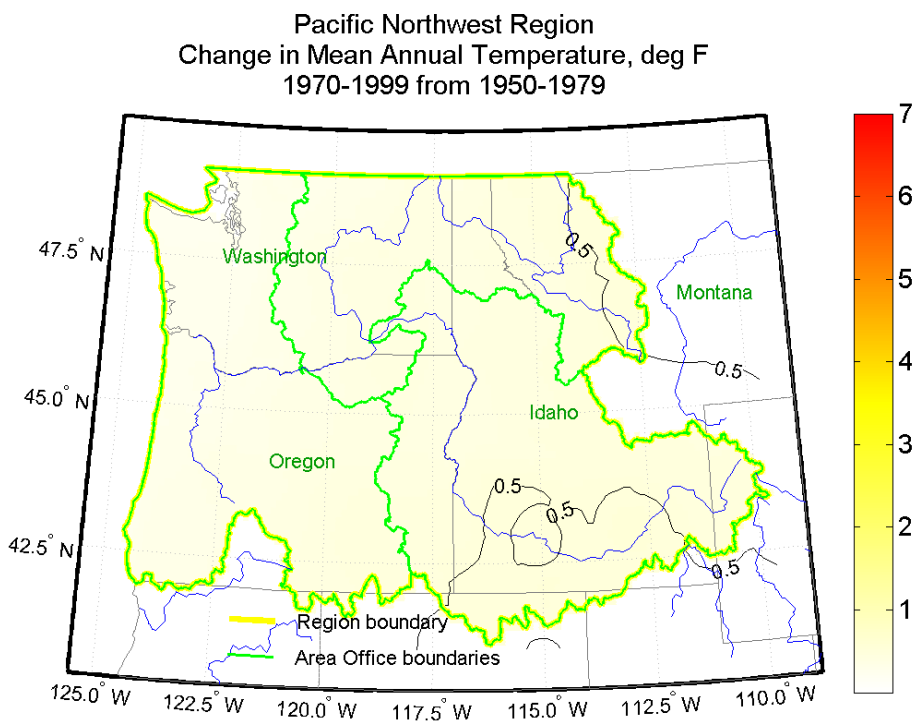


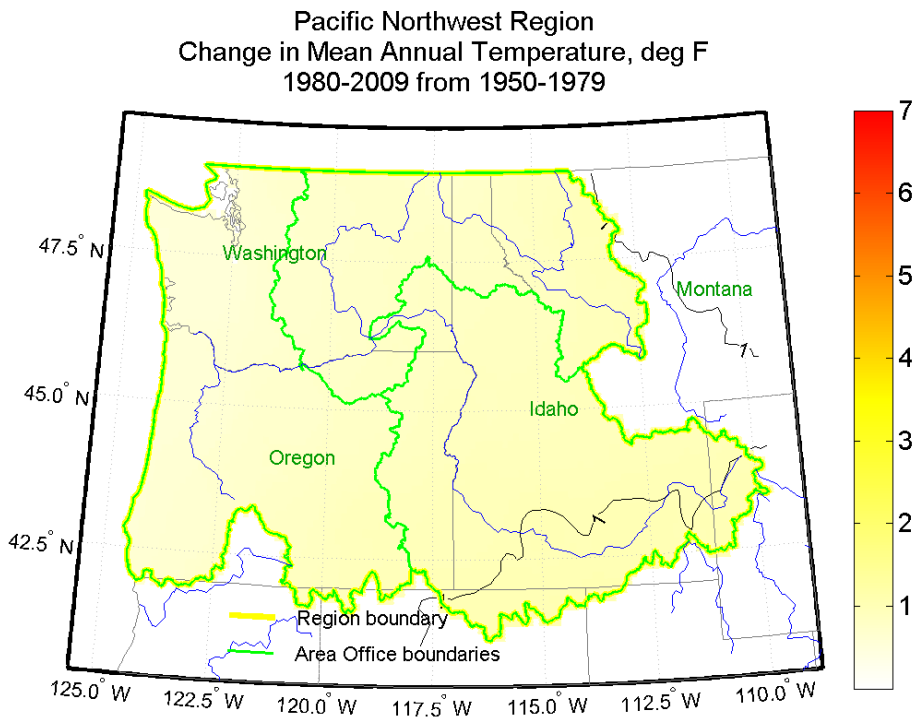

Great Plains Region
Change in Mean Annual Precipitation, Percentage
2060-2089 from 1950-1979
Montana
North Dakota
Minnesota
South Dakota
Wyoming
Iowa
Nebraska
Utah
Colorado
Kansas
Oklahoma
Arizona
New Mexico
Texas
Region boundary
Area Office boundaries
45° N
40° N
35° N
30° N
25° N
110° W
105° W
100° W
95° W
20
15
10
5
0
-5
-10
-15

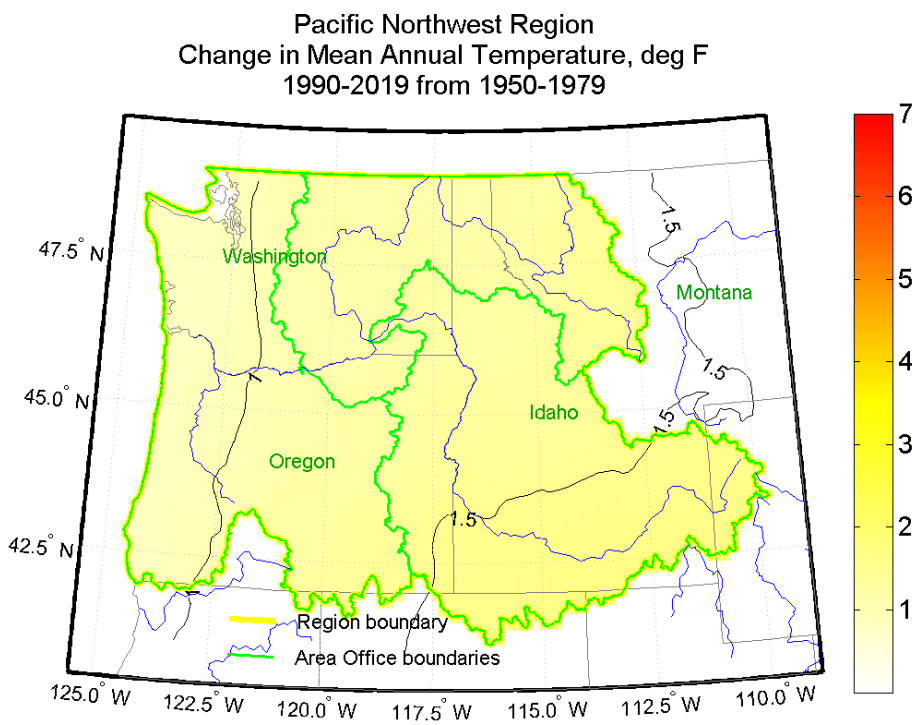

Great Plains Region
Change in Mean Annual Precipitation, Percentage
2070-2099 from 1950-1979
Montana
North Dakota
Minnesota
South Dakota
Wyoming
Iowa
Nebraska
Utah
Colorado
Kansas
Oklahoma
Arizona
New Mexico
Texas
Region boundary
Area Office boundaries
45° N
40° N
35° N
30° N
25° N
110° W
105° W
100° W
95° W
20
15
10
5
0
-5
-10
-15

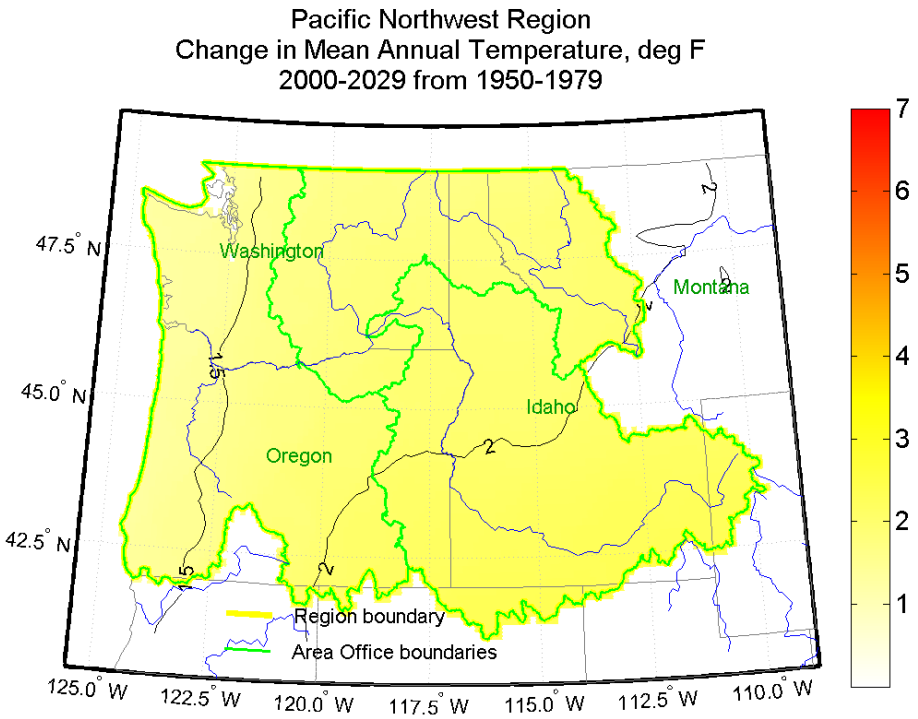
Pacific Northwest Region – Temperature Change


Pacific Northwest Region
Change in Mean Annual Temperature, deg F
1960-1989 from 1950-1979
Washington
Montana
Idaho
Oregon
Region boundary
Area Office boundaries
47.5° N
45.0° N
42.5° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
112.5° W
110.0° W
7
6
5
4
3
2
1


Pacific Northwest Region
Change in Mean Annual Temperature, deg F
1970-1999 from 1950-1979
Washington
Montana
Idaho
Oregon
0.5
Region boundary
Area Office boundaries
47.5° N
45.0° N
42.5° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
112.5° W
110.0° W
7
6
5
4
3
2
1


Pacific Northwest Region
Change in Mean Annual Temperature, deg F
1980-2009 from 1950-1979
Washington
Montana
Idaho
Oregon
1
Region boundary
Area Office boundaries
47.5° N
45.0° N
42.5° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
112.5° W
110.0° W
7
6
5
4
3
2
1


Pacific Northwest Region
Change in Mean Annual Temperature, deg F
1990-2019 from 1950-1979
Washington
Montana
Idaho
Oregon
1.5
Region boundary
Area Office boundaries
47.5° N
45.0° N
42.5° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
112.5° W
110.0° W
7
6
5
4
3
2
1


Pacific Northwest Region
Change in Mean Annual Temperature, deg F
2000-2029 from 1950-1979
Washington
Montana
Idaho
Oregon
Region boundary
Area Office boundaries
47.5° N
45.0° N
42.5° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
112.5° W
110.0° W
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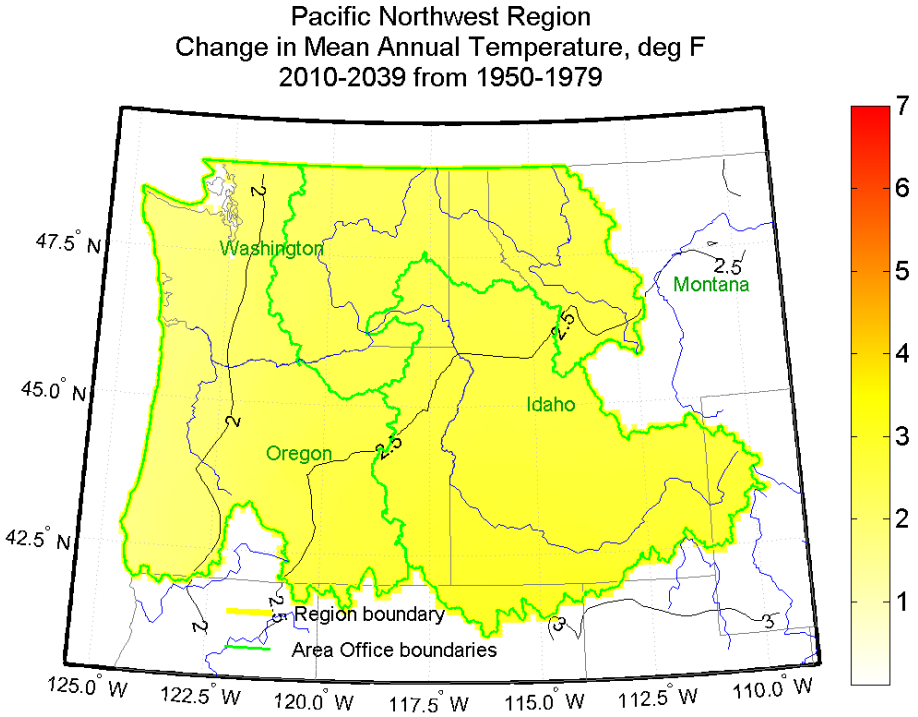
6
5
4
3
2
1


Pacific Northwest Region
Change in Mean Annual Temperature, deg F
2010-2039 from 1950-1979
Washington
Montana
Idaho
Oregon
Region boundary
Area Office boundaries
47.5° N
45.0° N
42.5° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
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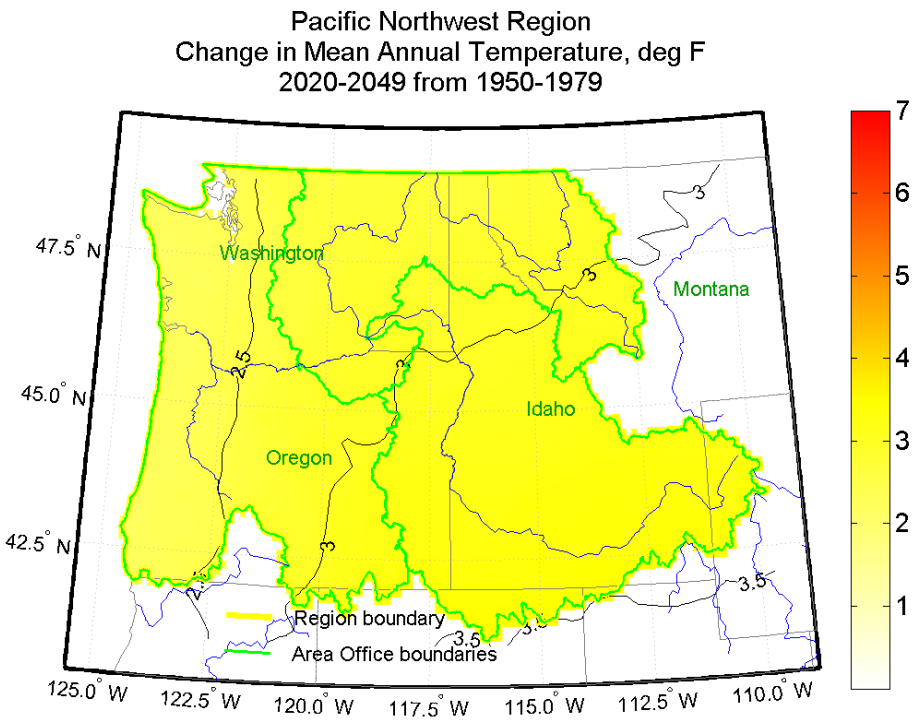
6
5
4
3
2
1


Pacific Northwest Region
Change in Mean Annual Temperature, deg F
2020-2049 from 1950-1979
Washington
Montana
Idaho
Oregon
Region boundary
Area Office boundaries
47.5° N
45.0° N
42.5° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
112.5° W
110.0° W
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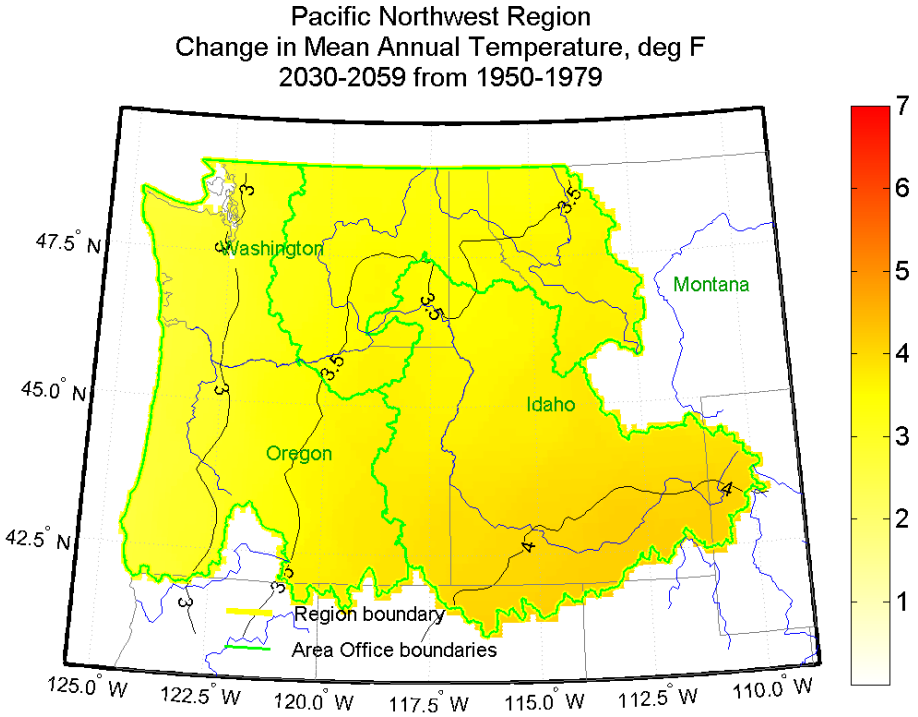
2
3
4
5
6
7


Pacific Northwest Region
Change in Mean Annual Temperature, deg F
2030-2059 from 1950-1979
Washington
Montana
Idaho
Oregon
Region boundary
Area Office boundaries
47.5° N
45.0° N
42.5° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
112.5° W
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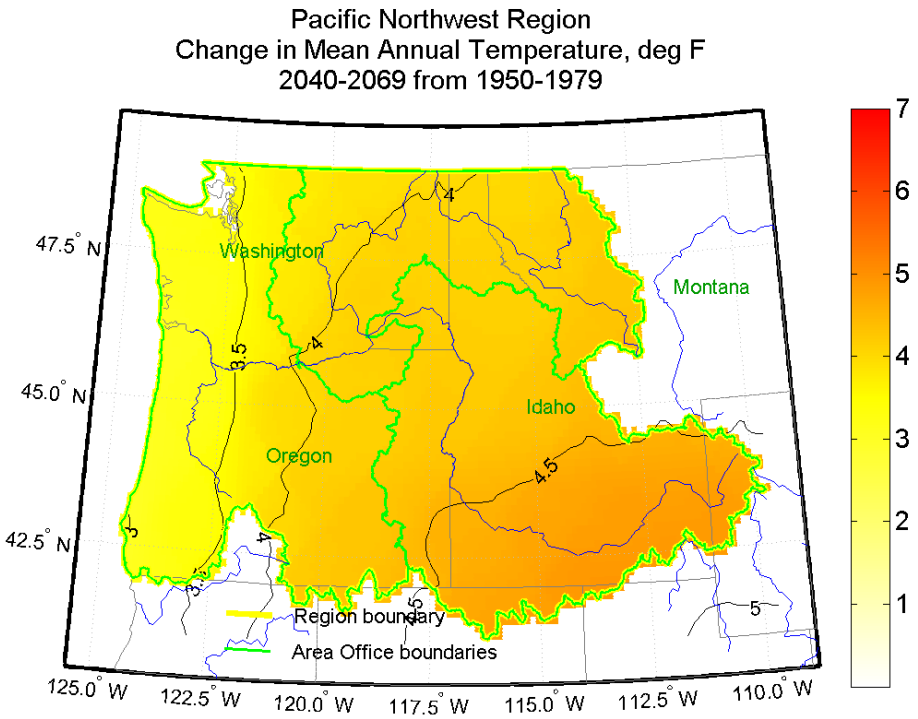
2
3
4
5
6
7


Pacific Northwest Region
Change in Mean Annual Temperature, deg F
2040-2069 from 1950-1979
Washington
Montana
Idaho
Oregon
Region boundary
Area Office boundaries
47.5° N
45.0° N
42.5° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
112.5° W
110.0° W
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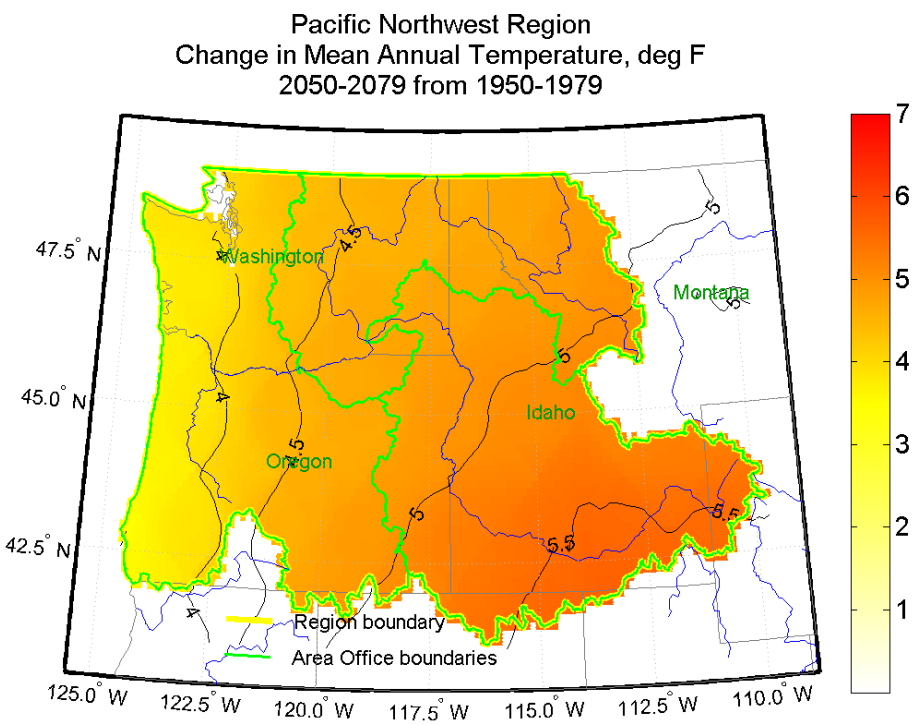
6
5
4
3
2
1


Pacific Northwest Region
Change in Mean Annual Temperature, deg F
2050-2079 from 1950-1979
Washington
Montana
Idaho
Oregon
Region boundary
Area Office boundaries
47.5° N
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42.5° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
112.5° W
110.0° W
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6
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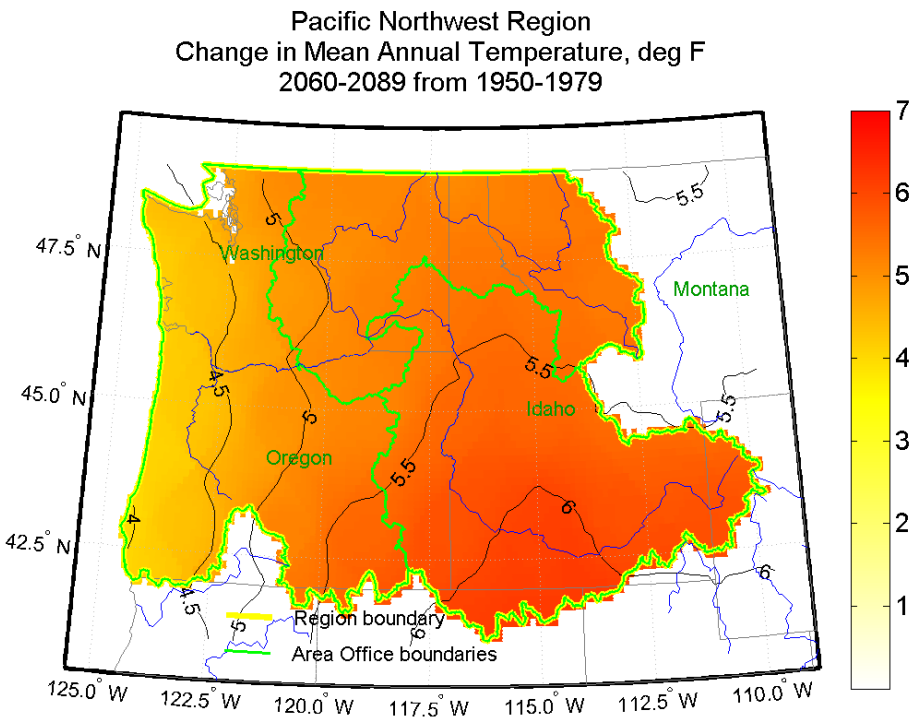
4
3
2
1


Pacific Northwest Region
Change in Mean Annual Temperature, deg F
2060-2089 from 1950-1979
Washington
Montana
Idaho
Oregon
Region boundary
Area Office boundaries
47.5° N
45.0° N
42.5° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
112.5° W
110.0° W
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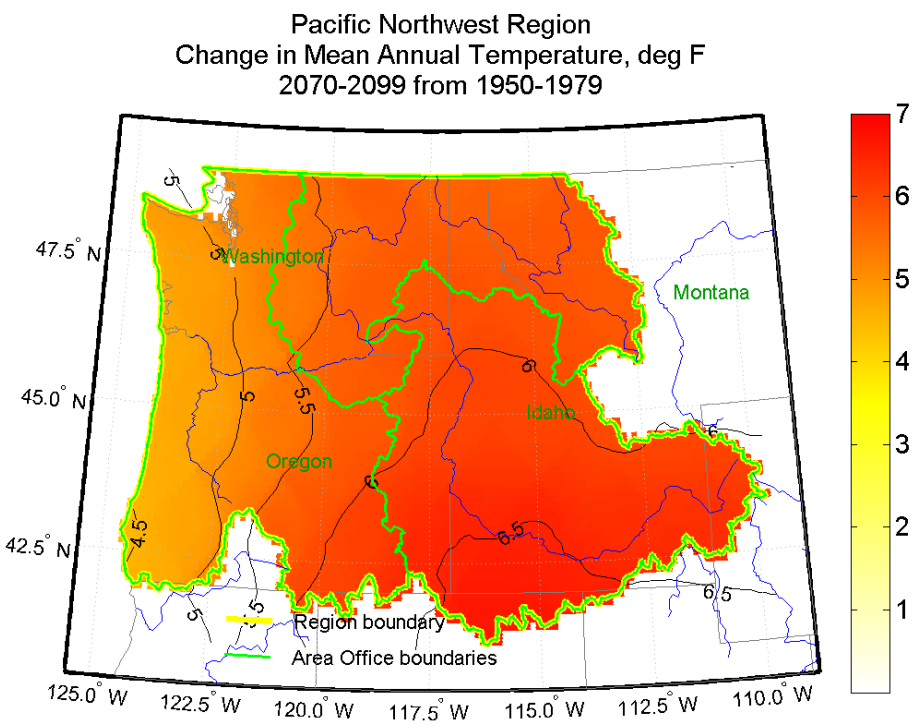
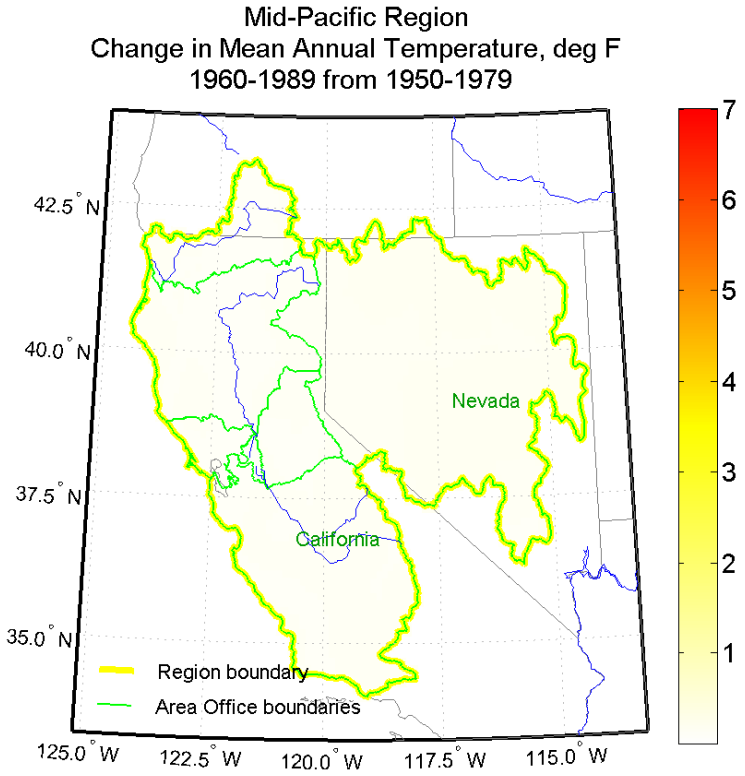
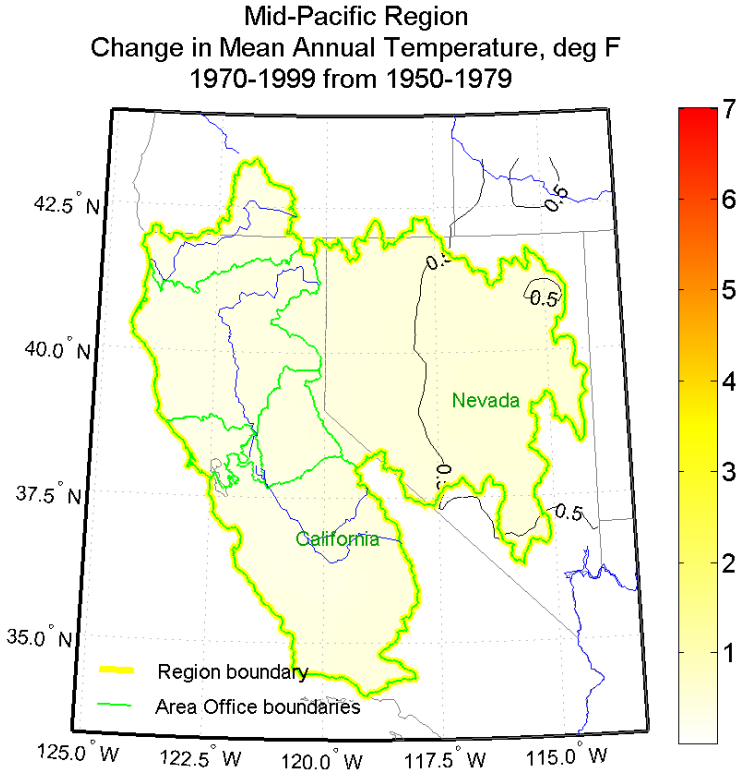
2
3
4
5
6
7


Pacific Northwest Region
Change in Mean Annual Temperature, deg F
2070-2099 from 1950-1979
Washington
Montana
Idaho
Oregon
Region boundary
Area Office boundaries
47.5° N
45.0° N
42.5° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
112.5° W
110.0° W
1
2
3
4
5
6
7

Mid-Pacific Region – Temperature Change


Mid-Pacific Region
Change in Mean Annual Temperature, deg F
1960-1989 from 1950-1979
42.5° N
40.0° N
37.5° N
35.0° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
Nevada
California
Region boundary
Area Office boundaries
7
6
5
4
3
2
1


Mid-Pacific Region
Change in Mean Annual Temperature, deg F
1970-1999 from 1950-1979
42.5° N
40.0° N
37.5° N
35.0° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
0.5
0.5
0.5
0.5
Nevada
California
Region boundary
Area Office boundaries
7
6
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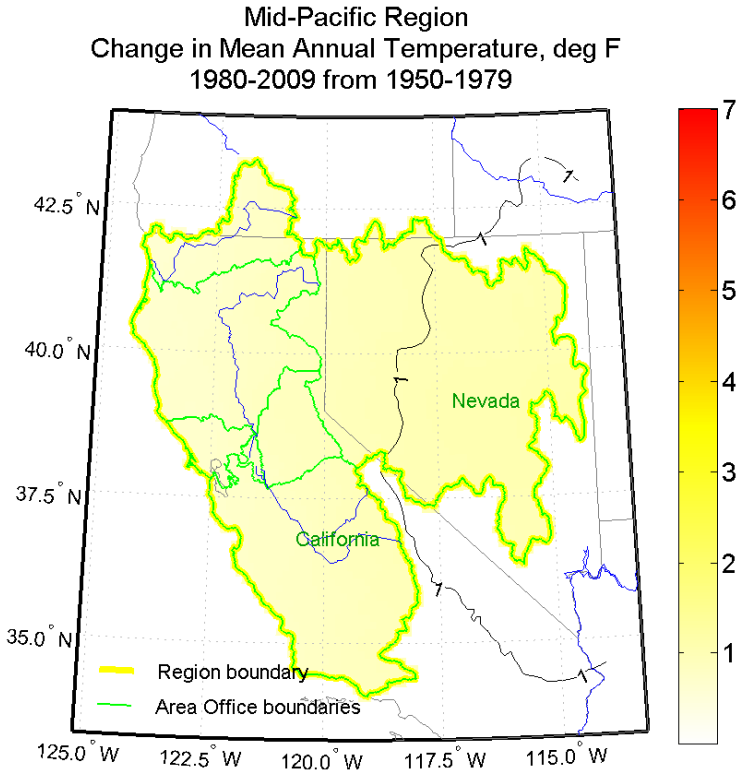
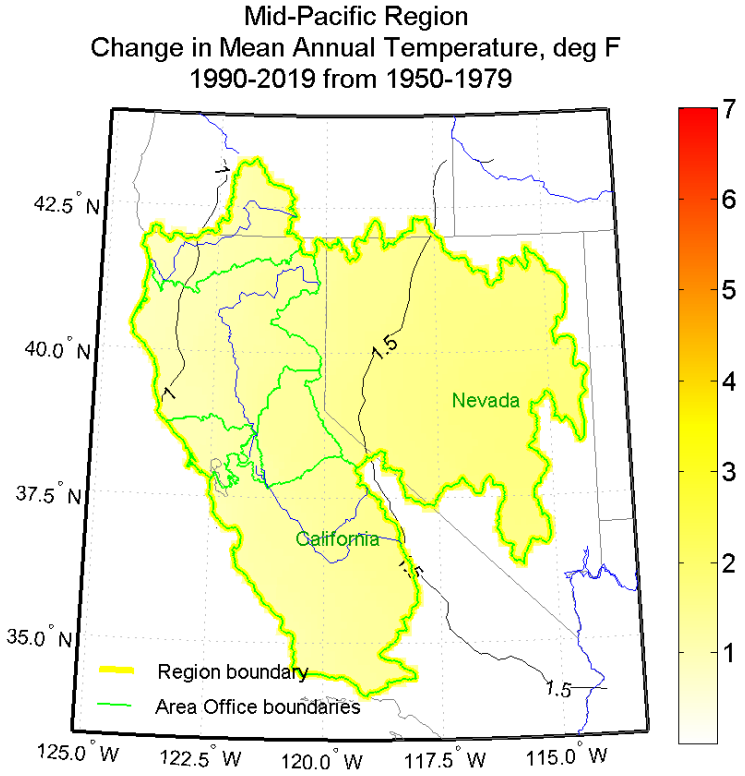
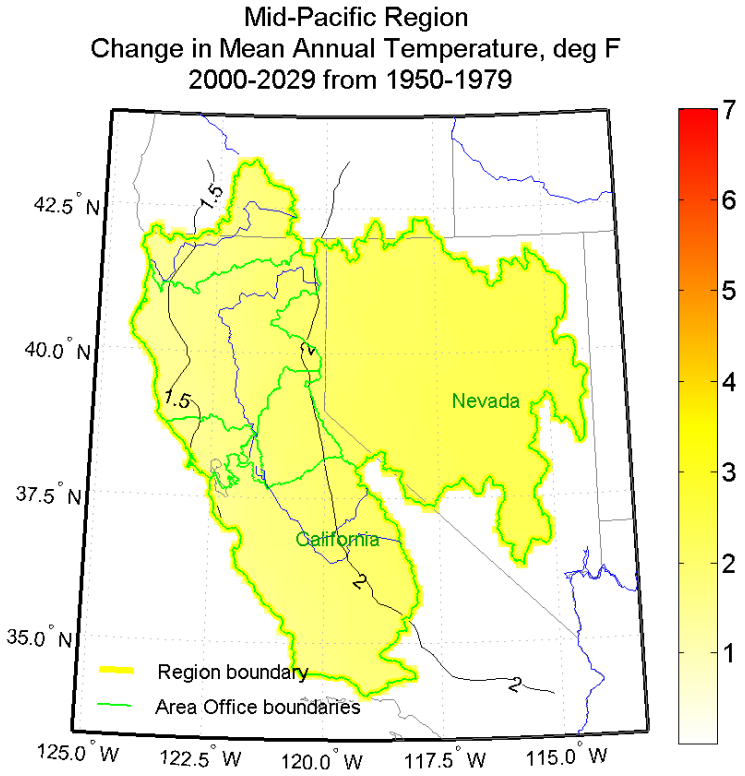
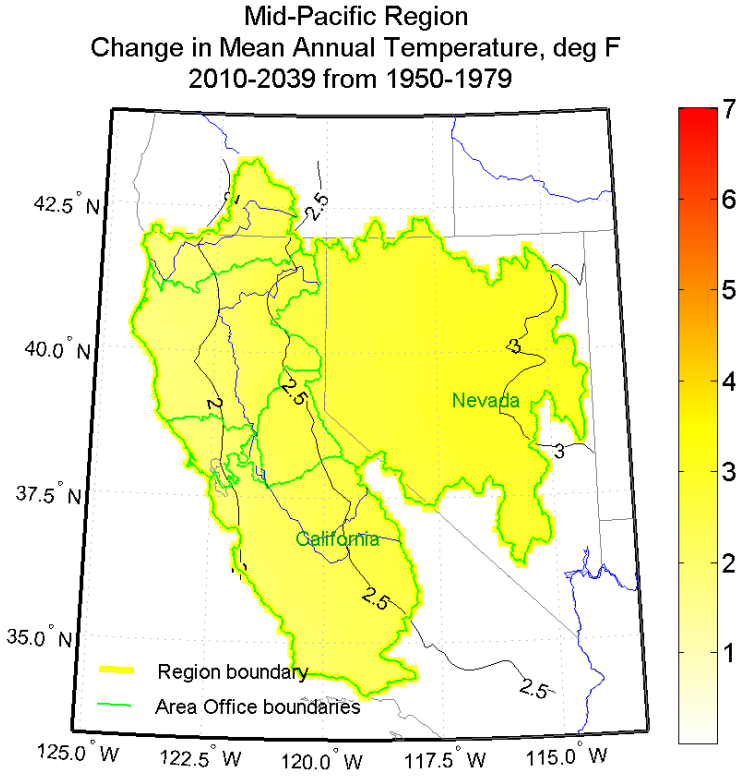
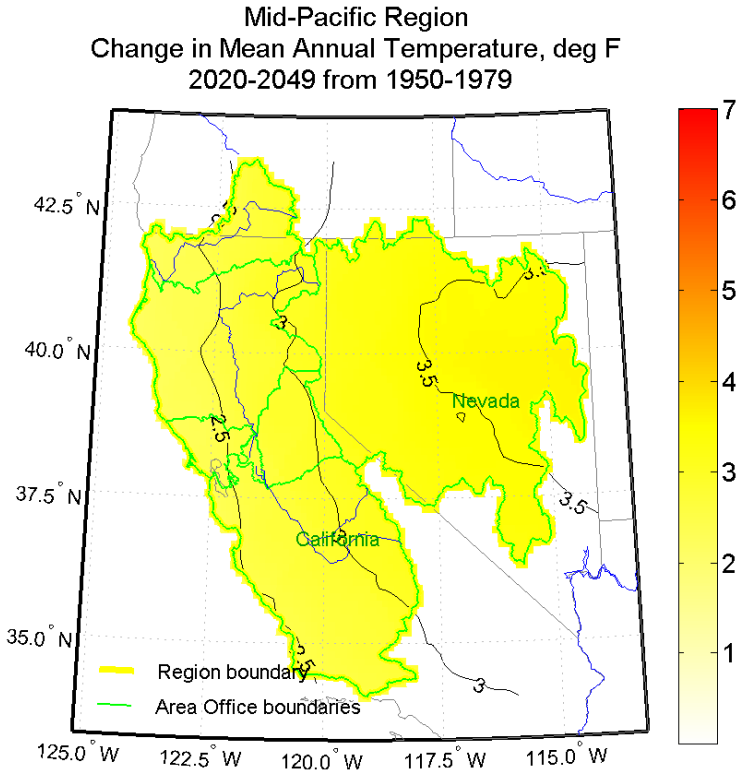
4
3
2
1

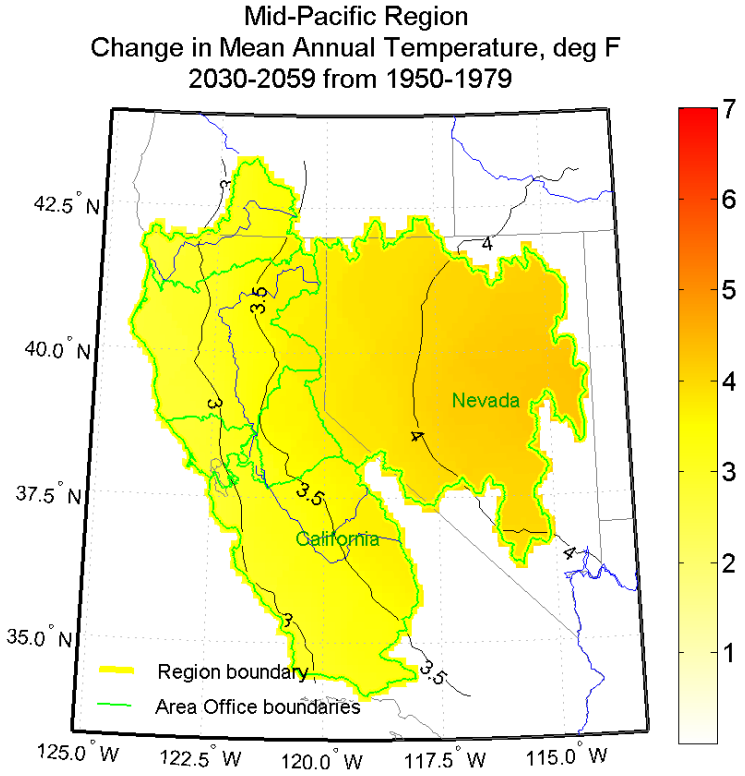

Mid-Pacific Region
Change in Mean Annual Temperature, deg F
1980-2009 from 1950-1979
42.5° N
40.0° N
37.5° N
35.0° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
Nevada
California
Region boundary
Area Office boundaries
7
6
5
4
3
2
1

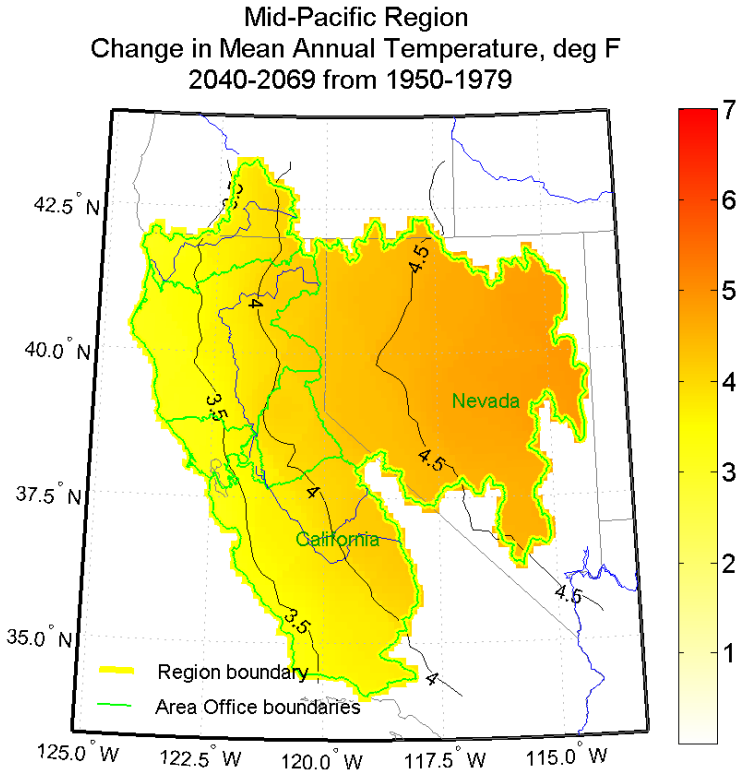

Mid-Pacific Region
Change in Mean Annual Temperature, deg F
1990-2019 from 1950-1979
42.5° N
40.0° N
37.5° N
35.0° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
1.5
Nevada
California
Region boundary
Area Office boundaries
7
6
5
4
3
2
1

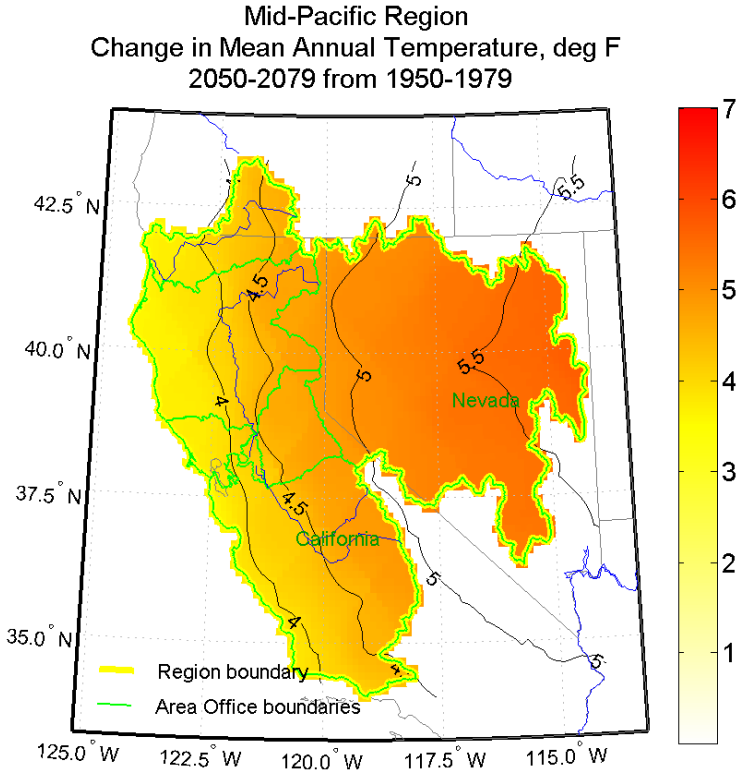

Mid-Pacific Region
Change in Mean Annual Temperature, deg F
2000-2029 from 1950-1979
42.5° N
40.0° N
37.5° N
35.0° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
Nevada
California
1.5
2
Region boundary
Area Office boundaries
7
6
5
4
3
2
1

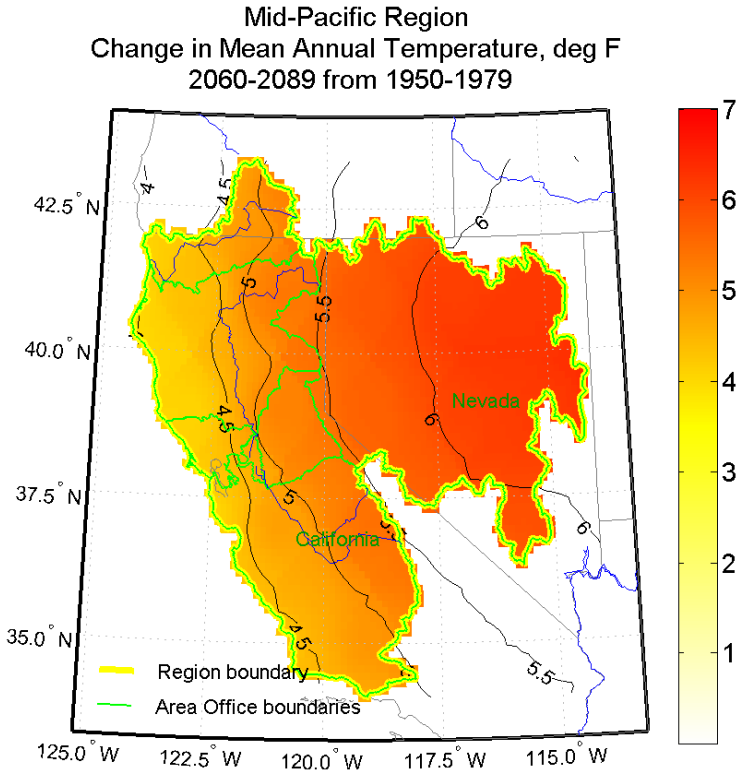

Mid-Pacific Region
Change in Mean Annual Temperature, deg F
2010-2039 from 1950-1979
42.5° N
40.0° N
37.5° N
35.0° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
Nevada
California
2
2.5
3
Region boundary
Area Office boundaries
7
6
5
4
3
2
1

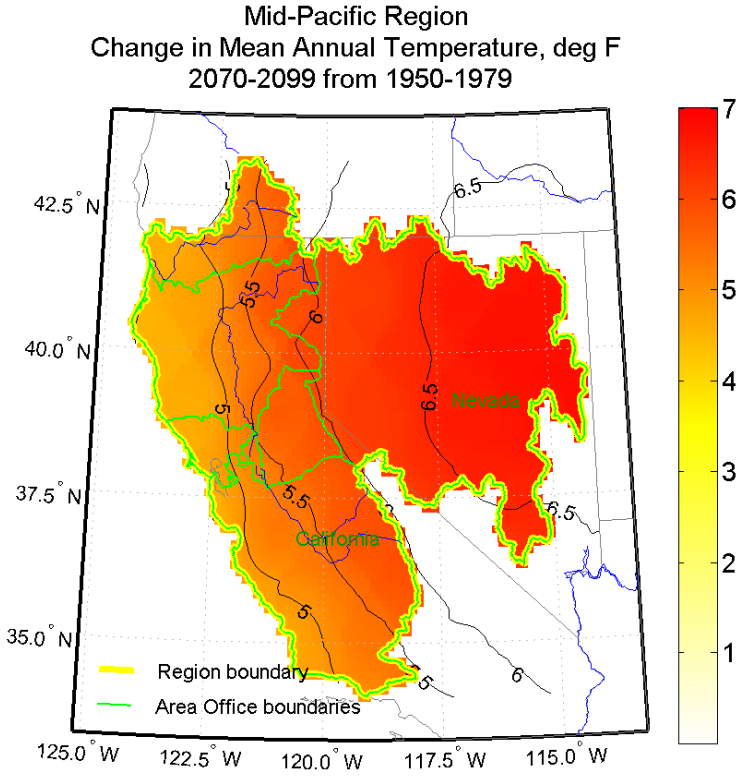

Mid-Pacific Region
Change in Mean Annual Temperature, deg F
2020-2049 from 1950-1979
42.5° N
40.0° N
37.5° N
35.0° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
Nevada
California
Region boundary
Area Office boundaries
7
6
5
4
3
2
1


Mid-Pacific Region
Change in Mean Annual Temperature, deg F
2030-2059 from 1950-1979
42.5° N
40.0° N
37.5° N
35.0° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
Nevada
California
Region boundary
Area Office boundaries
7
6
5
4
3
2
1

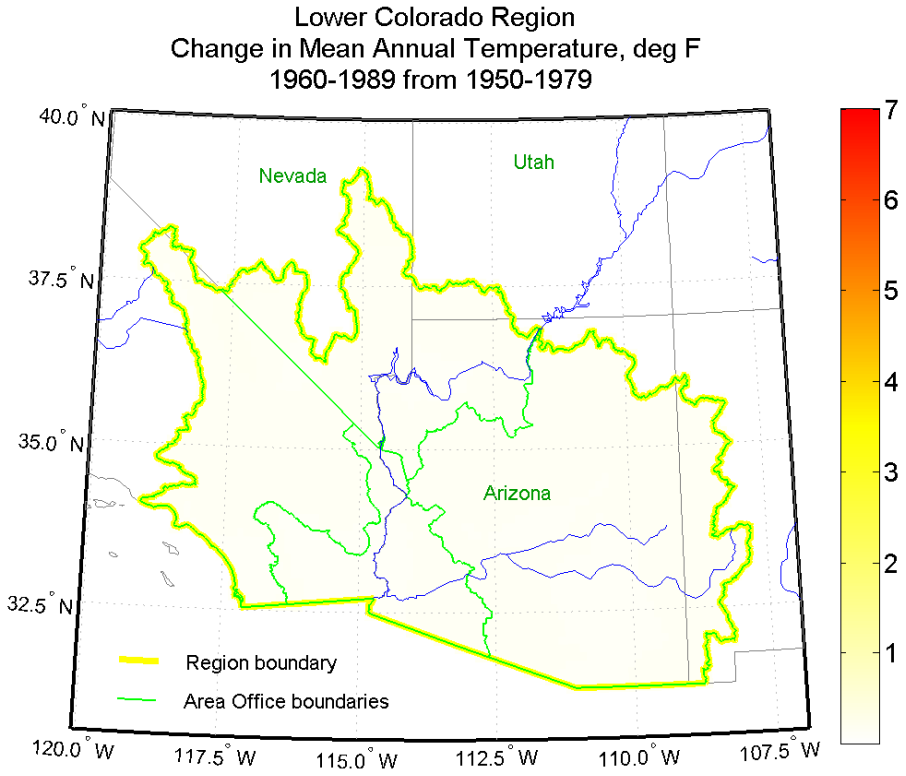

Mid-Pacific Region
Change in Mean Annual Temperature, deg F
2040-2069 from 1950-1979
42.5° N
40.0° N
37.5° N
35.0° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
Nevada
California
Region boundary
Area Office boundaries
7
6
5
4
3
2
1

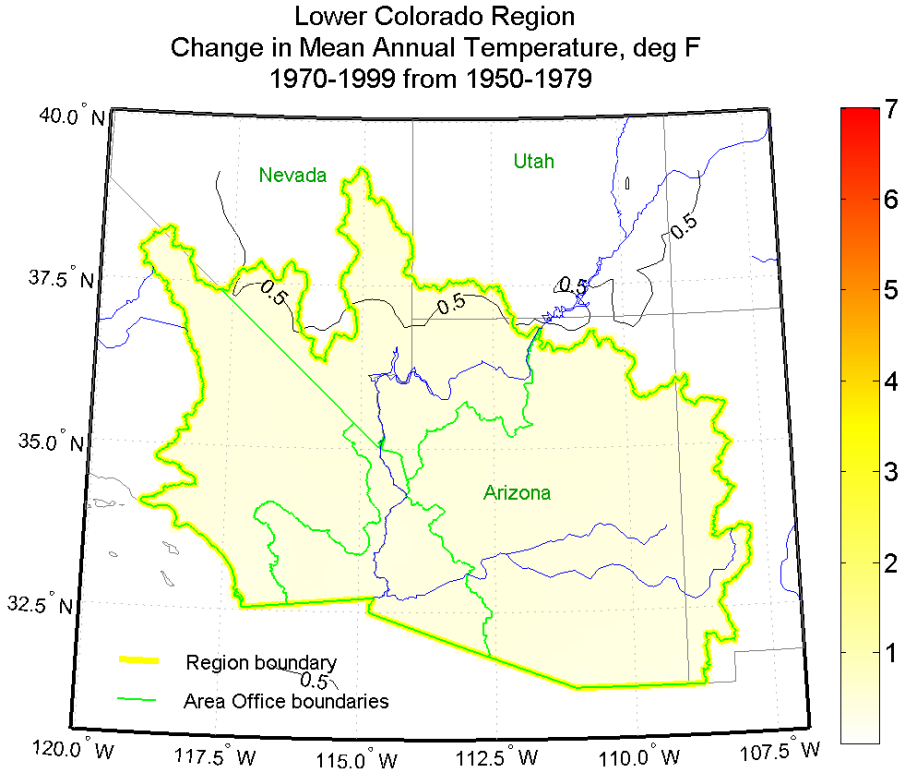

Mid-Pacific Region
Change in Mean Annual Temperature, deg F
2050-2079 from 1950-1979
42.5° N
40.0° N
37.5° N
35.0° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
Nevada
California
Region boundary
Area Office boundaries
7
6
5
4
3
2
1

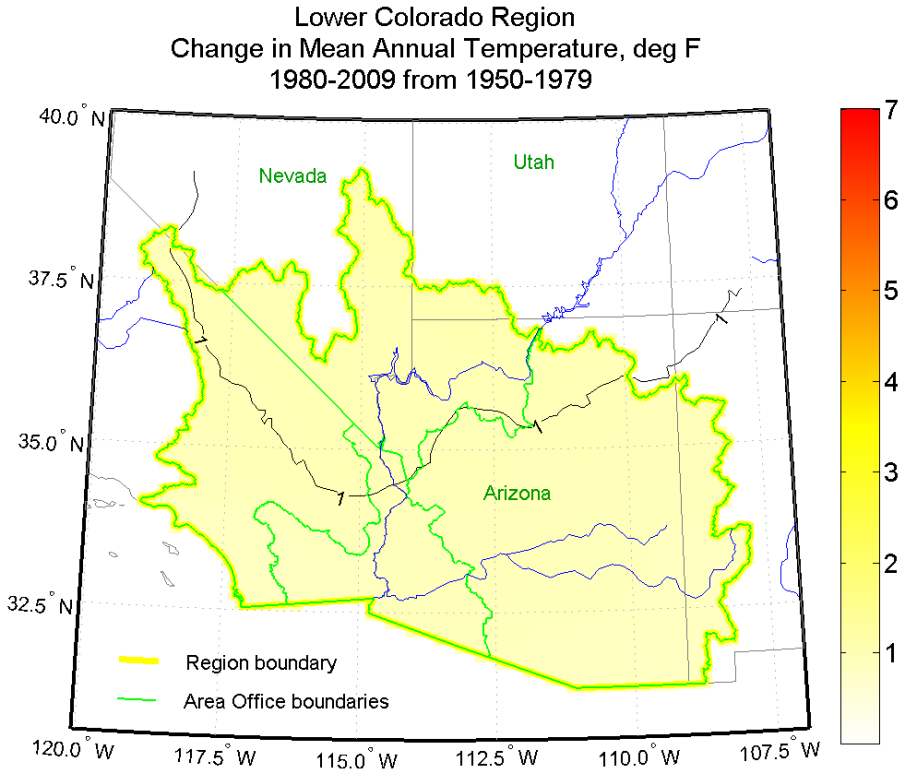

Mid-Pacific Region
Change in Mean Annual Temperature, deg F
2060-2089 from 1950-1979
42.5° N
40.0° N
37.5° N
35.0° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
Nevada
California
Region boundary
Area Office boundaries
7
6
5
4
3
2
1

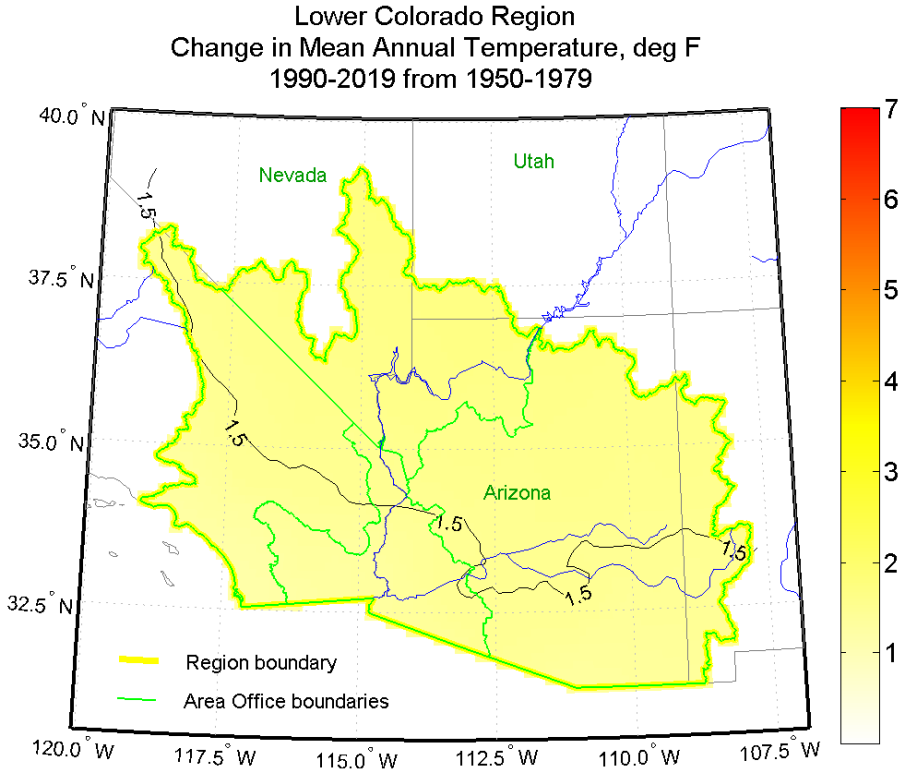

Mid-Pacific Region
Change in Mean Annual Temperature, deg F
2070-2099 from 1950-1979
42.5° N
40.0° N
37.5° N
35.0° N
125.0° W
122.5° W
120.0° W
117.5° W
115.0° W
Nevada
California
Region boundary
Area Office boundaries
7
6
5
4
3
2
1

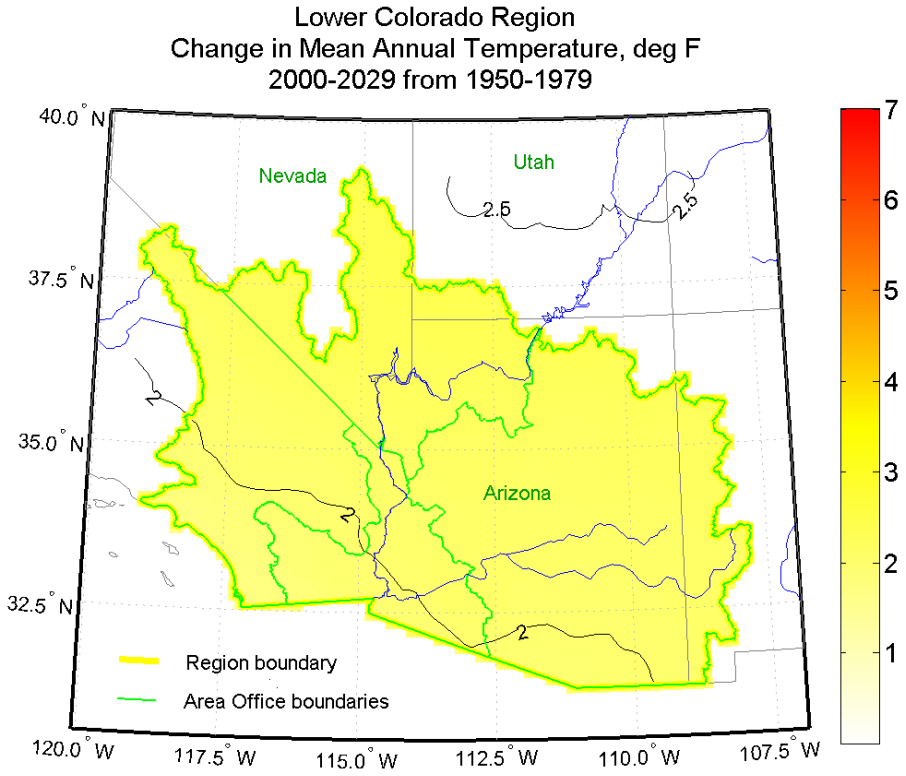
Lower Colorado Region – Temperature Change

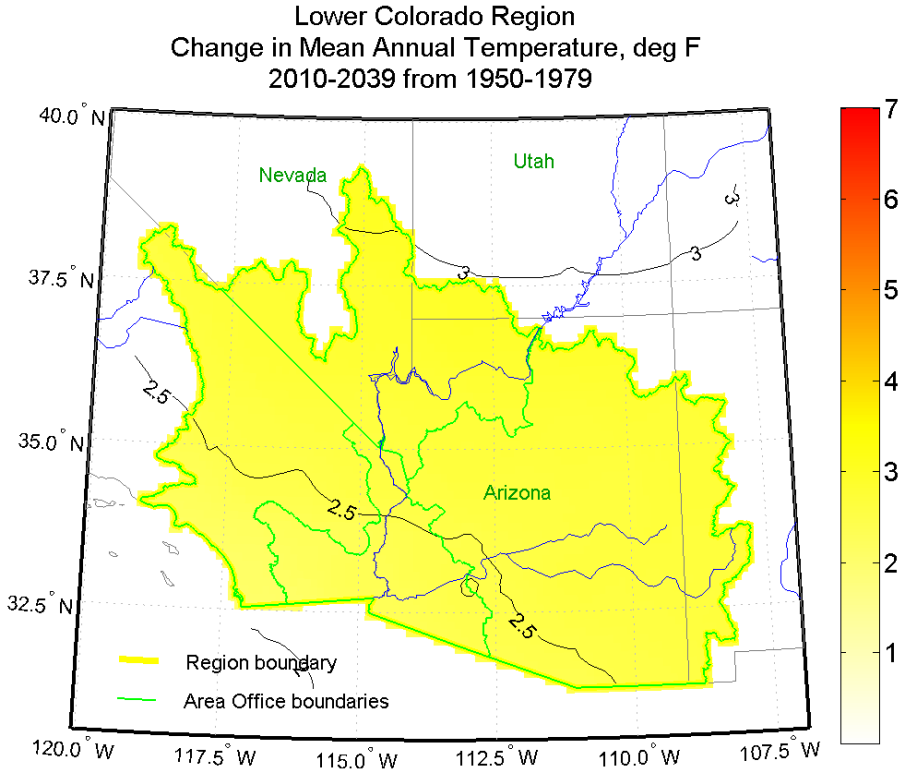

Lower Colorado Region
Change in Mean Annual Temperature, deg F
1960-1989 from 1950-1979
40.0° N
37.5° N
35.0° N
32.5° N
120.0° W
117.5° W
115.0° W
112.5° W
110.0° W
107.5° W
Nevada
Utah
Arizona
Region boundary
Area Office boundaries
7
6
5
4
3
2
1

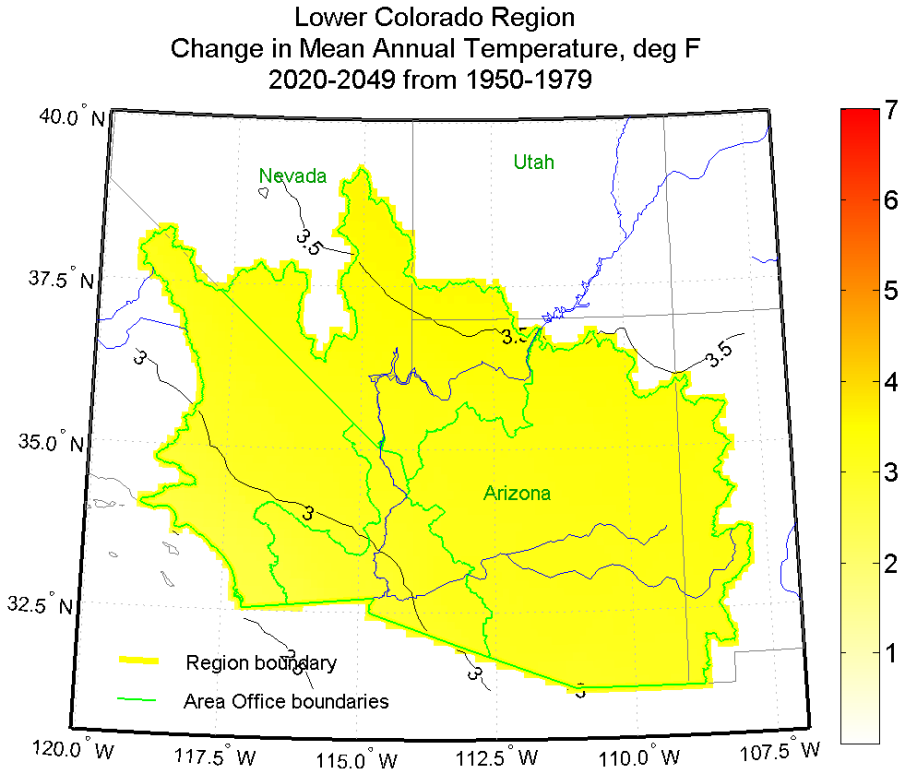

Lower Colorado Region
Change in Mean Annual Temperature, deg F
1970-1999 from 1950-1979
40.0° N
37.5° N
35.0° N
32.5° N
120.0° W
117.5° W
115.0° W
112.5° W
110.0° W
107.5° W
Nevada
Utah
Arizona
0.5
Region boundary
Area Office boundaries
7
6
5
4
3
2
1

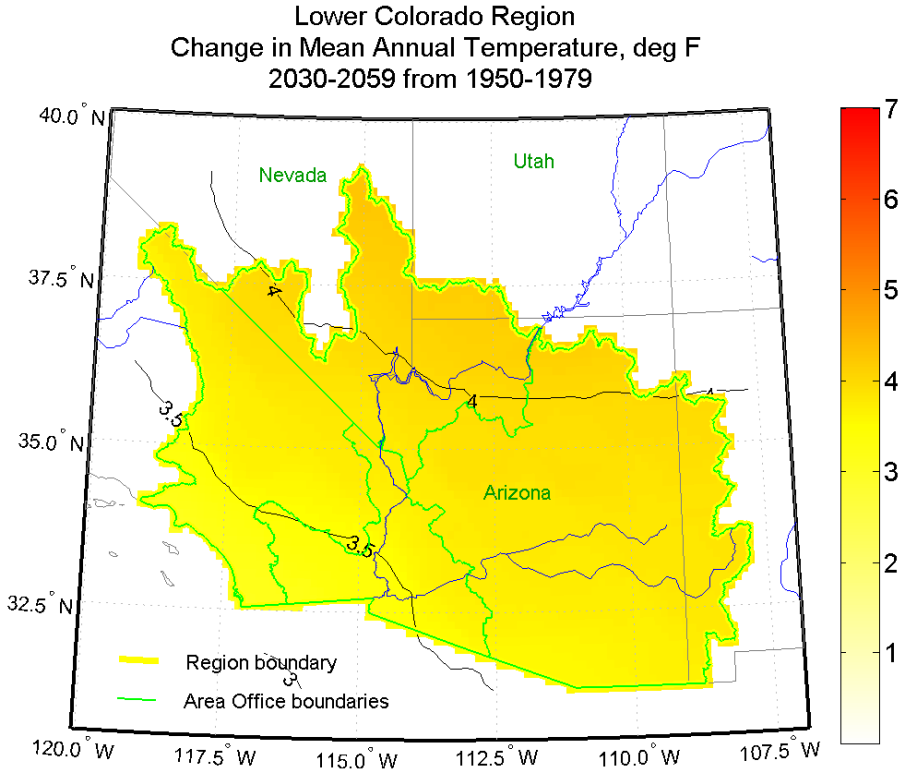

Lower Colorado Region
Change in Mean Annual Temperature, deg F
1980-2009 from 1950-1979
40.0° N
37.5° N
35.0° N
32.5° N
120.0° W
117.5° W
115.0° W
112.5° W
110.0° W
107.5° W
Nevada
Utah
Arizona
1
Region boundary
Area Office boundaries
7
6
5
4
3
2
1

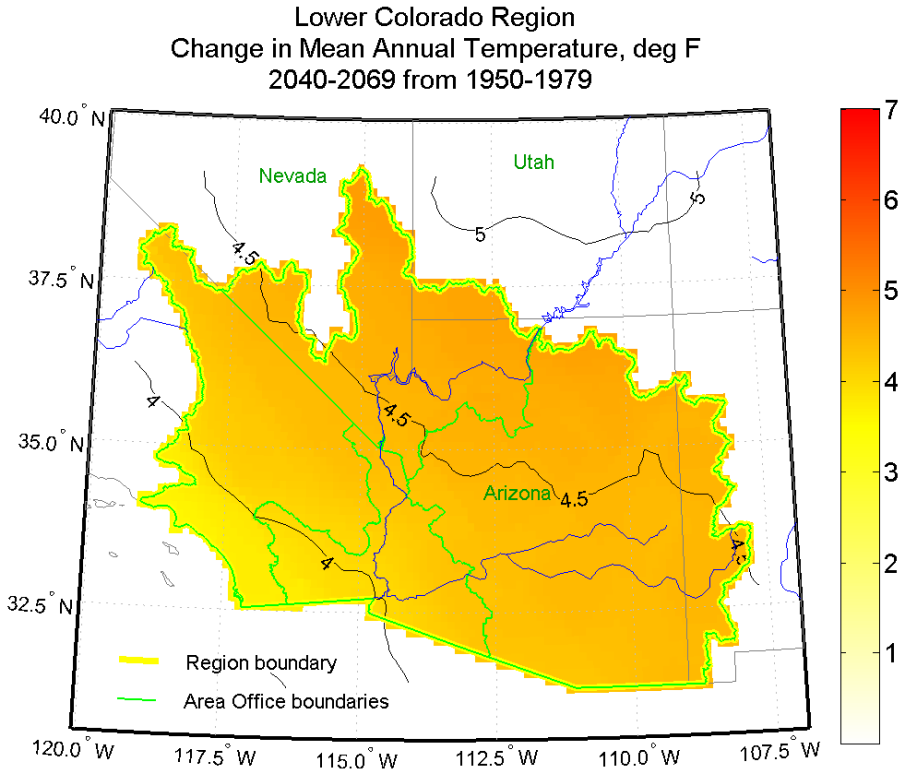

Lower Colorado Region
Change in Mean Annual Temperature, deg F
1990-2019 from 1950-1979
40.0° N
37.5° N
35.0° N
32.5° N
120.0° W
117.5° W
115.0° W
112.5° W
110.0° W
107.5° W
Nevada
Utah
Arizona
1.5
Region boundary
Area Office boundaries
7
6
5
4
3
2
1


Lower Colorado Region
Change in Mean Annual Temperature, deg F
2000-2029 from 1950-1979
40.0° N
37.5° N
35.0° N
32.5° N
120.0° W
117.5° W
115.0° W
112.5° W
110.0° W
107.5° W
Nevada
Utah
Arizona
2.5
2
Region boundary
Area Office boundaries
7
6
5
4
3
2
1


Lower Colorado Region
Change in Mean Annual Temperature, deg F
2010-2039 from 1950-1979
40.0° N
37.5° N
35.0° N
32.5° N
120.0° W
117.5° W
115.0° W
112.5° W
110.0° W
107.5° W
Nevada
Utah
Arizona
3.5
3
2.5
Region boundary
Area Office boundaries
7
6
5
4
3
2
1


Lower Colorado Region
Change in Mean Annual Temperature, deg F
2020-2049 from 1950-1979
40.0° N
37.5° N
35.0° N
32.5° N
120.0° W
117.5° W
115.0° W
112.5° W
110.0° W
107.5° W
Nevada
Utah
Arizona
3.5
3
Region boundary
Area Office boundaries
7
6
5
4
3
2
1


Lower Colorado Region
Change in Mean Annual Temperature, deg F
2030-2059 from 1950-1979
40.0° N
37.5° N
35.0° N
32.5° N
120.0° W
117.5° W
115.0° W
112.5° W
110.0° W
107.5° W
Nevada
Utah
Arizona
4
3.5
3
Region boundary
Area Office boundaries
7
6
5
4
3
2
1


Lower Colorado Region
Change in Mean Annual Temperature, deg F
2040-2069 from 1950-1979
40.0° N
37.5° N
35.0° N
32.5° N
120.0° W
117.5° W
115.0° W
112.5° W
110.0° W
107.5° W
Nevada
Utah
Arizona
4.5
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4
Region boundary
Area Office boundaries
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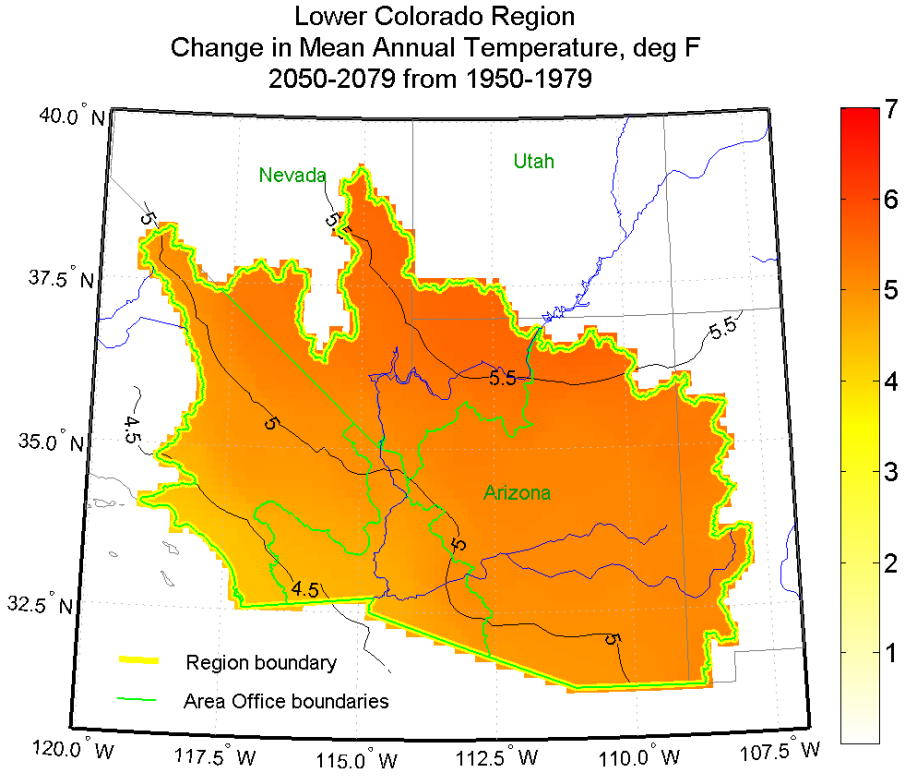
6
5
4
3
2
1


Lower Colorado Region
Change in Mean Annual Temperature, deg F
2050-2079 from 1950-1979
40.0° N
37.5° N
35.0° N
32.5° N
120.0° W
117.5° W
115.0° W
112.5° W
110.0° W
107.5° W
Nevada
Utah
Arizona
5.5
5
4.5
Region boundary
Area Office boundaries
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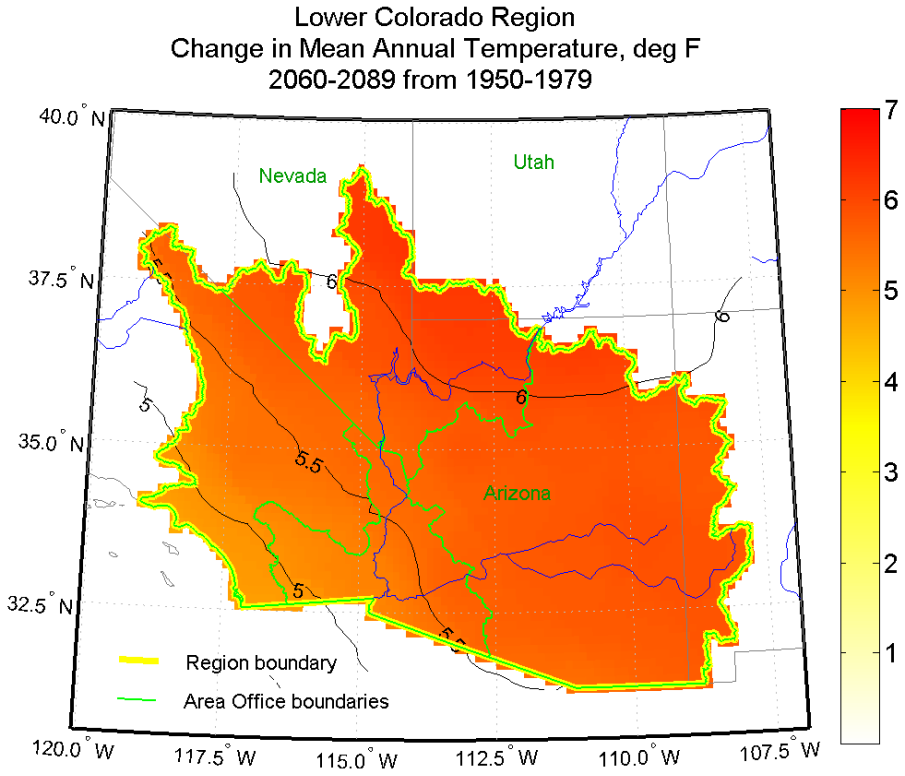
6
5
4
3
2
1


Lower Colorado Region
Change in Mean Annual Temperature, deg F
2060-2089 from 1950-1979
40.0° N
37.5° N
35.0° N
32.5° N
120.0° W
117.5° W
115.0° W
112.5° W
110.0° W
107.5° W
Nevada
Utah
Arizona
6
5.5
5
Region boundary
Area Office boundaries
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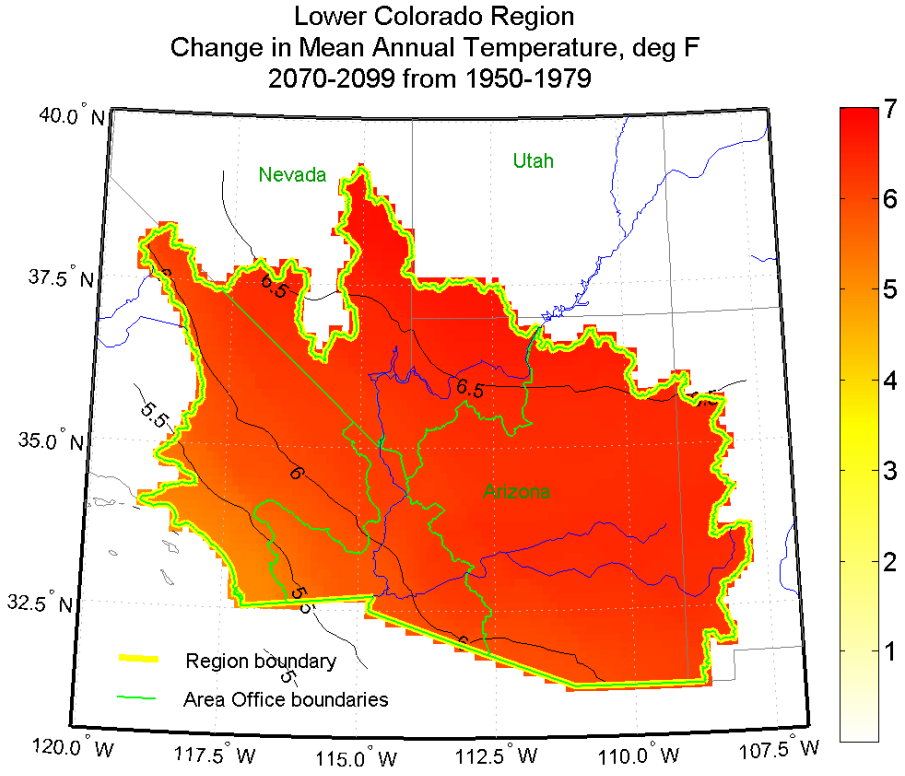
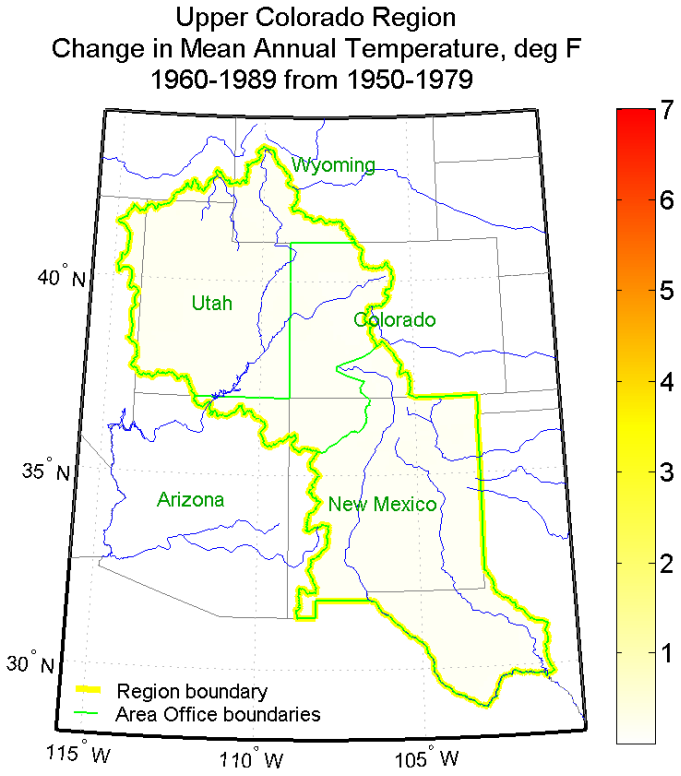
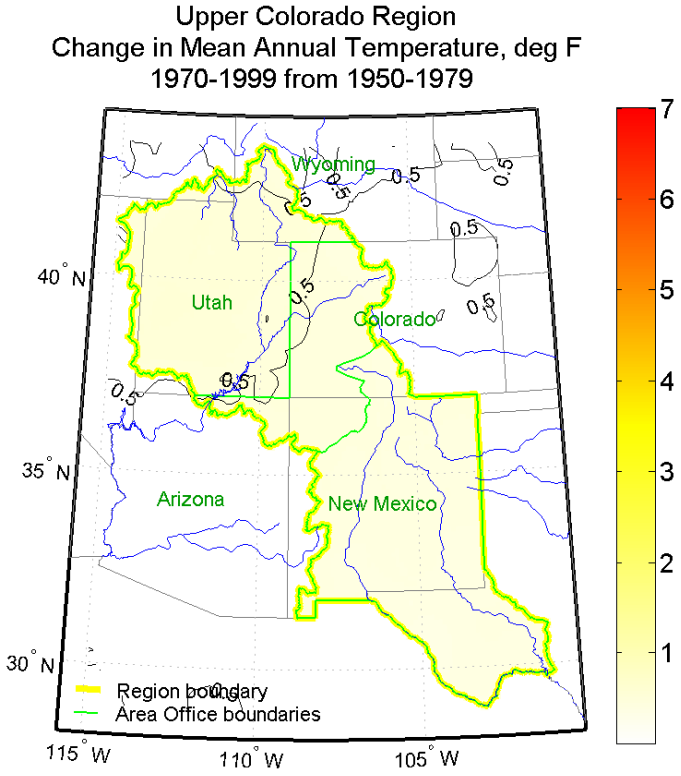
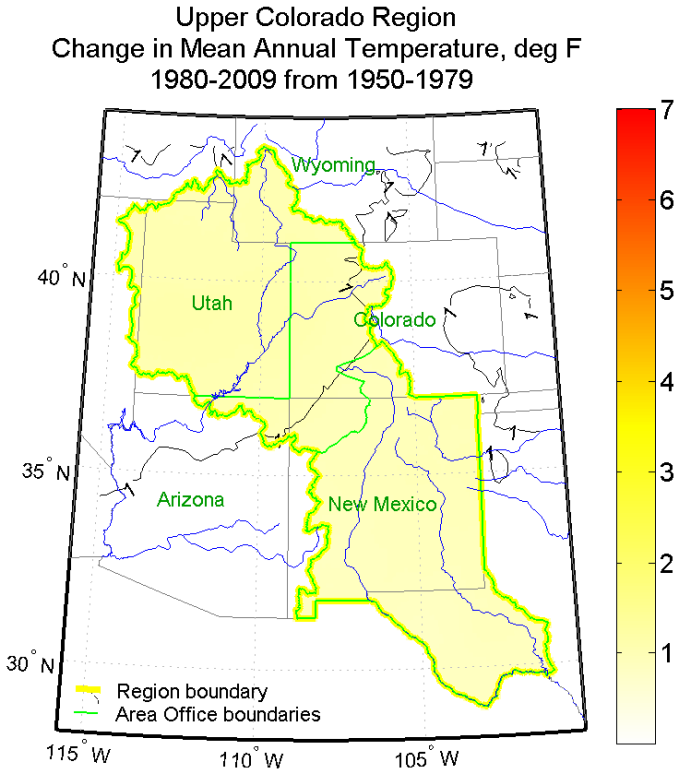
6
5
4
3
2
1

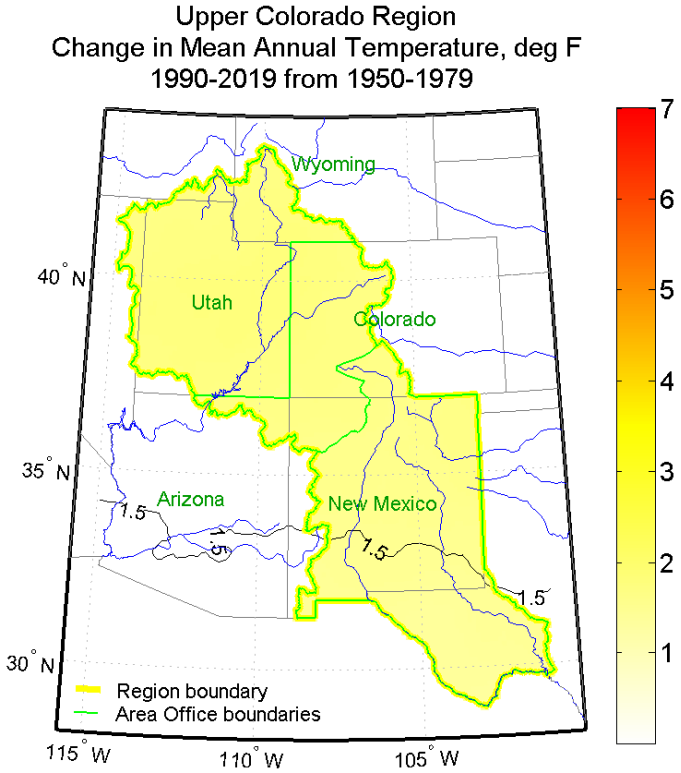

Lower Colorado Region
Change in Mean Annual Temperature, deg F
2070-2099 from 1950-1979
40.0° N
37.5° N
35.0° N
32.5° N
120.0° W
117.5° W
115.0° W
112.5° W
110.0° W
107.5° W
Nevada
Utah
Arizona
6.5
6
5.5
5
Region boundary
Area Office boundaries
7
6
5
4
3
2
1

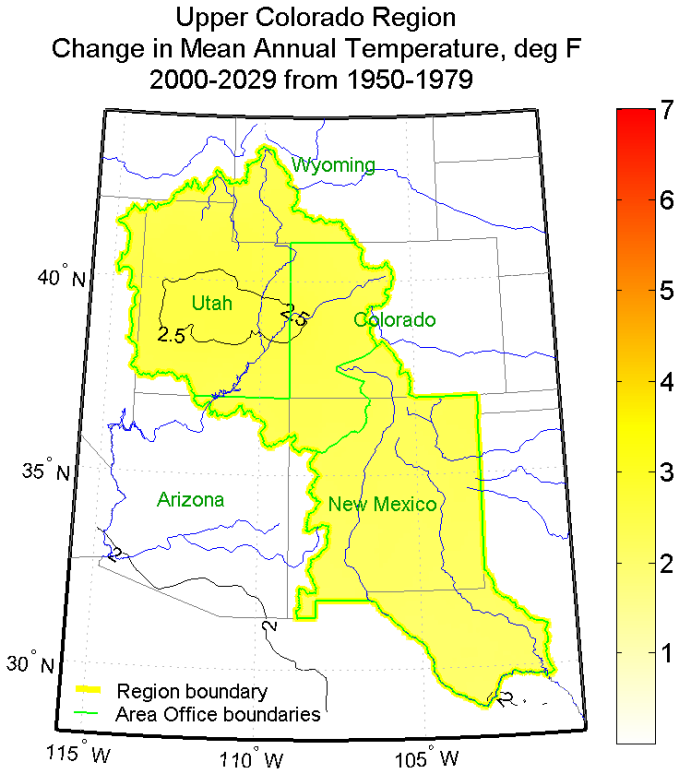
Upper Colorado Region – Temperature Change

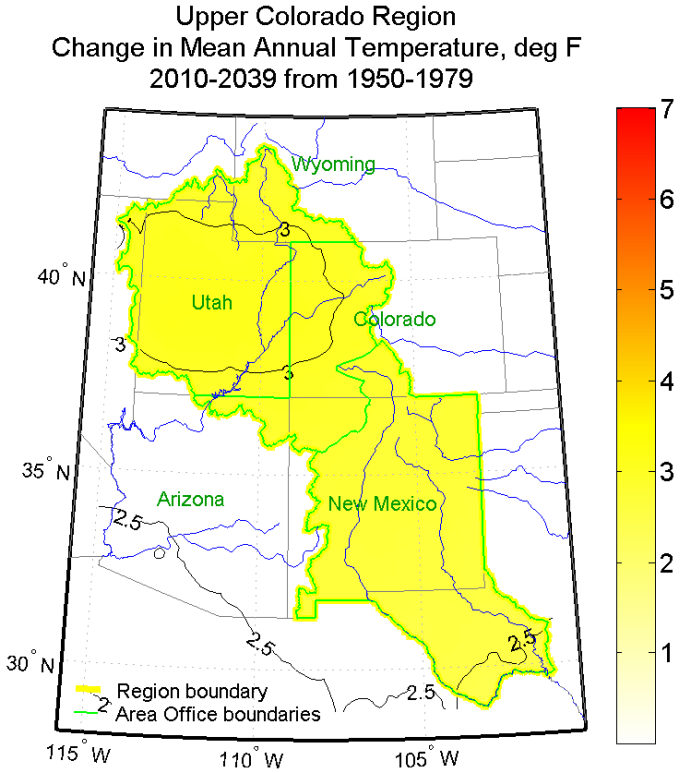

Upper Colorado Region
Change in Mean Annual Temperature, deg F
1960-1989 from 1950-1979
Wyoming
Utah
Colorado
Arizona
New Mexico
40° N
35° N
30° N
115° W
110° W
105° W
Region boundary
Area Office boundaries
7
6
5
4
3
2
1

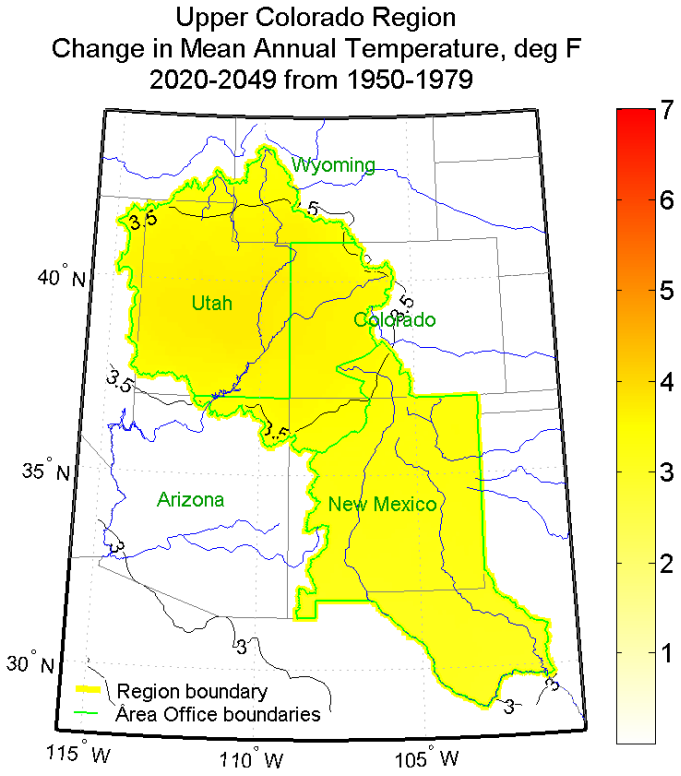

Upper Colorado Region
Change in Mean Annual Temperature, deg F
1970-1999 from 1950-1979
Wyoming
Utah
Colorado
Arizona
New Mexico
0.5
40° N
35° N
30° N
115° W
110° W
105° W
Region boundary
Area Office boundaries
7
6
5
4
3
2
1

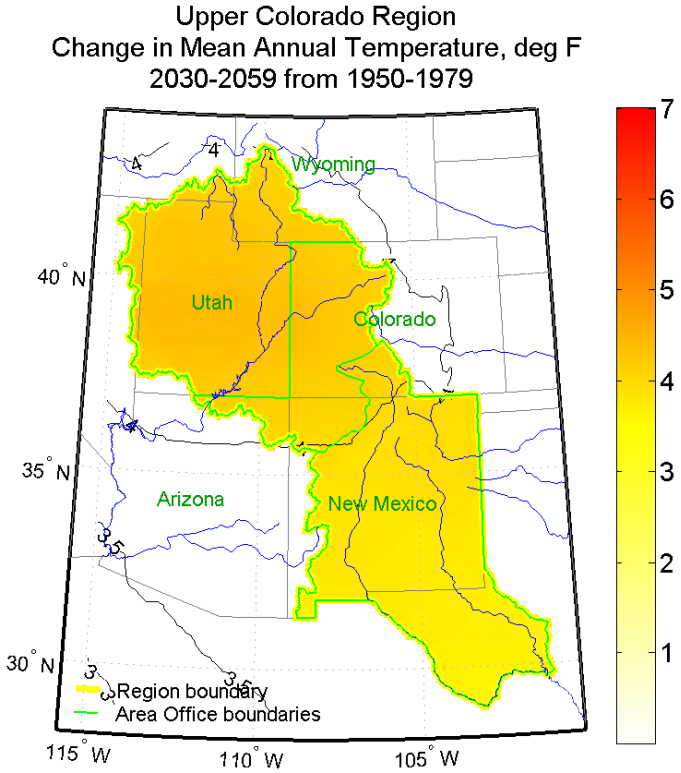

Upper Colorado Region
Change in Mean Annual Temperature, deg F
1980-2009 from 1950-1979
Wyoming
Utah
Colorado
Arizona
New Mexico
40° N
35° N
30° N
115° W
110° W
105° W
Region boundary
Area Office boundaries
7
6
5
4
3
2
1

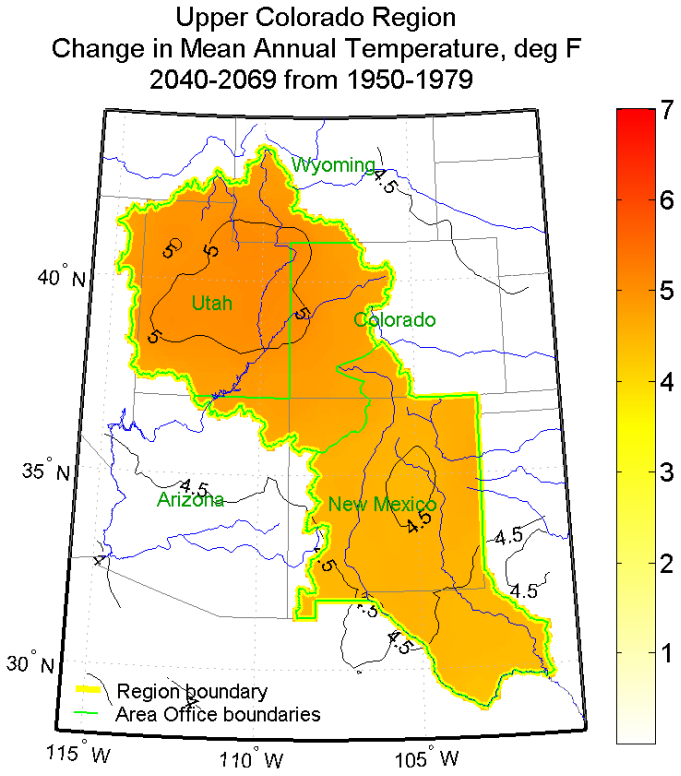

Upper Colorado Region
Change in Mean Annual Temperature, deg F
1990-2019 from 1950-1979
Wyoming
Utah
Colorado
Arizona
New Mexico
1.5
1.5
1.5
1.5
40° N
35° N
30° N
115° W
110° W
105° W
Region boundary
Area Office boundaries
7
6
5
4
3
2
1

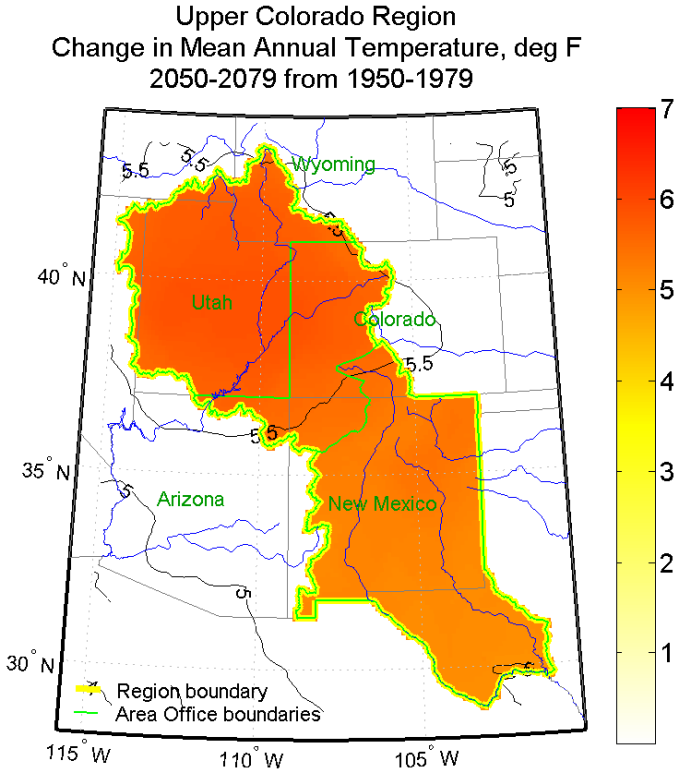

Upper Colorado Region
Change in Mean Annual Temperature, deg F
2000-2029 from 1950-1979
Wyoming
Utah
Colorado
Arizona
New Mexico
2.5
2
40° N
35° N
30° N
115° W
110° W
105° W
Region boundary
Area Office boundaries
7
6
5
4
3
2
1

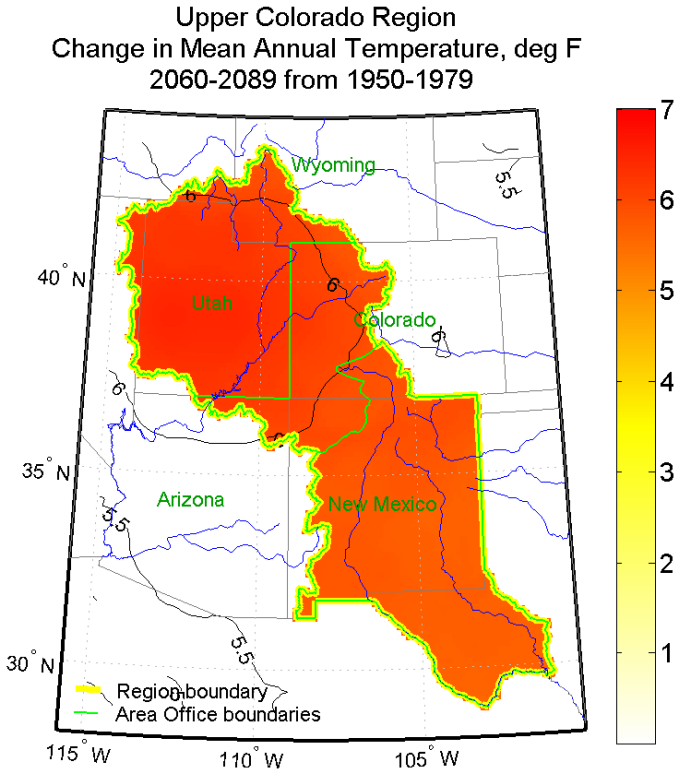

Upper Colorado Region
Change in Mean Annual Temperature, deg F
2010-2039 from 1950-1979
Wyoming
Utah
Colorado
Arizona
New Mexico
3
2.5
2
40° N
35° N
30° N
115° W
110° W
105° W
Region boundary
Area Office boundaries
7
6
5
4
3
2
1

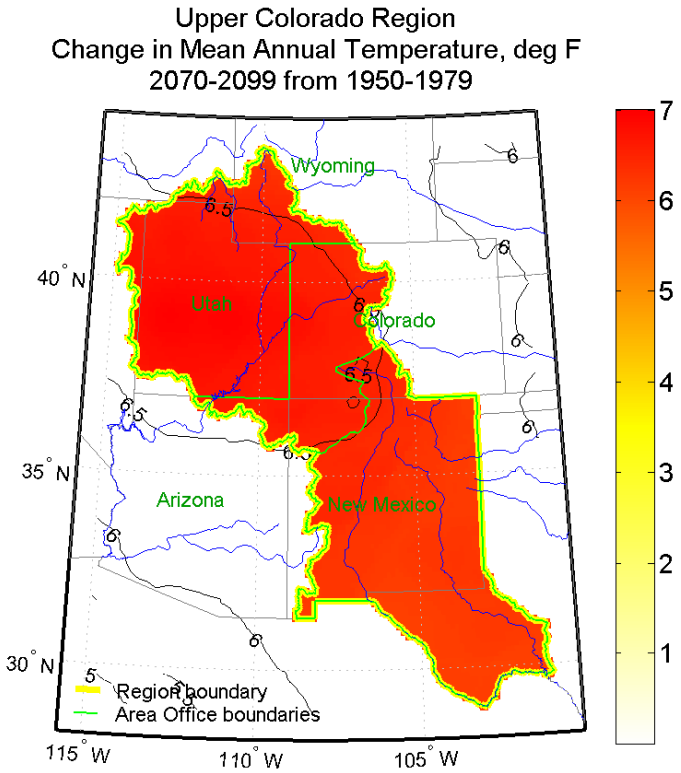

Upper Colorado Region
Change in Mean Annual Temperature, deg F
2020-2049 from 1950-1979
Wyoming
Utah
Colorado
Arizona
New Mexico
40° N
35° N
30° N
115° W
110° W
105° W
Region boundary
Area Office boundaries
7
6
5
4
3
2
1


Upper Colorado Region
Change in Mean Annual Temperature, deg F
2030-2059 from 1950-1979
Wyoming
Utah
Colorado
Arizona
New Mexico
40° N
35° N
30° N
115° W
110° W
105° W
Region boundary
Area Office boundaries
7
6
5
4
3
2
1

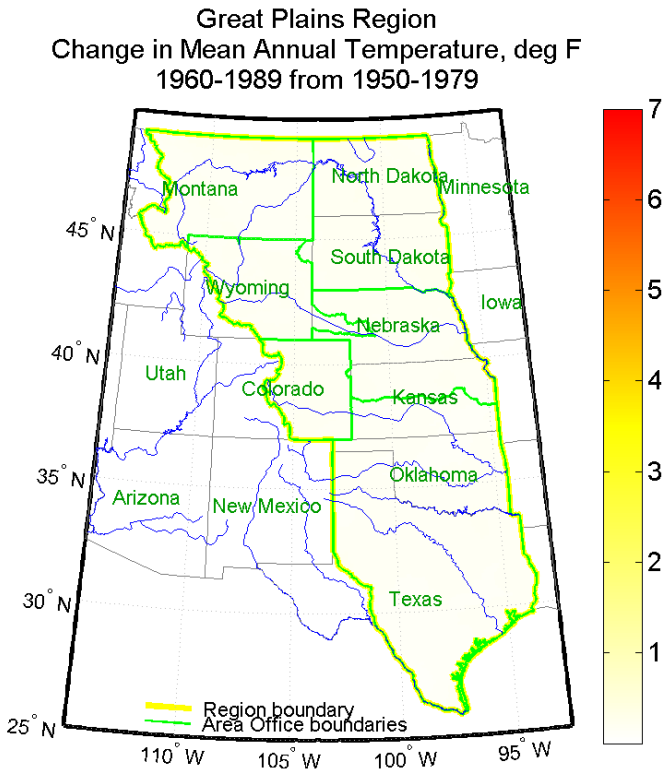

Upper Colorado Region
Change in Mean Annual Temperature, deg F
2040-2069 from 1950-1979
Wyoming
Utah
Colorado
Arizona
New Mexico
4.5
5
40° N
35° N
30° N
115° W
110° W
105° W
Region boundary
Area Office boundaries
7
6
5
4
3
2
1

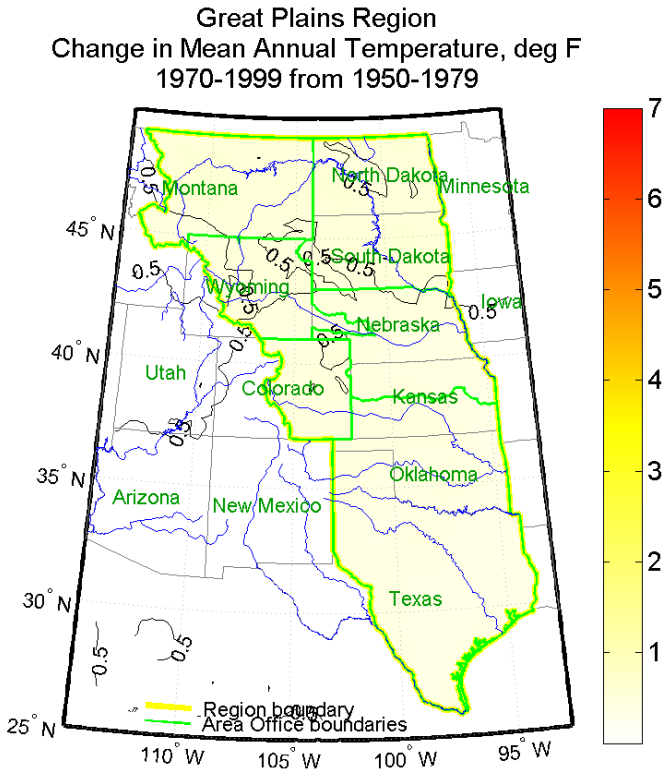

Upper Colorado Region
Change in Mean Annual Temperature, deg F
2050-2079 from 1950-1979
Wyoming
Utah
Colorado
Arizona
New Mexico
5.5
5
40° N
35° N
30° N
115° W
110° W
105° W
Region boundary
Area Office boundaries
7
6
5
4
3
2
1

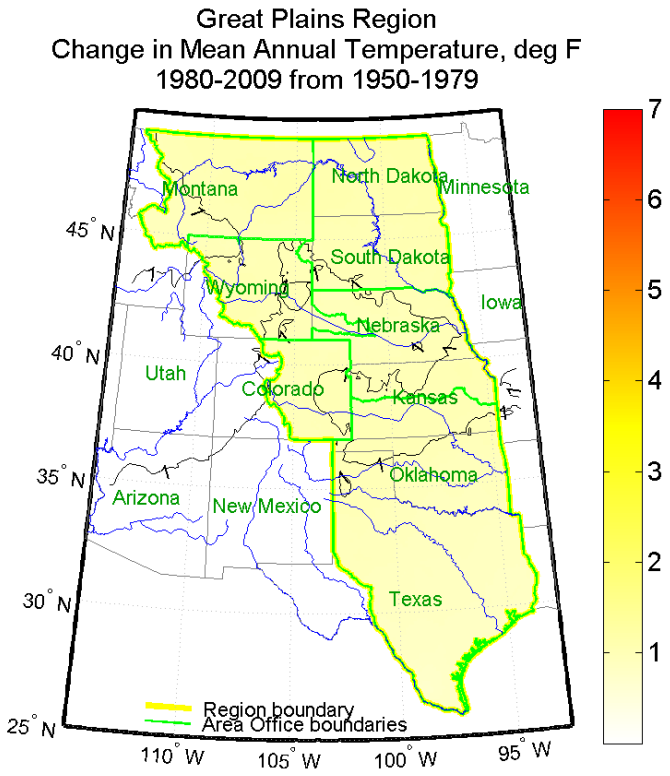

Upper Colorado Region
Change in Mean Annual Temperature, deg F
2060-2089 from 1950-1979
Wyoming
Utah
Colorado
Arizona
New Mexico
40° N
35° N
30° N
115° W
110° W
105° W
Region boundary
Area Office boundaries
7
6
5
4
3
2
1

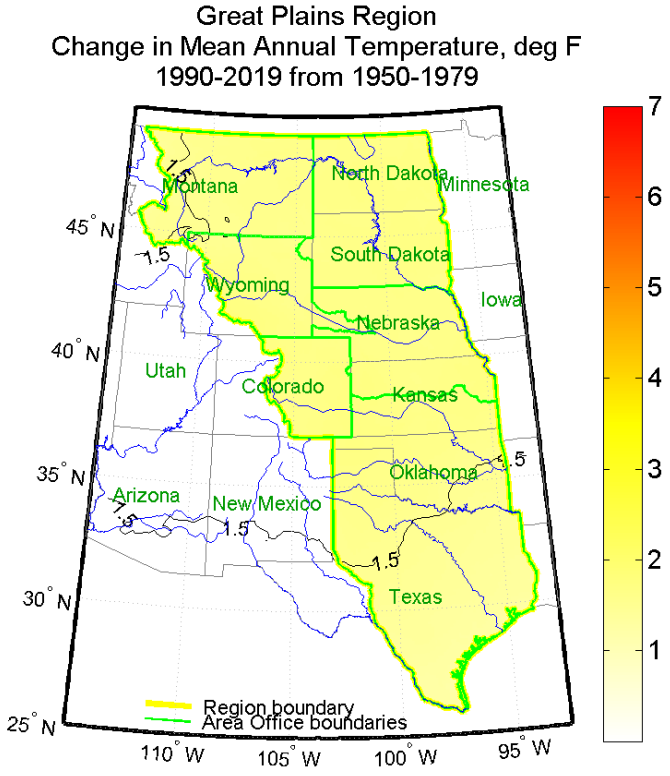

Upper Colorado Region
Change in Mean Annual Temperature, deg F
2070-2099 from 1950-1979
Wyoming
Utah
Colorado
Arizona
New Mexico
40° N
35° N
30° N
115° W
110° W
105° W
Region boundary
Area Office boundaries
7
6
5
4
3
2
1

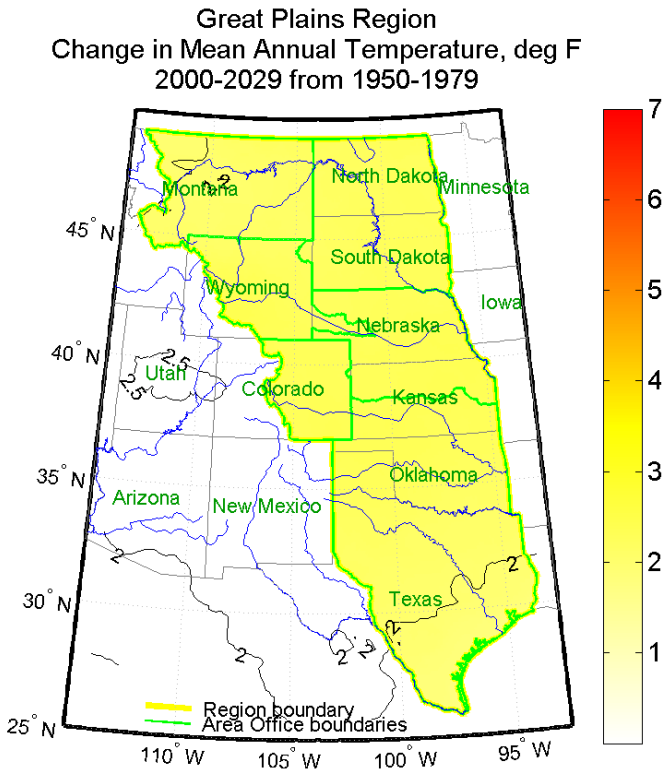
Great Plains Region – Temperature Change

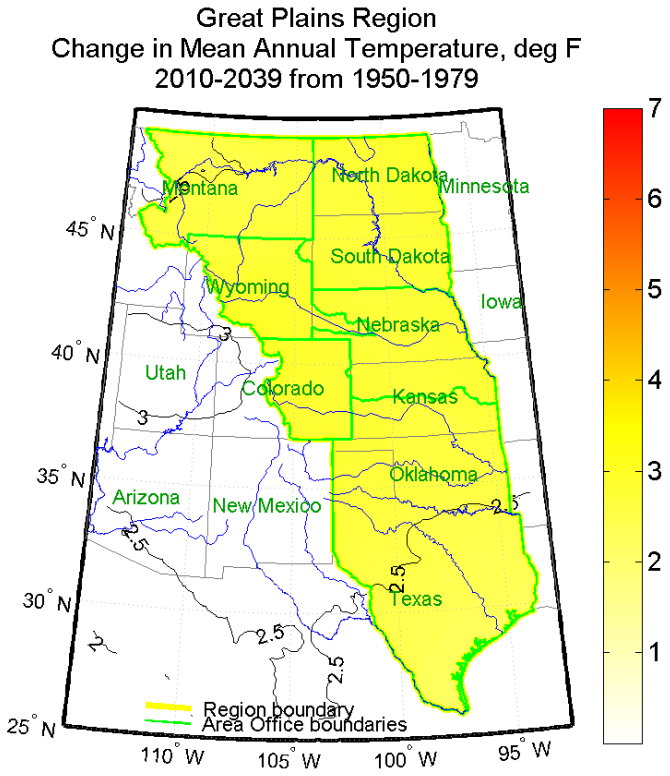

Great Plains Region
Change in Mean Annual Temperature, deg F
1960-1989 from 1950-1979
Montana
North Dakota
Minnesota
South Dakota
Wyoming
Iowa
Nebraska
Utah
Colorado
Kansas
Oklahoma
Arizona
New Mexico
Texas
Region boundary
Area Office boundaries
45° N
40° N
35° N
30° N
25° N
110° W
105° W
100° W
95° W
7
6
5
4
3
2
1

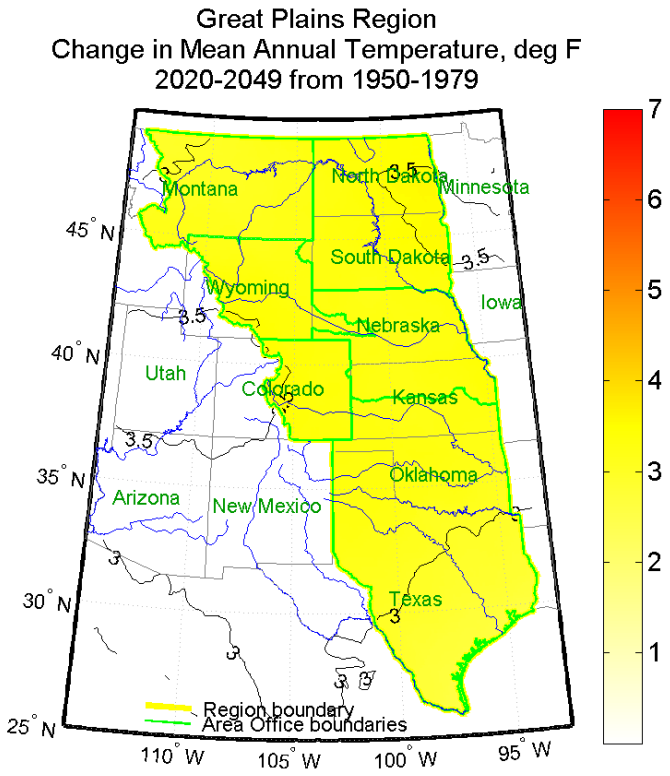

Great Plains Region
Change in Mean Annual Temperature, deg F
1970-1999 from 1950-1979
Montana
North Dakota
Minnesota
South Dakota
Wyoming
Iowa
Nebraska
Utah
Colorado
Kansas
Oklahoma
Arizona
New Mexico
Texas
0.5
-0.5
Region boundary
Area Office boundaries
45° N
40° N
35° N
30° N
25° N
110° W
105° W
100° W
95° W
7
6
5
4
3
2
1

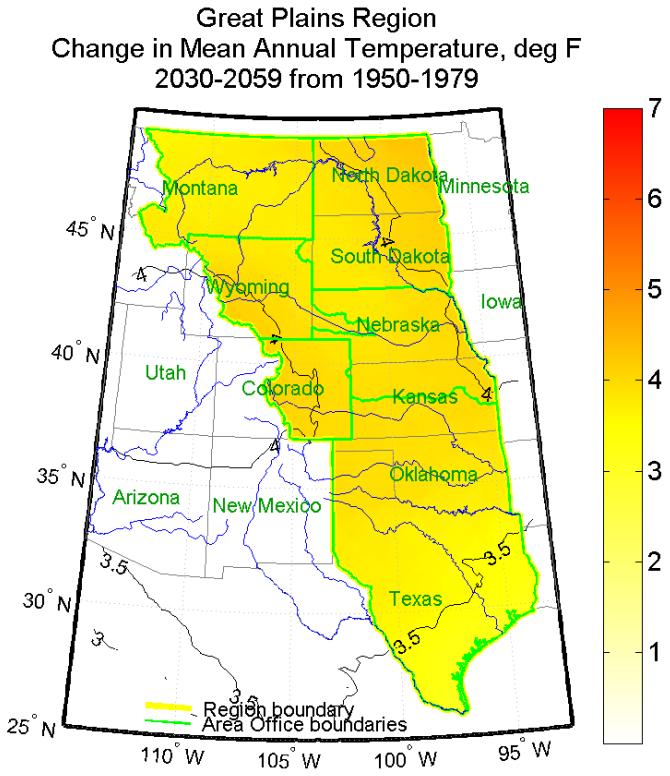

Great Plains Region
Change in Mean Annual Temperature, deg F
1980-2009 from 1950-1979
Montana
North Dakota
Minnesota
South Dakota
Wyoming
Iowa
Nebraska
Utah
Colorado
Kansas
Oklahoma
Arizona
New Mexico
Texas
45° N
40° N
35° N
30° N
25° N
110° W
105° W
100° W
95° W
Region boundary
Area Office boundaries
7
6
5
4
3
2
1


Great Plains Region
Change in Mean Annual Temperature, deg F
1990-2019 from 1950-1979
Montana
North Dakota
Minnesota
South Dakota
Wyoming
Iowa
Nebraska
Utah
Colorado
Kansas
Oklahoma
Arizona
New Mexico
Texas
1.5
45° N
40° N
35° N
30° N
25° N
110° W
105° W
100° W
95° W
Region boundary
Area Office boundaries
7
6
5
4
3
2
1


Great Plains Region
Change in Mean Annual Temperature, deg F
2000-2029 from 1950-1979
Montana
North Dakota
Minnesota
South Dakota
Wyoming
Iowa
Nebraska
Utah
Colorado
Kansas
Oklahoma
Arizona
New Mexico
Texas
Region boundary
Area Office boundaries
45° N
40° N
35° N
30° N
25° N
110° W
105° W
100° W
95° W
7
6
5
4
3
2
1


Great Plains Region
Change in Mean Annual Temperature, deg F
2010-2039 from 1950-1979
Montana
North Dakota
Minnesota
South Dakota
Wyoming
Iowa
Nebraska
Utah
Colorado
Kansas
Oklahoma
Arizona
New Mexico
Texas
Region boundary
Area Office boundaries
45° N
40° N
35° N
30° N
25° N
110° W
105° W
100° W
95° W
7
6
5
4
3
2
1


Great Plains Region
Change in Mean Annual Temperature, deg F
2020-2049 from 1950-1979
Montana
North Dakota
Minnesota
South Dakota
Wyoming
Iowa
Nebraska
Utah
Colorado
Kansas
Oklahoma
Arizona
New Mexico
Texas
3.5
3
45° N
40° N
35° N
30° N
25° N
110° W
105° W
100° W
95° W
Region boundary
Area Office boundaries
7
6
5
4
3
2
1


Great Plains Region
Change in Mean Annual Temperature, deg F
2030-2059 from 1950-1979
Montana
North Dakota
Minnesota
South Dakota
Wyoming
Iowa
Nebraska
Utah
Colorado
Kansas
Oklahoma
Arizona
New Mexico
Texas
4
3.5
45° N
40° N
35° N
30° N
25° N
110° W
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Region boundary
Area Office boundaries
7
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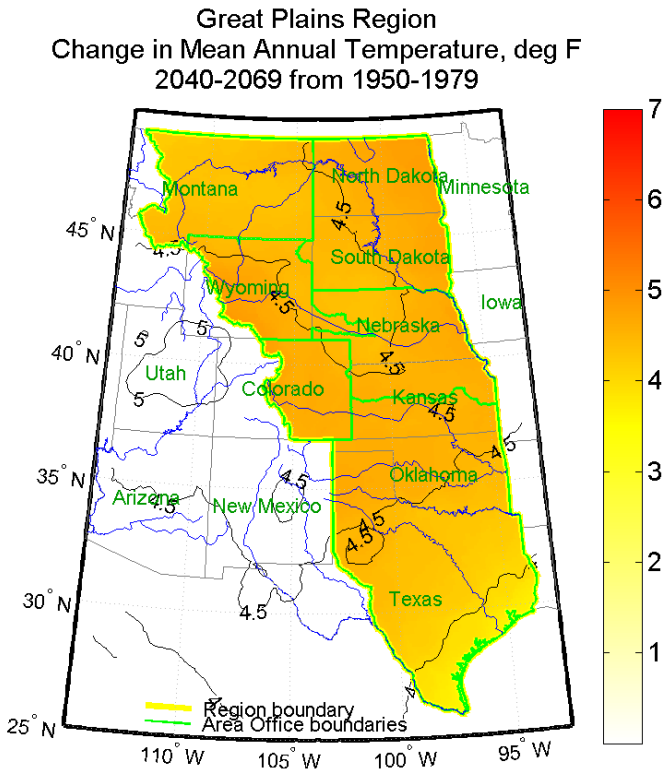
Great Plains Region
Change in Mean Annual Temperature, deg F
2040-2069 from 1950-1979
Montana
North Dakota
Minnesota
South Dakota
Wyoming
Iowa
Nebraska
Utah
Colorado
Kansas
Oklahoma
Arizona
New Mexico
Texas
Region boundary
Area Office boundaries
45° N
40° N
35° N
30° N
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110° W
105° W
100° W
95° W
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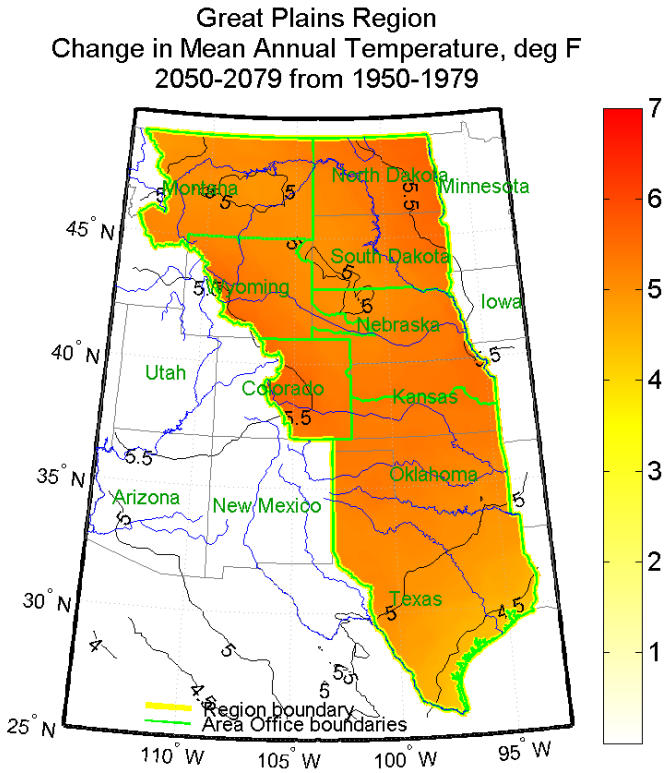
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Change in Mean Annual Temperature, deg F
2050-2079 from 1950-1979
Montana
North Dakota
Minnesota
South Dakota
Wyoming
Iowa
Nebraska
Utah
Colorado
Kansas
Oklahoma
Arizona
New Mexico
Texas
Region boundary
Area Office boundaries
45° N
40° N
35° N
30° N
25° N
110° W
105° W
100° W
95° W
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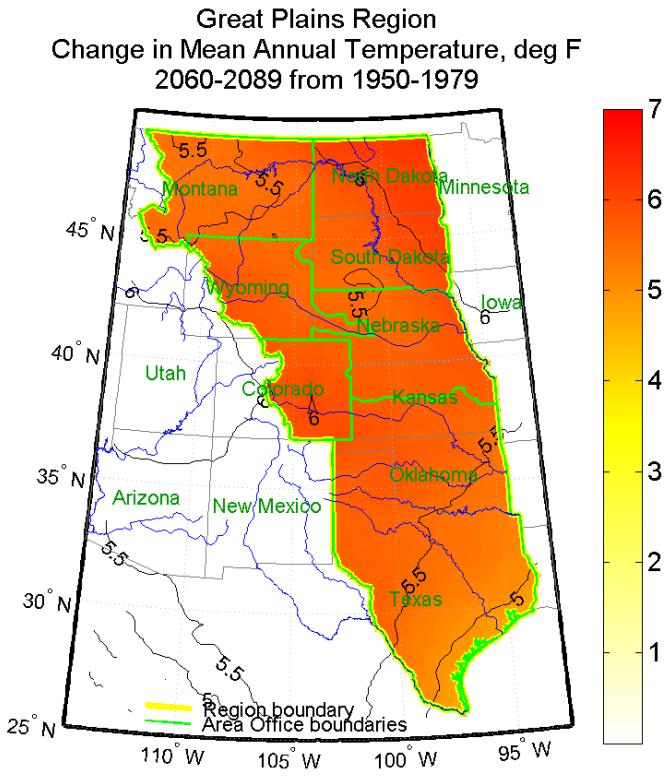
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Change in Mean Annual Temperature, deg F
2060-2089 from 1950-1979
Montana
North Dakota
Minnesota
South Dakota
Wyoming
Iowa
Nebraska
Utah
Colorado
Kansas
Oklahoma
Arizona
New Mexico
Texas
Region boundary
Area Office boundaries
45° N
40° N
35° N
30° N
25° N
110° W
105° W
100° W
95° W
1
2
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4
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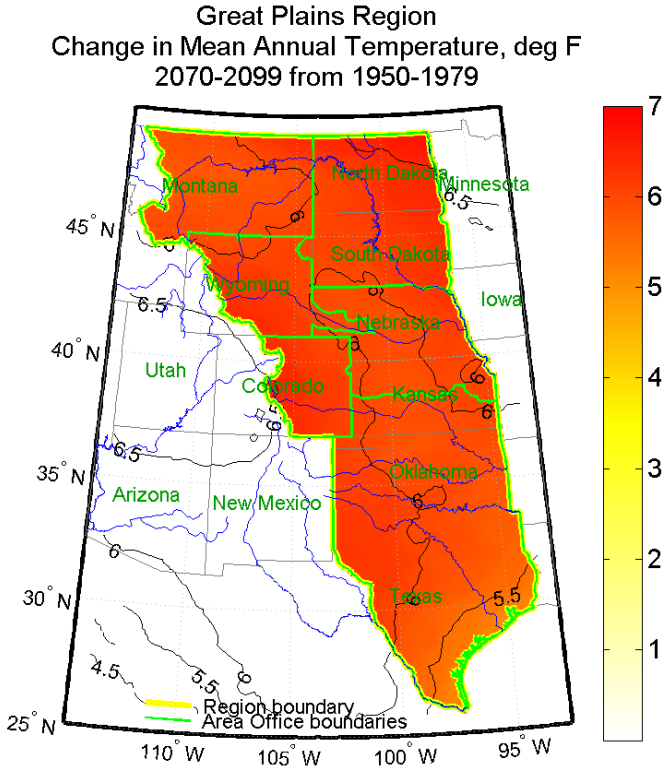
Great Plains Region
Change in Mean Annual Temperature, deg F
2070-2099 from 1950-1979
Montana
North Dakota
Minnesota
South Dakota
Wyoming
Iowa
Nebraska
Utah
Colorado
Kansas
Oklahoma
Arizona
New Mexico
Texas
Region boundary
Area Office boundaries
45° N
40° N
35° N
30° N
25° N
110° W
105° W
100° W
95° W
1
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4
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Appendix C. Glossary of Terms

Anthropogenic: Resulting from or produced by human beings.

Atmosphere-Ocean General Circulation Model (AOGCM): See Climate Model.

Bias correction: Simulations or forecasts of climate from dynamical models such as *AOGCMs* do not precisely correspond to reality (i.e., observations), thus, resulting in 'bias'. There are statistical methods to correct this and often referred to as 'bias correction' methods. Typically, they involve fitting a statistical model between the dynamical model simulations and the observations over a period. The fitted statistical model is used to correct future model simulations.

Climate (International Panel on Climate Change [IPCC], 2007): Climate, in a narrow sense, usually is 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 defining a climate normal is 30 years, as defined by the World Meteorological Organization. The relevant quantities for water resources are most often surface or near-surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system. Beginning with the view of local climate as little more than the annual course of long-term averages of surface temperature and precipitation, the concept of climate had broadened and evolved in recent decades in response to the increased understanding of the underlying processes that determine climate and its variability.

Climate Change (IPCC, 2007): Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external *forcings* or to persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: “a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.” The UNFCCC, thus, makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes. See also **Climate variability**.

Climate Model (IPCC, 2007): 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. 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.

> **Atmosphere-Ocean General Circulation Model (AOGCM)** (IPCC, 2007)**:** 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. These models simulate atmosphere and ocean circulation and their interactions with each other, land, and cryospheric processes. Simulations are forced by several factors, including time series assumptions on atmospheric greenhouse gas and aerosol concentrations.
>
> **General Circulation Models (GCMs):** Abbreviated term that could mean AOGCM, atmospheric global climate model (GCM) with specified ocean boundary condition (AGCM), ocean GCM with specified atmospheric boundary condition (OGCM), or global climate model which could be any of the aforementioned.

Climate Projection (IPCC, 2007): 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 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.

Climate System (IPCC, 2007): The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the land surface and the biosphere, and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations, and anthropogenic forcings such as the changing composition of the atmosphere and land-use change.

Climate Variability (IPCC, 2007): 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). See also **Climate change**.

Coupled Model Intercomparison Project phase 3 (CMIP3): In response to a proposed activity of the World Climate Research Programme's (WCRP's) Working Group on Coupled Modelling (WGCM), the Program for Climate Model Diagnosis and Intercomparison (PCMDI) volunteered to collect model output contributed by leading modeling centers around the world. Climate model output from simulations of the past, present, and future climate was collected by PCMDI mostly during the years 2005 and 2006, and this archived data constitutes phase 3 of the Coupled Model Intercomparison Project (CMIP3). In part, the WGCM organized this activity to enable those outside the major modeling centers to perform research of relevance to climate scientists preparing the Fourth Asssessment Report (AR4) of the IPCC.

Downscaling: This is the process of spatially translating relatively coarse-scale *climate projection* output from *AOGCMs* to a relatively fine-scale resolution that is often necessary for regional impacts assessment. The process can involve simulating atmospheric conditions at a finer spatial scale (i.e., dynamical downscaling), or it can involve identifying *empirical* relationships between finer-scale surface climate and coarse-scale output from the *AOGCMs* (i.e., statistical downscaling). Downscaling is a separate issue from *bias-correction*, which involves identifying and accounting for AOGCM tendencies to simulate climate that differs from observations (e.g., historical climate simulations that are too warm, cool, wet, or dry relative to observations).

Drought: A period of abnormally dry weather or below-normal runoff that is sufficiently long enough to cause stress for a given resource system (e.g., surface water supply versus demand, soil moisture availability versus plant water needs). Drought is a relative term; therefore, any discussion in terms of precipitation or hydrologic deficit must refer to the particular resource system in question.

Empirical: Relying upon or derived from observation or experiment; based on experimental data, not on a theory.

El Niño-Southern Oscillation (ENSO) (IPCC, 2007): The term El Niño initially was 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 2 to about 7 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.

Forcings: Factors influencing dynamic response in a system. For example, precipitation and temperature conditions drive hydrologic dynamics in a watershed and might be thought of as *forcings* on the watershed hydrologic system. In a modeling sense, *forcings* are often the input time series boundary conditions creating the dynamical system response during simulation (i.e., input time series assumptions for precipitation and temperature would be the meteorological *forcings* for the hydrologic simulation).

General Circulation Models (GCMs): See Climate Model.

Greenhouse Gas (GHG) (IPCC, 2007): 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 (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere. Moreover, there are a number of entirely human-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. Beside CO_2, N_2O, and CH_4, the Kyoto Protocol deals with the greenhouse gases sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs).

GHG emission scenario (IPCC 2007): A plausible representation of the future development of emissions of substances that are could contribute to *radiative forcing* (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 (Nakićenović and Swart, 2000) 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 IPCC (2007). See **SRES scenarios**.

Groundwater: Subsurface water that occupies the zone of saturation; thus, only the water below the water table, as distinguished from interflow and soil moisture.

Hydrology: The scientific study of the waters of the earth, especially with relation to the effects of precipitation and evaporation upon the occurrence and character of water in streams, lakes, and on or below the land surface.

Impaired inflows: In contrast to *natural flows*, these are reservoir or water system inflows affected by an upstream combination of natural runoff, human use, diversion, management, and/or allocation.

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

IPCC Fourth Assessment Report: The Fourth Assessment Report (AR4) "Climate Change 2007," 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.

Interpolation: The estimation of unknown intermediate values from known discrete values of a dependent variable.

Lees Ferry: A reference point in the Colorado River 1 mile below the mouth of the Paria River in Arizona which marks the division between Upper Colorado and Lower Colorado River Basins.

Million acre-feet (MAF): The volume of water that would cover 1 million acres to a depth of 1 foot.

National Environmental Policy Act (NEPA): The National Environmental Policy Act requires Federal agencies to integrate environmental values into their decisionmaking processes by considering the environmental impacts of their proposed actions and reasonable alternatives to those actions. To meet this requirement, Federal agencies prepare a detailed statement known as an environmental impact statement (EIS), disclosing the environmental effects of the proposed action being considered.

Natural Flow: Streamflow that has not been affected by upstream human activity, water diversions, or river regulation; also called virgin flows.

Paleoclimate (or "Paleo"): Climate during the period prior to the development of measuring instruments. This period includes historical and geologic time, for

which only proxy climate records are available. (Paleoclimatolgoy: The study of past climate throughout geologic and historic time and the causes of their variations.)

Paleo Streamflow Reconstruction: Using analyses from tree ring reconstructions, streamflow volumes prior to the gauge record can be estimated using a statistical model, which captures the relationship between tree growth and the gauge record during their period of overlap. Then, this model is applied to the tree ring data for the period prior to the gauge record.

Parts per million (ppm): Parts per million denotes one particle of a given substance for every 999,999 other particles.

Pacific Decadal Oscillation (PDO): See Pacific Decadal Variability.

Pacific Decadal Variability (IPCC, 2007): Coupled decadal-to-interdecadal variability of the atmospheric circulation and underlying ocean in the Pacific Basin. It is most prominent in the North Pacific, where fluctuations in the strength of the winter Aleutian Low pressure system co-vary with North Pacific sea surface temperatures and are linked to decadal variations in atmospheric circulation, sea surface temperatures, and ocean circulation throughout the whole Pacific Basin. Such fluctuations have the effect of modulating the El Niño-Southern Oscillation cycle. Key measures of Pacific decadal variability are the North Pacific Index (NPI), the Pacific Decadal Oscillation (PDO) index and the Interdecadal Pacific Oscillation (IPO) index.

Quantile: A generic term for any fraction that divides a collection of observations arranged in order of magnitude into two or more specific parts.

Radiative Forcing: Radiative forcing is the change in the net, downward minus upward, irradiance at the atmosphere's tropopause due to a change in an external driver of climate change, such as, for example, a change in the concentration of carbon dioxide or a change in solar output (IPCC, 2007). A net change in the irradiance causes change in other climate system conditions (e.g., the temperature changes accordingly).

Riparian: Of, on, or pertaining to the bank of a river, pond, or lake.

Shortage: In a given watershed, a water supply deficit relative to demands, attributed to below average streamflow volumes due to natural or managerial attributions.

Snow-water equivalent (SWE): The amount of water contained within the snowpack. It can be thought of as the depth of water that theoretically would result if you melted the entire snowpack instantaneously. SWE typically is measured by pushing a "snow tube" into the snowpack to measure the height of

the snow. The tube is then carefully lifted with the snow inside and weighed on a calibrated scale which gives the SWE directly.

SRES scenarios (IPCC, 2007): SRES scenarios are *GHG emission scenarios* developed by Nakićenović and Swart (2000) and used, among others, as a basis for some of the *climate projections* shown in IPCC, 2007. The following terms are relevant for a better understanding of the structure and use of the set of SRES scenarios:

> **Storyline:** A narrative description of a scenario (or family of scenarios), highlighting the main scenario characteristics, relationships between key driving forces, and the dynamics of their evolution.
>
> **Scenario family***:* Scenarios that have a similar demographic, societal, economic, and technical change storyline. Four scenario families comprise the SRES scenario set: A1, A2, B1 and B2. Generally speaking, the A1 scenarios are of a more integrated world. The A2 scenarios are of a more divided world. The B1 scenarios are of a world more integrated and more ecologically friendly. The B2 scenarios are of a world more divided but more ecologically friendly.
>
> **Illustrative Scenario:** A scenario that is illustrative for each of the six scenario groups reflected in the "Summary for Policymakers" of Nakićenović and Swart (2000). They include four revised scenario markers for the scenario groups A1B, A2, B1, B2 and two additional scenarios for the A1FI and A1T groups. All scenario groups are equally sound.

Stochastic hydrology: The science that pertains to the probabilistic description and modeling of the value of hydrologic phenomena, particularly the dynamic behavior and the statistical analysis of records of such phenomena.

Storage: The retention of water or delay of runoff either by planned operation, as in a reservoir, or by temporary filling of overflow areas, as in the progression of a flood wave through a natural stream channel.

Temporal: Of, relating to, or limited by time, i.e., temporal boundaries.

Variable Infiltration Capacity (VIC) model: VIC is a macroscale hydrologic model that solves full water and energy balances. VIC is a research model; and in its various forms, it has been applied to many watersheds including the Columbia River, the Ohio River, the Arkansas-Red Rivers, and the Upper Mississippi Rivers as well as being applied globally.

Water balance (Water budget): A summation of inputs, outputs, and net changes to a particular water resource system over a fixed period.

Watershed: All the land and water within the confines of a certain water drainage area; the total area drained by a river and its tributaries.

Water supply: Process or activity by which a given amount of water is provided for some use (e.g., municipal, industrial, and agricultural).

Water year: A continuous 12-month period selected to present data relative to hydrologic or meteorological phenomena during which a complete annual hydrologic cycle normally occurs. The water year used by the U.S. Geological Survey runs from October 1 through September 30 and is designated by the year in which it ends.