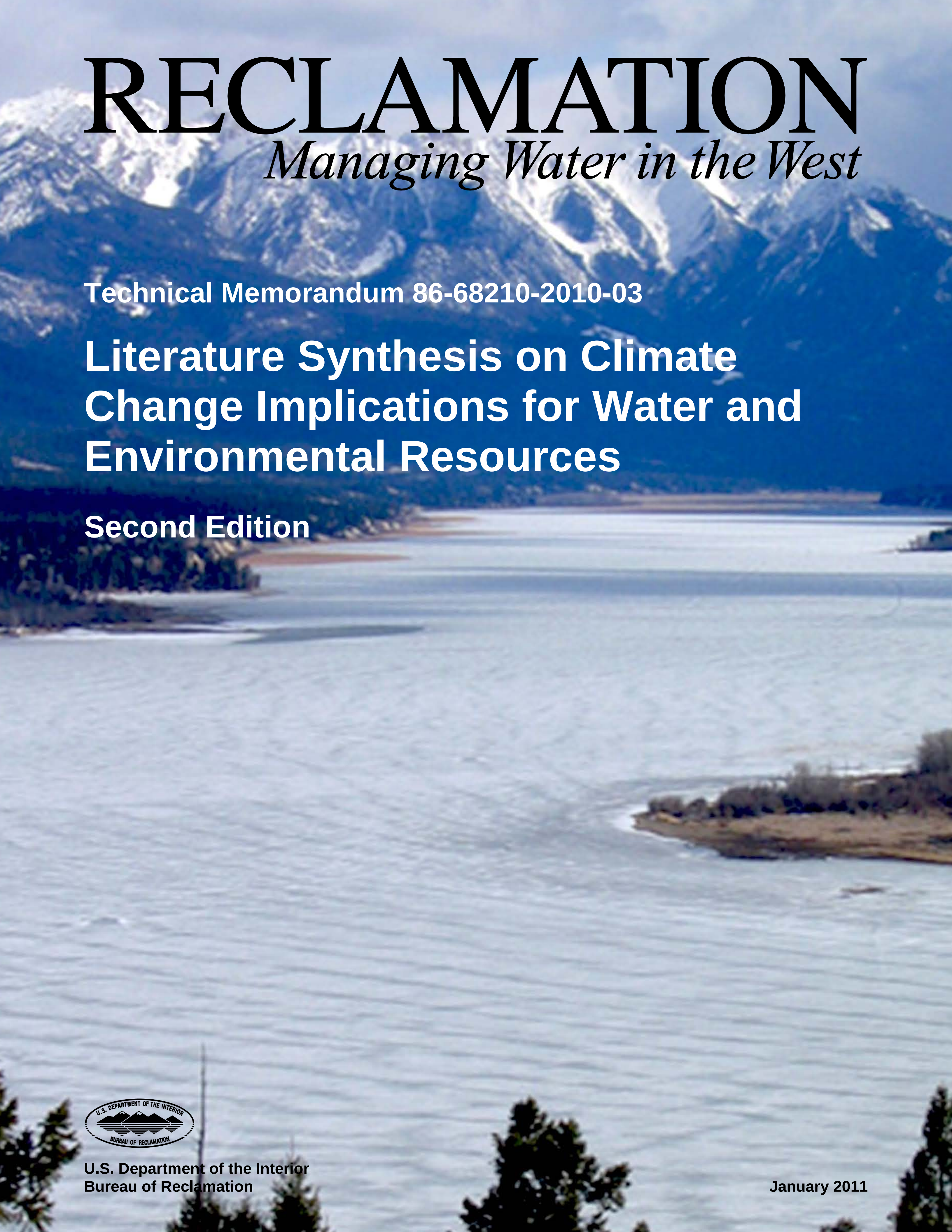

RECLAMATION
Managing Water in the West

Technical Memorandum 86-68210-2010-03

Literature Synthesis on Climate Change Implications for Water and Environmental Resources

Second Edition

U.S. Department of the Interior
Bureau of Reclamation

January 2011

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

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.

Technical Memorandum 86-68210-2010-03

Literature Synthesis on Climate Change Implications for Water and Environmental Resources

Second Edition

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U.S. Department of the Interior
Bureau of Reclamation
Research and Development Office
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Acronyms

AOGCM – Atmosphere-Ocean General Circulation Model
AR4 – the IPCC’s Fourth Assessment Report
CA DWR – California Department of Water Resources
CAT – Climate Action Team
CBO – Congressional Budget Office
C-CAWWG – Climate Change and Western Water Group
CCSP – Climate Change Science Program
CIG – Climate Impacts Group
CIMIS – California Irrigation Management Information System
CLIMAS – Climate Assessment for the Southwest
cm – centimeter
CMIP – Coupled Model Intercomparison Project
CMIP3 – Coupled Model Intercomparison Project phase 3 (see Appendix C, Glossary of Terms)
CNAP – California Nevada Applications Program CNAP
CO_2 – carbon dioxide
COOP – Cooperative Observer Program
CRSS – Colorado River Storage System
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
GCM – global climate model or general circulation model (see Appendix C, Glossary of Terms, Climate Model)
GFDL – Geophysical Fluid Dynamics Laboratory
GHG – greenhouse gas (see Appendix C, Glossary of Terms)
GP – Great Plains
IPCC – International Panel on Climate Change
IPO – Interdecadal Pacific Oscillation
ISB – Independent Science Board
LC – Lower Colorado
MAF – million acre-feet (see Appendix C, Glossary of Terms)

MP – Mid-Pacific
NCAR – National Center for Atmospheric Research
NEPA – National Environmental Policy Act (see Appendix C, Glossary of Terms)
NPI – North Pacific Index
NOAA – National Oceanic and Atmospheric Administration
PCM – Parallel Climate Model
PCMDI – Program for Climate Model Diagnosis and Intercomparison
PDO – Pacific decadal oscillation (see Appendix C, Glossary of Terms)
PDSI – Palmer Drought Severity Index
PN – Pacific Northwest
PRISM – Precipitation Regression on Independent Slopes Method
R&D – research and development
Reclamation – Bureau of Reclamation
RISA – regional integrated sciences and assessments
SAP – Synthesis and Assessment Product
SCIPP – Southern Climate Impacts Planning Program
SFE –snowfall liquid water equivalent
Shortage Guidelines FEIS – Final Environmental Impact Statement, Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead
SRES – Special Report on Emissions Scenarios
SST – sea surface temperature
SWE – snow water equivalent (see Appendix C, Glossary of Terms)
Tmin – minimum temperature
UC – Upper Colorado
UNEP - United Nations Environmental Programme
UNFCCC – Framework Convention on Climate Change
U.S. – United States
USGS – United States Geological Survey
USHCN – United States Historical Climatology Network
VEMAP – Vegetation/Ecosystem Modeling and Analysis Project
VIC – Variable Infiltration Capacity Model (see Appendix C, Glossary of Terms)
WACCIA – Washington Climate Change Impacts Assessment
WCRP – World Climate Research Programme
WMO – World Meteorological Organization
WWA – Western Water Assessment
°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 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 reflect 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 Water Work Group (C-CAWWG).[1] 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 and water resources impacts in the United States.

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[1] Originally, C-CAWWG had a Western United States focus, stood for Climate Change and Western Water Group, and consisted of three Federal entities: Reclamation, the U.S. Geological Survey (USGS), and National Oceanic and Atmospheric Administration (NOAA). Since 2009, C-CAWWG interests have broadened to a national view with membership now including the U.S. Army Corps of Engineers, U.S. Environmental Protection Agency and the Federal Emergency Management Agency.

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 (later documented in USGS Circular 1331 [Brekke et al. 2009a]). 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. The first such review was completed in September 2009 (Reclamation 2009). This document is the second issue and maintains with the original issue's synthesis framework. Key changes in this update include the representation of new literature published since approximately mid-2008 and also featuring additional synthesis in under-represented areas or sectors from the 2009 issue, as indicated in the next section.

1.2 About This Document

The scope of this 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 then to 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, water resources, and environmental 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. The following list provides a brief overview of document contents.

Chapter 1 provides context for document scope and intent. The synthesis is meant to tell a representative story covering significant climate change literature from the last couple of decades, but it does not provide an exhaustive citation of all the literature.

Chapters 2 and 3 offer Reclamation region-specific “starting-point” narratives for including climate change background in planning documents associated with NEPA and ESA compliance.

Chapter 4 discusses graphical resources in Appendix B that show a central-tendency of projected climate changes over the each Reclamation region. It is significant to note that there are many ways to graphically package the projected climate information—this is only one way.

Chapter 5 is a bibliography of all cited references.

Appendix A provides a tabulated summary of all cited and related literature and an associated comprehensive bibliography.

Appendix B provides map resources which describe geographic climate change information evident in current climate projections. The data used to generate Appendix B are at: http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/dcpInterface.html.

Appendix C offers a glossary.

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.

It is envisioned that the various sections of the report will be used by Reclamation staff as boilerplate narratives, and the authors invite these staff to use these narratives as a starting point for literature review sections in their planning documents (e.g., NEPA environmental impact statements, biological assessments under Federal/State ESA, general planning feasibility studies). In such applications, study teams may wish then to abbreviate or augment these starting narratives, depending on the needs of the given study document.

This 2010 version of the report generally is informed by literature surveyed through summer 2010. As with the first issue (Reclamation 2009), this synthesis update was subjected to external review provided by staff from each of the five western NOAA Regional Integrated Sciences and Assessments (RISAs) located in the Western United States (http://www.climate.noaa.gov/cpo_pa/risa/: Climate

Impacts Group [CIG][2], Climate Assessment for the Southwest [CLIMAS], California Nevada Applications Program CNAP, Western Water Assessment [WWA], and Southern Climate Impacts Planning Program [SCIPP]). Reviews of the first issue also were conducted by staff from each of Reclamation's regional offices.[3] When the first issue was released, it was emphasized that it provided an initial synthesis and that the report would be a living document undergoing annual updates. It also was noted that readers may have found the content in Reclamation (2009) to be sparse for some resource and geographic areas. Attempts were made during this synthesis update to address such areas (e.g., climate change impacts on ecosystems and water demands and climate change impacts for the eastern Great Plains Region).

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[2] CIG was formerly funded by RISA, although they are no longer a RISA.

[3] Reclamation regional offices reviewers included: Stephen Grabowski and Robert Hamilton, Pacific Northwest Region; Michael Tansey, Mid-Pacific Region; Carly Jerla, Lower Colorado Region; Nancy Coulam, Katrina Grantz and Jim Prairie, Upper Colorado Region; and Gary Davis, Great Plains Region.

2.0 Literature Summary

This chapter presents a synthesis of climate change literature relevant to hydrology and water and environmental 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. Contrasting from other regions' summaries, the summaries for Mid-Pacific Region also include a discussion on sea level rise.

While the authors attempted to craft consistent narratives across the regions, the disparity of literature and different review emphases led to some differences in content between the narratives. For example, note the additional wealth of information in on the Lower Colorado (LC) Region studies of historical drought (section 2.3.1) critique of climate models' projections over the LC Region (section 2.3.2). It is intended to create parallel discussions for the other regions with more consistent narratives in the next edition of this 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 (1994–2010) demonstrating evidence of regional climate change during the 20th century and exploring water and environmental resources impacts associated with various climate change scenarios.

2.1.1 Historical Climate and Hydrology

Over the course of the 20th century, it appears that all areas of the PN Region became warmer, and some areas received more winter precipitation. Cayan et al. (2001) report 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) report increased winter precipitation trends during 1950–1999 at many Western United States 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 United States stations (Knowles et al. 2007). Regonda et al. (2005) evaluated 1950–1999 data from 89 stream gauges in the Western United States and reports trends of earlier peak runoff at most stations during the period, and significant trends toward earlier runoff were found in the Pacific Northwest. Luce and Holden (2009) report on distribution of streamflow reductions observed during 1948–2006, showing significant trends in annual streamflow reductions during dry years.

Villarini et al. (2009) analyzed annual peak discharge records from 50 stations in the United States with 100 years of record and attempted to document reduced stationarity. However, their results were equivocal, due to evidence of human modifications affecting runoff generation (e.g., changes in land use and land cover), fluvial transportation (e.g., construction of dams and pools), and changes in measurements, all of which can induce nonclimatic nonstationarity. Consequently, they reported that they were "not able to assess whether the observed variations in annual maximum instantaneous peak discharge were due to natural climate variability or anthropogenic climate change."

Focusing on changes in precipitation extremes, the former U.S. Climate Change Science Program issued Synthesis and Assessment Product (SAP) 3.3 (CCSP 2008), wherein chapter 3 focuses on mechanisms for observed changes in extremes and reports that heavy precipitation events averaged over North America have increased over the past 50 years (Gutowski et al. 2008). Kunkel (2003) presents an analysis of extreme precipitation events and indicates there has been an increase in their frequency since the 1920s/1930s in the United States. Madsen and Figdor (2007) evaluated 1948–2006 trends in extreme precipitation events for each State using the method of Kunkel et al. (1998) and report similar findings. Rosenberg et al. (2010) examined both historical precipitation records and simulations of future rainfall to evaluate past and prospective changes in the probability distributions of precipitation extremes across Washington State and found evidence suggesting that drainage infrastructure designed using mid-20th century rainfall records may be subject to a future rainfall regime that differs from current design standards. Extreme runoff due to changes in the statistics of extreme events will present flood control challenges to varying degrees at many locations.

It is important to note that linear trends in hydrologically important variables (including springtime SWE, indices of runoff timing, and surface air temperature) depend on the time period considered in the analysis. Mote et al. (2008), for instance, show that SWE trends for the Washington and Oregon Cascades computed with an end date of 2006 and a start date within a decade of 1955 are robust, while those computed through 2006 from later start dates differ dramatically (but 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 climate variations on interdecadal time scales and longer-term anthropogenic trends that are part of many climate records for the 20th century.

On explaining historical trends in regional climate and hydrology, chapter 4 of the U.S. Climate Change Science Program[4] SAP 4.3 discusses several studies that indicate most observed trends for SWE, soil moisture, and runoff in the Western United States are the result of increasing temperatures rather than precipitation effects (Lettenmaier et al. 2008). This assertion is supported by a collection of journal articles that targeted 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 naturally originating climate variations in explaining observed trends. 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 1950–1999 co-vary. They concluded, with a high statistical significance, that up to 60 percent (%) 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; Hidalgo et al. (2009) for streamflow timing changes; and Das et al. (2009) for temperature, snow/rain days ratio, SWE, and 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. 2009).

While the trends in Western United States river flow, winter air temperature, and snow pack might be partially explained by anthropogenic influences on climate, Hoerling et al. (2010) show that it remains difficult to attribute historical precipitaton variability to anthropogenic forcings. They evaluated regional precipitation data from around the world (observed and modeled) for 1977–2006. They suggest that the relationship between sea temperatures and rainfall changes are generally not symptomatic of human-induced emissions of greenhouse gases and aerosols. Rather, their results suggest that trends during this period are consistent with atmospheric response to observed sea surface temperature variability. Shin and Sardeshmukh (2010) show that the 20th century trends in the Palmer Drought Severity Index (PDSI) are consistent with forcing by tropical sea-surface temperature (SST) trends and discuss that the SST trends are due to a combination of natural and anthropogenic forcing. These two studies reinforce the fact that tropical SSTs can act as a “middleman” for anthropogenic climate change in the West.

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[4] Now known as the U.S. Global Change Research Program.

McAfee and Russell (2008) examined connections between the observed poleward migration of the Northern Hemisphere storm track (a global warming response suggested by current climate projections, sometimes referred to as Hadley Cell expansion [Seager et al. 2007]), atmospheric circulation over North America, and precipitation and temperature responses in the Western United States. They found that during the transition to spring, following a Northern Annular Mode (also called Arctic Oscillation) high-index winter, which is associated with poleward storm track shift, there is a weakening of the storm track over the northeastern Pacific, resulting in warmer and drier conditions west of the Rocky Mountains. They note that these results are consistent with observations of early spring onset in the Western United States.

Several recent studies have examined the climate sensitivity of snowpack in Washington’s Cascade Mountains. Stoelinga et al. (2010) and Smoliak et al. (2010) estimated the contribution of variations in circulation patterns to the observed trends and interannual variations in Cascade Mountain snowpack over the 1930–2007 period. Using similar regression techniques, Stoelinga et al. (2010) identified three atmospheric circulation patterns that account for 71% of the variance in their springtime snowpack time series, while Smoliak et al. (2010) identified two circulation patterns that account for 70% of the variance in the same snowpack timeseries. Casola et al. (2009) used scaling arguments to estimate the sensitivity of Cascades springtime snowpack to be a 16% loss per °C of warming. Minder (2010) used idealized, physically based models of mountain snowfall to simulate Cascade Mountains snowpack accumulation under current and warmed climates, estimated a 14.8–18.1% loss per °C warming, and noted that circulation changes might influence the loss of mountain snowpack under climate warming via impacts on orographic precipitation enhancement. Moreover, Stewart (2009) examined global snowpack and melt responses and noted that the greatest responses have been observed for areas that remain close to freezing throughout the winter season.

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 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.

2.1.2 Climate Change Impacts on Hydrology and Water Resources

Several studies have been conducted to relate potential future climate scenarios to PN Region runoff and water resources management impacts. A recent paper by the Congressional Budget Office (CBO) (CBO 2009) presents an overview of the current understanding of the impacts of climate change in the United States, including that warming will tend to be greater at high latitudes and in the interiors of the United States. CBO 2009 suggests that future climate conditions will feature less snowfall and more rainfall, less snowpack development, and earlier snowmelt runoff. The report also suggests that warming will lead to more intense and heavy rainfall that will tend to be interspersed with longer relatively dry periods. Lundquist et al. (2009) report similar findings. In general, there is greater agreement reported between model projections and, thus, higher confidence in future temperature change relative to precipitation change.[5]

The CBO findings are qualitatively consistent with findings in the Washington Climate Change Impacts Assessment (WACCIA), developed and reported by the University of Washington Climate Impacts Group. The WACCIA reports on future climate change possibilities and associated impacts to hydrology, water resources, ecosystems, and other sectors. The WACCIA's report on future climate conditions over the greater Columbia River Basin (Mote and Salathé 2010) suggests increases in average annual Pacific Northwest temperature of 1.1–3.3 °F by the 2020s (2010–2039), 1.5–5.2°F by the 2040s (2030–2059), and 2.8–9.7 °F by the 2080s (2070–2099), compared to 1970–1999. Projected changes in average 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. Although the multimodel average suggested small chnages in average-annual precipitation, the range of changes from individual models was relatively broad. For example, among the 39 different future climate scenarios based on 20 climate models and 2 greenhouse gas emissions scenarios, the WACCIA reported that 2080s annual average precipitation change relative to historical conditions could vary from -10 to +20%. These climate changes translate into impacts on hydrology, particularly regional snowpack and runoff seasonality (Elsner et al. 2010). For example, WACCIA findings suggest that under a multiprojection average representing 10 of the 20 climate models referenced above, each simulating the A1b[6] emissions scenario, April 1 snowpack is projected to decrease by 28% across Washington State by the 2020s, 40% by the 2040s, and 59% by the 2080s (relative to the 1916–2006 historical average). As a result, seasonal streamflow timing likely will shift significantly in sensitive watersheds.

Switching focus to extreme precipitation events, the former U.S. Climate Change Science Program issued SAP 3.3 (CCSP 2008), which focuses on mechanisms for

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[5] Note that some researchers caution that agreement between models is not a sufficient metric for judging projection credibility (Pirtle et al. 2010), noting that the modeling community has yet to demonstrate sufficient independence between models that can be similarly flawed or biased as a result of sharing code or parameterizations.

[6] As defined by the International Panel on Climate Change (IPCC) *Special Report on Emissions Scenarios* (SRES) (Nakićenović, N., and R. Swart [eds.] 2000).

observed changes in extreme precipitation to better interpret projected future changes in extremes (Gutowski et al. 2008). SAP 3.3 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. Sun et al. (2007) also report on climate change and precipitation extremes. Using regional climate models for Washington State, Salathe et al. (2009) predict positive or very small statewide trends and considerable increases in future extreme precipitation events relative to 20^{th} century conditions.

These recent assessments on future climate and hydrology are consistent with earlier studies. 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, which would create significant increased competition among 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. Mastin et al. (2008) predicted Yakima River basin runoff impacts given average annual termperature increases of 1 and 2 °C combined with no change in precipitation. Their results suggest modest decreases in annual runoff and significant late spring and summer runoff decreases under both scenarios. Rauscher et al. (2008) used a high-resolution, nested climate model to investigate future changes in snowmelt-driven runoff over the Western United States. Results include that runoff could occur as much as 2 months earlier than present, particularly in the Northwest, and earlier runoff timing of at least 15 days in early-, middle-, and late-season flow is projected for almost all mountainous areas where runoff is snowmelt driven. On extreme hydrologic events, Raff et al. 2009 introduced a framework for estimating flood frequency in the context of climate projections or time-developing climate information. The framework was applied to a set of four diverse basins in the Western United States (i.e., the Boise River above Lucky Peak Dam, the San Joaquin River above Friant Dam, the James River above Jamestown Dam, and the Gunnison River above Blue Mesa Dam). Results for three of the four basins (Boise, San Joaquin, and James) showed that, under current climate projections, probability distributions of annual maximum discharge would feature greater flow rates at all quantiles. For the fourth basin (Gunnison), greater flow rates were projected for roughly the upper third of quantiles. Granted, this study represents a preliminary effort and primarily focuses on introducing a framework for estimating flood frequency in a changing climate. Results are limited by various uncertainties, including how the climate projections used in the analysis did not reflect potential changes in storm frequency and duration (only changes in storm intensity relative to historical storm events).

Such future impacts on hydrology have been shown to have implications for water resources management. Chapter 4 of SAP 4.3 focuses on water resources effects and suggests that management of Western United States reservoir systems is very likely to become more challenging as net annual runoff decreases and interannual patterns continue to change as the result of climate change (Lettenmaier et al. 2008). The WACCIA includes assessment of reservoir operations in the Yakima River Basin under a multimodel average climate change scenario (Vano et al. 2010) and suggests that impacts to snowpack and runoff seasonality translate into reduced ability (compared to 1970–2005) to supply water to all users, especially those with junior water rights. Without adaptation, their results suggest that shortages likely would occur 32% of years in the 2020s, 36% of years in the 2040s, and 77% of years in the 2080s (compared to 14% of years 1916–2006). Focusing on the greater Columbia River Basin, Payne et al. (2004) evaluated reservoir operations under projected hydrologic conditions 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. To maintain current levels of instream flows, a 10–20% reduction in firm hydropower production would be required. Lee et al. (2009) performed a similar analysis on the Columbia River Basin system with findings consistent with Payne et al. (2004). Their results suggest that current Columbia River Basin reservoir systems could be operated to provide flood control and reservoir refill under climate change scenarios, provided that current flood rule curves are updated.

2.1.3 Climate Change Impacts on Environmental Resources

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.[7] Predicted impacts are primarily associated with projected increases in air and water temperatures and include species range shifts poleward, adjustment of migratory species arrival and departure, amphibian population declines, and effects on pests and pathogens in ecosystems. Climate change also has affected forest insect species range and abundance through changes in insect survival rates, increases in life cycle development rates, facilitation of range expansion, and effect on host plant capacity to resist attack (Ryan et al. 2008). Cayan et al. (2001) document earlier blooming of lilacs and honeysuckles correlated to increasing spring temperatures.

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[7] Ansu and McCarney (2008) offer a categorized bibliography of articles related to climate change and environmental resources impacts. Readers are encouraged to review this bibliography for additional articles relevant to their specific interests.

Chapter 2 of SAP 4.3 discusses the effects of climate change on agriculture and water resources (Hatfield et al. 2008). It addresses the many issues associated with future agricultural water demands and discusses that only a few studies have attempted to predict climate change impacts on irrigation demands. These limited study findings suggest significant irrigation requirement increases for corn and alfalfa due to increased temperatures and carbon dioxide (CO_2) and reduced precipitation. 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 and assuming that farming practices could adapt to this opportunity by planting more crop cycles per growing season. 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). Christidis et al. (2007) point out that increases in growing season length also have ramifications for phenological events, with possible cascading impacts related to water storage, peak flows, and pollinators. The International Panel on Climate Change (IPCC) Technical Paper on Climate Change and Water includes similar discussions (Bates et al. 2008) on the above issues and noting that only a few studies have attempted to predict climate change impacts on irrigation demands.

Increased air temperatures could increase aquatic temperatures and affect fisheries habitat. In general, studies of climate change impacts on freshwater ecosystems are more straightforward with streams and rivers, which are typically well mixed and track air temperature closely, as opposed to lakes and reservoirs, where thermal stratification and depth affect habitat (Allan et al. 2005). Ficke et al. (2007) present an extensive synthesis and bibliography of literature on climate change impacts on freshwater fisheries. Fang et al. (2004a and 2004b) predicted changes to cold water fisheries habitat in terms of water temperature and dissolved oxygen under a doubled CO_2 climate change regional warming scenario for 27 lake types in the United States, including Western United States lakes. Their findings suggest an overall decrease in the average length of good-growth periods, and the area for which lakes cannot support cold water fish would extend significantly further north. Reported average reductions in the number of locations where lakes presently have suitable year-round cold water fish habitat are 28, 90, and 65 locations for shallow, medium depth, and deep lakes, respectively. Williams et al. (2009) predict future adverse impacts to several species of cutthroat trout due to increased summer temperatures, uncharacteristic winter flooding, and increased wildfires resulting from climate change. Haak et al. (2010) present similar predictions for various salmonid species of the inland Western United States.

The WACCIA (Mantua et al. 2010) reports that rising stream temperatures likely will reduce the quality and extent of freshwater salmon habitat in Washington

State. The WACCIA goes on to suggest that the duration of periods that cause thermal stress and migration barriers to salmon is projected to at least double (low emissions scenario, B1) and perhaps quadruple (medium emissions scenario, A1B) by the 2080s for most analyzed streams and lakes. The WACCIA indicated regions of greatest expected increases in thermal stress, including the interior Columbia River Basin. These findings are consistent with other studies in the region. Battin et al. (2007) focused on the impacts of climate change on the effectiveness of proposed salmon 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. However, Battin et al. (2007) also suggested that scenarios for freshwater habitat restoration could partially or completely mitigate the projected negative impacts of anthropogenic climate change.

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). Burkett and Kusler (2000) discuss potential impacts to wetlands caused by climate change. Potential impacts to five different types of wetlands are discussed as well as how impacts may vary by region. Allan et al. (2005) suggest that, although freshwater ecosystems will adapt to climate change as they have to other stresses (e.g., land use change, acid rain, habitat degradation, and pollution), the adaptation to climate change likely will entail a diminishment of native biodiversity.

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 also could 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.

Switching to nonaquatic species and ecosystem impacts, McCarty (2001) reports the abundance of Sooty Shearwaters (a seabird) declined by 90% between 1987 and 1994 associated with rapid warming of the California current. Ray et al. (2010) present a synthesis of existing climate change prediction data sets adjusted and downscaled to support efforts to determine the need of listing the American Pika under the Endangered Species Act. Significant increasing temperature trends and earlier snowmelt implications to Pika habitat are presented. Beever et al. (2010) report study findings associated with potential climate change impacts to the American Pika that include results of testing alternative models of climate-mediated extirpations.

Another potential effect of climate change impacts on ecosystems and watershed hydrology involves changes in vegetation disturbances due to wildfires and forest dieback. In the Western United States, increases in spring-summer temperatures leads to attenuated snow melt, reduced soil moisture, and reduced fuel moisture conditions. This, in turn, affects wildland fire activity. Such effects are discussed in chapter 3 of SAP 4.3 (Ryan et al. 2008) and also Westerling et al. (2006), which documents large increases in fire season duration and fire frequency, especially at mid-elevations, in the Western United States. Coincident with trends toward warmer and drier climate in the Western United States over the past two decades (1990–2009), forest fires have grown larger and more frequent. Both the frequency of large wildfires and fire season length increased substantially since 1985, and these changes were closely linked with advances in the timing of spring snowmelt. Hot and dry weather also allows fires to grow exponentially, covering more acreage (Lettenmaier et al. 2008).

Several studies have focused on potential future forest impacts under climate change. Westerling et al. (2006) document large increases in fire season duration and fire frequency, especially at mid-elevations. The WACCIA reports similar potential impacts (Littell et al. 2009), suggesting that due to increased summer temperature and decreased summer precipitation, the annual area burned by fire regionally is projected to double by the 2040s and triple by the 2080s (relative to 1916–2006 annual average). These findings are consistent with earlier studies. Brown et al. (2004) evaluated future (2006–2099) Western United States wildfire potential based on climate change scenarios relative to current climate conditions and current wildfire potential quantified using the Forest Service National Fire Rating System. The study predicts increased potential for large wildfires throughout most of the Western United States with the exception of the Pacific Northwest and with the greatest increase in the northern Rockies, Great Basin, and the Southwest United States. 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. These authors also discuss how some plant and animal species that are sensitive to fire may decline, whereas the distribution and abundance of species favored by fire may be enhanced due to increased wildfires resulting from climate change. Beukema et al. (2007) discuss the potential for increased fire risk and insect and pathogen impacts to East Cascades ponderosa pine forest ecosystems resulting from climate change. Robinson et al. (2008) describe and compare several ecological models that estimate vegetation development (productivity or vegetation type) under climate change conditions.

Climate changes also can 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). For example, Ryan et al. (2008) report that several insect outbreaks recently have occurred or are occurring in the United States, and increased temperature and drought likely influenced these outbreaks. Climate change appears to have affected forest insect species range and abundance through changes in insect survival rates, increases in life cycle development rates, facilitation of range expansion, and effect on host plant capacity to resist attack. The WACCIA also reports that in areas primarily east of the Cascades, mountain pine beetles likely will reach higher elevations, and pine trees likely will be more vulnerable to attack by beetles.[8] 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.

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 (1994–2010) demonstrating evidence of regional climate change during the 20th century and exploring water resources, environmental resources, and sea level impacts associated with various climate change scenarios.[9]

2.2.1 Historical Climate and Hydrology

Over the course of the 20th century, it appears that all areas of the MP Region became warmer, and some areas received more winter precipitation. Cayan et al. (2001) report that Western United States 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) report increased winter precipitation trends during 1950–1999 at many Western United States sites, including several in California's Sierra Nevada; but a consistent region-wide trend is not apparent.

Other notable assessments of historical climate trends include Bonfils et al. (2007), which report that 1914–1999 and 1950–1999 observed temperature increase trends at eight California sites are inconsistent with model-based

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[8] Numerous articles on invasive bark beetle topics are available at http://wwa.colorado.edu/ecology/beetle/references.html.

[9] For the MP Region within California, Vicuna and Dracup (2007) offer an exhaustive literature review of prior studies pertaining to climate change impacts on California hydrology and water resources.

estimates of natural internal climate variability, which imply 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) report 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. Gershunov et al. (2009) report on the positive trend in heat wave activity over the entire California-Nevada region that is expressed mostly in night time rather than daytime temperature extremes. The authors discuss the relative contributions of the factors identified and possible relations to climate change.

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 United States stations (Knowles et al. 2007). Regonda et al. (2005) report monthly SWE trends during 1950–1999 and suggest that there were statistically significant declines in monthly SWE over roughly half of the Western United States sites evaluated for 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. Stewart (2009) examined global snowpack and melt responses and noted that the greatest responses have been observed for areas that remain close to freezing throughout the winter season.

Villarini et al. (2009) analyzed annual peak discharge records from 50 stations in the United States with 100 years of record and attempted to document reduced stationarity. However, their results were equivocal, due to evidence of human modifications affecting runoff generation (e.g., changes in land use and land cover), fluvial transportation (e.g., construction of dams and pools), and changes in measurements—all of which can induce nonclimatic nonstationarity. Consequently, they reported that they were "not able to assess whether the observed variations in annual maximum instantaneous peak discharge were due to natural climate variability or anthropogenic climate change."

Focusing on changes in precipitation extremes, the former U.S. Climate Change Science Program issued SAP 3.3 (CCSP 2008), wherein chapter 3 focuses on mechanisms for observed changes in extremes and reports that heavy precipitation events averaged over North America have increased over the past 50 years (Gutowski et al. 2008). Kunkel (2003) presents an analysis of extreme precipitation events and indicates there has been an increase in their frequency since the 1920s/1930s in the United States, although very small trends (1931–1996) were shown for the climate divisions of the MP Region. Madsen and

Figdor (2007) evaluated 1948–2006 trends in extreme precipitation events for each State using the method of Kunkel et al. (1998) and report similar findings.

It is important to note that linear trends in hydrologically important variables (including springtime SWE, indices of runoff timing, and surface air temperature) depend on the time period considered in the analysis. For example, Mote et al. (2008), show that SWE trends for the Washington and Oregon Cascades computed with an end date of 2006 and a start date within a decade of 1955 are robust, while those computed through 2006 from later start dates differ dramatically (but 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 climate variations on interdecadal time scales and longer-term anthropogenic trends that are part of many climate records for the 20th century.

On explaining historical trends in regional climate and hydrology, chapter 4 of the U.S. Climate Change Science Program SAP 4.3 discusses several studies that indicate most observed trends for SWE, soil moisture, and runoff in the Western United States are the result of increasing temperatures rather than precipitation effects (Lettenmaier et al. 2008). This assertion is supported by a collection of journal articles that targeted 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 naturally originating climate variations explaining observed trends. Barnett et al. (2008) performed a multiple variable formal detection and attribution study and showed how the changes in Tmin, SWE, precipitation and CT for 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, Hidalgo et al. (2009) for streamflow timing changes, and Das et al. (2009) for temperature, snow/rain days ratio, SWE, and 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. 2009).

While the trends in Western United States river flow, winter air temperature, and snow pack might be partially explained by anthropogenic influences on climate, Hoerling et al. (2010) show that it remains difficult to attribute historical precipitaton variability to anthropogenic forcings. They evaluated regional precipitation data from around the world (observed and modeled) for 1977–2006. They suggest that the relationship between sea temperatures and rainfall changes are generally not symptomatic of human-induced emissions of greenhouse gases and aerosols. Rather, their results suggest that trends during this period are consistent with atmospheric response to observed sea surface temperature variability. Shin and Sardeshmukh (2010) show that the 20th century trends in PDSI are consistent with forcing by tropical sea-surface temperature trends and discuss that the SST trends are due to a combination of natural and anthropogenic forcing. These two studies reinforce the fact that tropical SSTs can act as a "middleman" for anthropogenic climate change in the West. McAfee and Russell (2008) examined connections between the observed poleward migration of the Northern Hemisphere storm track (a global warming response suggested by current climate projections, sometimes referred to as Hadley Cell expansion [Seager et al. 2007]), atmospheric circulation over North America, and precipitation and temperature responses in the Western United States. They found that during the transition to spring, following a Northern Annular Mode (also called Arctic Oscillation) high-index winter, which is associated with poleward storm track shifts, there is a weakening of the storm track over the northeastern Pacific, resulting in warmer and drier conditions west of the Rocky Mountains. They note that these results are consistent with observations of early spring onset in the Western United States.

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 cause reduced snowpack development during winter, more runoff during the winter season, and earlier spring peak flows associated with an earlier snowmelt.

2.2.2 Projected Future Climate and Hydrology

Several studies have been conducted to relate potential future climate scenarios to MP Pegion runoff and water resources management impacts. In general, there is greater agreement reported between model projections and, thus, higher confidence in future temperature change relative to precipitation change.[10] A recent paper by the Congressional Budget Office (CBO 2009) presents an overview of the current understanding of the impacts of climate change in the United States, including that warming will tend to be greater at high latitudes and in the interiors of the United States. CBO 2009 suggests that future climate conditions will feature less snowfall and more rainfall, less snowpack development, and earlier snowmelt runoff. The report also suggests that warming will lead to more intense and heavy rainfall that will tend to be interspersed with longer relatively dry periods. Lundquist et al. (2009) report similar findings.

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[10] Note that some researchers caution that agreement between models is not a sufficient metric for judging projection credibility (Pirtle et al. 2010), noting that the modeling community has yet to demonstrate sufficient independence between models that can be similarly flawed or biased as a result of sharing code or parameterizations.

Moser et al. (2009) report specifically on future climate possibilities over California[11] and suggest that warmer temperatures are expected throughout the State during the 21st century, with an end-of-century increase of 3–5.5 °F under a lower emissions scenario (B1), 8–10.5 °F under a higher emissions scenario (A1FI), and intermediate temperature increase under the A2 emissions scenario.

Switching focus to extreme precipitation events, chapter 3 of SAP 3.3 (CCSP 2008) comments on projected future changes in extremes (Gutowski et al. 2008), suggesting 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. Sun et al. (2007) report that under 21st century modeled emissions scenarios B1 (low), A1B (medium), and A2 (high), all models consistently show a trend towards more intense and extreme precipitation for the globe as a whole and over various regions.

Several studies have examined potential hydrologic impacts associated with projected climate change. Rauscher et al. (2008) found consistent results using a high-resolution, nested climate model to investigate future changes in snowmelt-driven runoff over the Western United States. Their analyses showed that runoff could occur as much as 2 months earlier than present, and earlier runoff timing of at least 15 days in early-, middle-, and late-season flow is projected for almost all mountainous areas where runoff is snowmelt driven. Maurer (2007) examined global climate model (GCM) and hydrologic model based climate change impacts for four river basins in the western Sierra Nevada and reports that the majority of GCMs show increased winter precipitation; but this was quite variable among the models while temperature increases and associated SWE projections appear more consistent. Null et al. (2010) report on climate change impacts for 15 western-slope watersheds in the Sierra Nevada under warming scenarios of 2-, 4-, and 6-°C increase in mean-annual air temperature relative to historical conditions. Under these scenarios, total runoff decreased and earlier runoff was predicted in all watersheds relative to increasing temperature scenarios, and decreased runoff was most severe in the north where there is more vegetation evapotranspiration (ET) forcing. The model also predicted that the high elevation southern-central region appears most susceptible to earlier runoff and the central areas appear most vulnerable to longer low flow periods. On extreme hydrologic events, Raff et al. 2009 introduced a framework for estimating flood frequency in the context of climate projections, or time-developing climate information. The framework was applied to a set of four diverse basins in the Western United States (i.e., the Boise River above Lucky Peak Dam, the San Joaquin River above Friant Dam, the James River above Jamestown Dam, and the Gunnison River above Blue Mesa Dam). Results for three of the four basins (Boise, San Joaquin, and James) showed that, under current climate projections, probability distributions of annual

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[11] Moser et al. (2009) provide an interim summary on the latest climate change science for California and implications for multiple resource sectors. It was prepared as part of the Second Biennial Science Report to the California Climate Action Team.

maximum discharge would feature greater flow rates at all quantiles. For the fourth basin (Gunnison), greater flow rates were projected for roughly the upper third of quantiles. Granted, this study represents a preliminary effort and primarily focuses on introducing a framework for estimating flood frequency in a changing climate. Results are limited by various uncertainties, including how the climate projections used in the analysis did not reflect potential changes in storm frequency and duration (only changes in storm intensity relative to historical storm events).

Such future impacts on hydrology have been shown to have implications for water resources management. Chapter 4 of SAP 4.3 focuses on water resources effects and suggests that management of Western United States reservoir systems is very likely to become more challenging as net annual runoff decreases and interannual patterns continue to change as the result of climate change (Lettenmaier et al. 2008). Many studies have been conducted on projected future climate and hydrology in California's Central Valley and what that could mean for related water and environmental resources. A summary of studies through 2005 is offered by Vicuna and Dracup (2007). 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.

Recent studies by Moser et al. (2009), Anderson et al. (2008), and Brekke et al. (2009b) suggest water resources impacts generally consistent with those reported by Van Rheenan et al. (2004) but for more recently developed climate projection scenarios. Moser et al. (2009) suggest that current climate projections over California would lead to decreased snowpack by the end of the century (20 to 40% depending on emissions scenarios), increased risk of winter flooding, earlier timing of meltwater runoff and greater vulnerability to summer shortfalls, decreased hydropower generation (under dry warming), and decreased quality of winter recreation. Brekke et al. (2009b) 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. Other studies also have suggested that changes in extreme precipitation and related runoff may present flood control challenges to varying degrees at many locations, but possibly to lesser degrees in snowmelt dominated basins. For example, Hamlet and Lettenmaier (2007) cite decreasing flood quantiles in snowmelt dominated systems due to lower spring snowpack. It should be noted that this is an area where the existence of dust-on-snow complicates matters, since this phenomenon can lead to rapid snowmelt.

Other notable water resources management studies include Harou et al. (2010) who evaluated economically driven California water resources management and reservoir systems operations using a hydroeconomic model. As a proxy for climate change, their simulations where driven by hydrology reflecting extreme drought from the paleorecord. The authors synthesized a 72-year drought with half of mean historical inflows (1921–1991) using random sampling of historical dry years. Model results include time series of optimized monthly operations and water allocations to maximize statewide net economic benefits that predict impacts to be expensive but not catastrophic for the overall economy; however, severe burdens would be imposed on the agricultural sector and environmental water use. Vicuna et al. (2010) present an optimization algorithm for climate change and water resources management-related studies and report the results of its application on three Merced River basin scenarios. The algorithm explicitly accounts for probabilistic uncertainty using a combination of sampling stochastic dynamic programming and nonlinear programming methods. The application scenarios included 1) limited adaptive management under existing constraints, 2) long-term adaptive management with adjustments to existing constraints, and 3) a hypothetical new reservoir assuming no existing reservoir. The respective results for scenarios 1 and 2 showed declining and increasing benefits. The results for scenario 3 showed the value of including uncertainty about future hydrologic conditions in the decision to build a new reservoir.

Switching to water 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.

2.2.3 Studies of Impacts on Natural Resources

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.[12] Predicted impacts are primarily associated with projected increases in air and water temperatures and include species range shifts poleward, adjustment of migratory species arrival and departure, amphibian population declines, and effects on pests and pathogens in ecosystems. Climate change also has affected forest insect species range and abundance through changes in insect survival rates, increases in life cycle development rates, facilitation of range expansion, and the effect on host plant capacity to resist attack (Ryan et al. 2008). Cayan et al. (2001) document earlier blooming of lilacs and honeysuckles correlated to increasing spring temperatures.

Chapter 2 of SAP 4.3 discusses the effects of climate change on agriculture and water resources (Hatfield et al. 2008). It addresses the many issues associated with future agricultural water demands and discusses that only a few studies have attempted to predict climate change impacts on irrigation demands. These limited study findings suggest significant irrigation requirement increases for corn and alfalfa due to increased temperatures and CO_2 and reduced precipitation. 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 and assuming that farming practices could adapt to this opportunity by planting more crop cycles per growing season. 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). Christidis et al. (2007) point out that increases in growing season length also have ramifications for phenological events, with possible cascading impacts related to water storage, peak flows, and pollinators. The International Panel on Climate Change Technical Paper on Climate Change and Water includes similar discussions (Bates et al. 2008) on the above issues and noting that only a few studies have attempted to predict climate change impacts on irrigation demands.

Increased air temperatures could increase aquatic temperatures and affect fisheries habitat. In general, studies of climate change impacts on freshwater ecosystems are more straight-forward with streams and rivers, which are typically well mixed and track air temperature closely, as opposed to lakes and reservoirs, where thermal stratification and depth affect habitat (Allan et al. 2005). Ficke et al. (2007) present an extensive synthesis and bibliography of literature on climate change impacts on freshwater fisheries. Fang et al. (2004a and 2004b) predicted changes to cold water fisheries habitat in terms of water temperature and dissolved oxygen under a doubled CO_2 climate change regional warming scenario for 27 lake types in the United States, including Western United States lakes.

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[12] Ansu and McCarney (2008) offer a categorized bibliography of articles related to climate change and environmental resources impacts. Readers are encouraged to review this bibliography for additional articles relevant to their specific interests.

They report an overall decrease in the average length of good-growth periods, and the area for which lakes cannot support cold water fish would extend significantly further north. Williams (2009) predict future adverse impacts to several species of cutthroat trout due to increased summer temperatures, uncharacteristic winter flooding, and increased wildfires resulting from climate change. Haak et al. (2010) present similar predictions for various salmonid species of the inland Western United States.

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). Burkett and Kusler (2000) discuss potential impacts to wetlands caused by climate change. Potential impacts to five different types of wetlands are discussed as well as how impacts may vary by region. Allan et al. (2005) suggest that, although freshwater ecosystems will adapt to climate change as they have to other stresses (e.g., land use change, acid rain, habitat degradation, and pollution), the adaptation to climate change likely will entail a diminishment of native biodiversity.

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 also could 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.

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Several studies have focused on potential future forest impacts under climate change, both through slowly evolving change in vegetation community and through changes spawned by disturbances involving forest fire or pest invasions. Focusing on evolving vegetation communities, Battles et al. (2007) evaluated the effects of climate change on the productivity and health of a mixed conifer forest at Blodgett Forest Research Station in El Dorado County, California. The authors report projected conifer tree growth decline under all four climate scenarios evaluated. The worst case decreased productivity, based on stem volume increment, in mature stands overall was 19% by 2100 with more severe reductions in yield (25%) for pine plantations. These findings are the result of increased summer temperatures since no precipitation trends were included in the model future conditions. Focusing on future potential for fire disturbance, Moser et al. (2009) suggest that the number of large wildfires in California will increase by 12–53% statewide depending on emissions scenario, with larger increases in northern California. The report also suggests that projected climate change will affect coverage of certain tree species and alter the competition among species—such as a gain in broad-leaved species at the expense of needle-leaved species.

Westerling et al. (2006) document large increases in fire season duration and fire frequency, especially at mid-elevations. Brown et al. (2004) evaluated future (2006–2099) Western United States wildfire potential based on climate change scenarios relative to current climate conditions and current wildfire potential quantified using the Forest Service National Fire Rating System. The study predicts increased potential for large wildfires throughout most of the Western United States with the exception of the Pacific Northwest and with the greatest increase in the northern Rockies, Great Basin, and the Southwest United States. 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. These authors also discuss how some plant and animal species that are sensitive to fire may decline, whereas the distribution and abundance of species favored by fire may be enhanced due to increased wildfires resulting from climate change. Westerling and Bryant (2008) projected California wildfire risks for A2 and B1 Special Report on Emissions Scenarios (SRES) scenarios, using the National Center for Atmospheric Research (NCAR) Parallel Climate Model (PCM) and Geophysical Fluid Dynamics Laboratory (GFDL) models. They found that "On average, however, the results presented here indicate that increasing temperatures would likely result in a substantial increase in the risk of large wildfires in energy-limited wildfire regimes, while the effects in moisture-limited fire regimes will be sensitive to changes in both temperature and precipitation." They also noted that "while higher temperatures tended to promote fire risk overall, reductions in moisture due to lower precipitation and higher temperatures led to reduced fire risk in dry areas that appear to have moisture-limited fire regimes." Robinson et al. (2008) describe and compare several ecological models that estimate vegetation development (productivity or vegetation type) under climate change.

Climate changes also can 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 effects on soil moisture, evapotranspirational demand, chronic water stress, and carbon starvation (via reduced gas exchange) are a key factor in conifer species die-off in western North America (Breshears et al. 2005; Weiss et al. 2009; Adams et al. 2010; McDowell et al. 2010). 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). For example, Ryan et al. (2008) report that several large insect outbreaks recently have occurred or are occurring in the United States, and increased temperature and drought likely influenced these outbreaks.[13] Climate change has affected forest insect species range and abundance through changes in insect survival rates, increases in life cycle development rates, facilitation of range expansion, and effect on host plant capacity to resist attack. 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. Numerous articles on invasive bark beetle topics are available at http://wwa.colorado.edu/ecology/beetle/references.html.

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 and White 2006; Beckley et al. 2007). Sea levels are expected to continue to rise due to increasing air temperatures that will cause thermal expansion of the ocean and melting of land-based ice, such as ice on Greenland and in southeastern Alaska (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

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[13] Numerous articles on invasive bark beetle topics are available at http://wwa.colorado.edu/ecology/beetle/references.html.

from current 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. Figure 10.32 in IPCC 2007 accounts for these local derivations and 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. Yin et al. (2010) used 12 of the best performing models to estimate spatial variability of sea level rise in the 21st century.

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. The relationship is based on the assumption that sea level response to temperature change is very long relative to the time scale of interest (approximately 100 years). 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 (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 feet with an uncertainty range spanning 0.5 to 1.3 feet. By the end of the century, sea level rise projections ranged from 1.8 to 3.1 feet, with an uncertainty range spanning from 1.0 to 3.9 feet. 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). Alternative to Rahmstorf (2007), Veermeer and Rahmstorf (2009) present a duel component relationship with short- and long-term sea level response components to temperature change. Based on this work and applying the IPCC emission scenarios, by 2100, seal levels are predicted to be 1–2 meters higher than at present. It should be noted that projections using 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.

Some studies have explored implications of sea level rise for the San Francisco Bay-Delta region. Knowles (2010) developed a hydrodynamic model of the San Francisco Bay estuary driven by GCM-based projections of hourly water levels at Presidio, California, during 2000–2100. The model indicates that, for the San Francisco Bay as a whole; the 1-year peak sea level event by 2050 nearly equals the 100-year peak event for 2000. Other findings include predicted increased risks to wetlands and some developed fill areas in the north portion of the bay and increased risks to developed areas in the south.

2.3 Lower Colorado Region

Numerous studies have been conducted on the potential consequences of climate change for water resources in Reclamation's Lower Colorado Region. This section summarizes findings from recent studies (1994–2010) demonstrating evidence of regional climate change during the 20th century and exploring water and environmental resources impacts associated with various climate change scenarios.[14]

2.3.1 Historical Climate and Hydrology

Over the course of the 20th century, it appears that all areas of the LC Region became warmer, but the causes of precipitation trends are more uncertain. Cayan et al. (2001) report that Western United States spring temperatures have increased 1–3 °C since the 1970s. Based on data available from the Western Climate Mapping Initiative,[15] 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

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[14] 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).

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

Colorado River Basin.[16] 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 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 1930–1997 and 1950–1997. Hoerling and Eischeid (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 United States 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). Easterling's findings are corroborated by Christidis et al. (2007), who found that the lengthening of the growing season is primarily an outcome of earlier springs and that the change in growing season length cannot be explained by internal climate variability or natural external forcings, either globally or at the scale of North America, for 1950–1999.

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.

Switching from temperature to precipitation, 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 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 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

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

precipitation trends from 1916 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." Guentchev et al. (2010) analyzed homogeneity of three gridded precipitation datasets that have been used in studies of the Colorado River Basin; they report that all three datasets show breakpoints in 1977 and 1978, and suggest that these may be due to an anomalously rapid shift in the Pacific Decadal Oscillation. They note that, for 1950-1999, the data are sufficiently homogeneous for analyses of precipitation variability, when aggregated on a subregional scale.

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 United States 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 at SNOTEL stations (U.S. Department of Agriculture-Natural Resources Conservation Corps automated Snowpack Telemetry) in the LC Region; SNOTEL stations usually are 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. Moreover, Stewart (2009) examined global snowpack and melt responses and noted that the greatest responses have been observed for areas that remain close to freezing throughout the winter season. 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).

Knowles et al. (2007) note that warming during December–March have the greatest influence on snow deposition, whereas warming in April–June accelerates snow melt, which results in earlier center of mass of streamflow[17] (Stewart et al. 2005). 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 trends of reduced SWE and peak runoff occurring 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) demonstrate that trends toward earlier center of mass of spring streamflow in the Upper Colorado River Basin is well correlated with increasing temperatures.

Villarini et al. (2009) analyzed annual peak discharge records from 50 stations in the United States with 100 years of record and attempted to document reduced stationarity. However, their results were equivocal, due to evidence of human modifications affecting runoff generation (e.g., changes in land use and land cover), fluvial transportation (e.g., construction of dams and pools), and changes in measurements, all of which can induce nonclimatic nonstationarity. Consequently, they reported that they were "not able to assess whether the observed variations in annual maximum instantaneous peak discharge were due to natural climate variability or anthropogenic climate change."

Focusing on changes in precipitation extremes, the former U.S. Climate Change Science Program issued SAP 3.3 (CCSP 2008), wherein chapter 3 focuses on mechanisms for observed changes in extremes and and reports heavy precipitation events averaged over North America have increased over the past 50 years (Gutowski et al. 2008). Kunkel (2003) presents an analysis of extreme precipitation events and indicates there has been an increase in their frequency since the 1920s/1930s in the United States, although very small trends (1931–1996) were shown for the climate divisions of the LC Region. It should be noted, however, trends for certain LC Region areas are not statistically significant (northwestern Arizona and western California). Madsen and Figdor (2007) evaluated 1948–2006 trends in extreme precipitation events for each State using the method of Kunkel et al. (1998) and report similar findings.

Painter et al. (2010) discuss the role of dust deposition on snowmelt timing and runoff amount. The relevance to climate change is that the impact of warming on runoff timing is less for dusty snow because a greater fraction of the energy needed for snowmelt comes from sunlight, not air-temperature. Also, dust can impact even relatively cold, high-elevation snowpack. Dust-on-snow is very prevalent in the Upper Colorado River Basin, with a likely origin due to human-

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[17] Center of mass of streamflow is measured by the date when 50% of total annual streamflow is recorded.

caused land disturbance on the Colorado Plateau. Understanding the role of dust is important for interpreting the historical record since it is important not to attribute all the changes in runoff timing to warmer temperatures.

Although the preceding studies speak to the general effects of warming in snowmelt-dominated basins, many of these findings are somewhat less applicable in the LC Region. This is because much of the region lies at a lower elevation where hydrology is rainfall-runoff dominated rather than snowmelt-dominated.

Other notable studies have assessed trends in hydrologic drought over the LC Region. Andreadis and Lettenmaier (2006) examined drought-related parameters over 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 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; Hughes and Diaz 2008; MacDonald et al. 2008) and in streams feeding the LC Region, such as the Colorado River (Woodhouse et al. 2006; Meko et al. 2007). Shin and Sardeshmukh (2010) show that the 20th century trends in PDSI are consistent with forcing by tropical sea-surface temperature trends and discuss that the SST trends are due to a combination of natural and anthropogenic forcing. These two studies reinforce the fact that Tropical SSTs can act as a “middleman” for anthropogenic climate change in the West.

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; Woodhouse et al. 2009; Cook et al. 2010). 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. This 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. Woodhouse et al. (2009) examined signatures of atmospheric circulation associated with North American drought and found two primary modes: one related to the El Niño Southern Oscillation (ENSO) and one related to high latitude Northern Hemisphere circulation, such as the Northern Annular Mode (Arctic Oscillation). The ENSO mode plays a key, but not exclusive, role in the Lower Colorado Region drought and wet periods;

Woodhouse et al. (2009) note that the early 20th century pluvial, which coincided with the signing of the Colorado River Compact, was characterized by a strength and persistence of both atmospheric circulation modes that was unprecedented back to the 1400s. They also note that the medieval drought, associated with the most persistent low flows in the Colorado River Basin, was kicked off by the ENSO mode, but other factors influenced the drought after the mid-1100s. Recent work by Ben Cook and colleagues (Cook et al. 2010) demonstrate that the Pacific Ocean is the primary driver of drought in the Lower Colorado River, and while the direct influence of the Atlantic on drought is relatively weak, it may significantly amplify forcing from the Pacific. Cook et al. (2010) also note that land surface factors can amplify drought, such as in the Dust Bowl drought of the 1930s. This insight resonates with Painter et al.'s (2010) finding that a five-fold increase in dust loading, from anthropogenically disturbed soils in the Southwest, decreased snow albedo and shortened the duration of snow cover by several weeks during the last 100 years. They attribute a loss of 5% of annual average Colorado River flow, measured at Lees Ferry, to increased dust loading on snow, generating early runoff and increased evapotranspiration from vegetation and exposed soils.

Work by MacDonald et al. (2008) suggests 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 long-term droughts has likely been amplified by local greenhouse gas warming in recent decades." Cayan et al. (2010) used combined GCM and hydrologic models to conclude that the early 21st century Colorado River Basin drought has been the most extreme in over a century. This study defines extreme drought years as those when the area-averaged soil moisture falls below the 10th percentile for the 1951–1999 period; there were 11 such years during 1916–2008, including 2002, 2007, and 2008.

On explaining historical trends in regional climate and hydrology, chapter 4 of the U.S. Climate Change Science Program SAP 4.3 discusses several studies that indicate most observed trends for SWE, soil moisture, and runoff in the Western United States are the result of increasing temperatures rather than precipitation effects (Lettenmaier et al. 2008). This assertion is supported by a collection of journal articles that targeted 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 naturally originating climate variations explaining observed trends. Barnett et al. (2008) performed a multiple variable formal detection and attribution study and showed how the changes in Tmin, SWE, precipitation, and CT for 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; Hidalgo et al. (2009) for streamflow timing changes; and Das et al. (2009) for temperature, snow/rain days ratio, SWE, and 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. 2009).

While the trends in Western United States river flow, winter air temperature, and snow pack might be explained partially by anthropogenic influences on climate, Hoerling et al. (2010) show that it remains difficult to attribute historical precipitaton variability to anthropogenic forcings. They evaluated regional precipitation data from around the world (observed and modeled) for 1977–2006. They suggest that the relationship between sea temperatures and rainfall changes generally are not symptomatic of human-induced emissions of greenhouse gases and aerosols. Rather, their results suggest that trends during this period are consistent with atmospheric response to observed sea surface temperature variability. Shin and Sardeshmukh (2010) show that the 20th century trends in PDSI are consistent with forcing by tropical sea-surface temperature trends and discuss that the SST trends are due to a combination of natural and anthropogenic forcing. These two studies reinforce the fact that tropical SSTs can act as a “middleman” for anthropogenic climate change in the West. McAfee and Russell (2008) examined connections between the observed poleward migration of the Northern Hemisphere storm track (a global warming response suggested by current climate projections, sometimes referred to as Hadley Cell expansion [Seager et al. 2007]), atmospheric circulation over North America, and precipitation and temperature responses in the Western United States. They found that, during the transition to spring, following a Northern Annular Mode (also called Arctic Oscillation) high-index winter, which is associated with poleward storm track shifts, there is a weakening of the storm track over the northeastern Pacific, resulting in warmer and drier conditions west of the Rocky Mountains. They note that these results are consistent with observations of early spring onset in the Western United States.

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 Climate Change Impacts on Hydrology and Water Resources

Several studies have been conducted to relate potential future climate scenarios to LC Region runoff and water resources management impacts. A recent paper by the Congressional Budget Office (CBO 2009) presents an overview of the current understanding of the impacts of climate change in the United States, including that warming will tend to be greater at high latitudes and in the interiors of the United States. CBO 2009 suggests that future climate conditions will feature less snowfall and more rainfall, less snowpack development, and earlier snowmelt runoff. The report also suggests that warming will lead to more intense and heavy rainfall that will tend to be interspersed with longer relatively dry periods. Lundquist et al. (2009) report similar findings.

On future temperature and precipitation projections over the Colorado River Basin and LC Region, there is greater agreement reported between model projections and, thus, higher confidence in future temperature change.[18] There is much less agreement in the sign of change and, thus, less confidence in projections for precipitation change for *middle latitude* regions (Dai 2006) like the Upper Colorado River Basin. However, 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; Cayan et al. 2010; Gutzler and Robbins 2010). For example, Seager and Vecchi (2010) discuss that the 24 climate models used by IPCC Fourth Assessment Report (AR4) robustly predict that the Southwestern United States will dry throughout the current century and rising temperatures are leading to a shorter snow season with later onset and earlier snowmelt and more winter precipitation falling as rain instead of snow. Gutzler and Robbins (2010) note that projected trends in PDSI imply that higher evaporation rates, associated with positive temperature trends, exacerbate drought severity to the extent such that “the projected trend toward warmer temperatures inhibits recovery from droughts caused by decade-scale precipitation deficits.” Garfin et al. (2010), using statistically downscaled data generated by Eischeid, examined projected changes for the southern Colorado Plateau and point out that GCM agreement is greatest for the region’s May–June arid foresummer, with A1B scenario (modest

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[18] Note that some researchers caution that agreement between models is not a sufficient metric for judging projection credibility (Pirtle et al. 2010), noting that the modeling community has yet to demonstrate sufficient independence between models that can be similarly flawed or biased as a result of sharing code or parameterizations.

GHG increases) projections showing 11–45% declines in May–June precipitation. This result is significant, because historical climate observations point to this season as critical for driving vegetation evaporative demand (Weiss et al. 2009) and generating water stress that leads to conifer mortality (Breshears et al. 2005; Allen et al. 2010).

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). Nevertheless, Dominguez et al. (2010) evaluated the ability of IPCC AR4 coupled models to represent the climate of the Southwest. Using a reliability ensemble average statistic (Giorgi and Mearns 2002), they selected two GCMs (MPI ECHAM5 and UKMO HadCM3) that most realistically captured seasonal precipitation, temperature, and atmospheric circulation—including the summer monsoon and ENSO. Their projections suggest that future aridity of the Lower Colorado Region will be dramatically amplified during La Niña conditions, which will be much more severe—warmer and drier—than during the historic period.

Rauscher et al. (2008) found consistent results using a high-resolution, nested climate model to investigate future changes in snowmelt-driven runoff over the Western United States. Their analyses showed that runoff could occur as much as 2 months earlier than present, and earlier runoff timing of at least 15 days in early-, middle-, and late-season flow is projected for almost all mountainous areas where runoff is snowmelt driven. 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. 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.

In a subsequent study, using a large suite of CMIP3 and dynamically downscaled climate model experiments, Diffenbaugh and colleagues found that the intensification of hot extremes could result from relatively small increases in GHGs (Diffenbaugh and Ashfaq 2010). They noted that this intensification is associated with a shift toward more anticyclonic warm season atmospheric circulation and that the duration of heat waves in the Lower Colorado Region will exceed 1951–1999 levels from 2–5 times per decade between 2020–2039, depending on location in the Lower Colorado Region. They note that extremes during the hottest season will be exceeded with increasing frequency over the course of the 21st century. Diffenbaugh et al. (2008) identify the Southwest United States and northwestern Mexico as persistent hot spots of climate change vulnerability due to high precipitation variability and projected higher temperatures. Meehl et al. (2004), using the NCAR 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 nine 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.

Switching focus to extreme precipitation events, chapter 3 of SAP 3.3 (CCSP 2008) comments on projected future changes in extremes (Gutowski et al. 2008), suggesting 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. Sun et al. (2007) report that, under 21st century modeled emissions scenarios B1 (low), A1B (medium), and A2 (high), all models consistently show a trend towards more intense and extreme precipitation for the globe as a whole and over various regions. Diffenbaugh et al. (2005), using a regional climate model, project increases in the fraction of annual precipitation falling as extreme precipitation for more than half of the LC Region, a result that is consistent with independent projections for the western part of the LC Region (Bell and Sloan 2006). Favre and Gershunov (2008), using a comparison of National Centers for Environmental Prediction (NCEP)-NCAR reanalysis data and CNRM-CM3 projections, found alterations of North Pacific storm track and storm frequency in western North America; their analysis points to lower precipitation frequencies in the Lower Colorado Region, by the last half of the 21st century, due to synoptic-scale atmospheric circulation that favors more anticyclonic conditions off the North American mid-latitude coast.

Several studies have examined potential hydrologic impacts under projected climate conditions. Focusing on the Colorado River Basin, 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).[19] 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.[20] Third, the choice of GCMs and emissions scenarios used in the aforementioned studies also had some effect on the projected Colorado River Basin changes (Lettenmaier et al. 2008). A systematic comparison of these studies (Hoerling et al. 2009) yields some interesting insights into hydrology models, input data, and likely levels of Colorado River runoff decline. First, Hoerling and Eischeid (2007) now believe that their estimate of 45% runoff reduction overstates potential Colorado River losses. Using different, but equally valid downscaling methods, Variable Infiltration Capacity Model (VIC) model projections of future runoff changed from a 5% reduction by 2050 (Christensen and Lettenmaier 2007) to a 10% reduction. A key difference between hydrology models used in Colorado River runoff projections is the runoff sensitivity to temperature changes; Hoerling et al. (2010) found that sensitivity ranged from 2–9% runoff reduction per degree Celsius increase in temperature—which implies a large range of runoff reductions, 4–18% by 2050. Based on their assessment of these and other factors, Hoerling et al. estimate 2050 Colorado River flow declines of 5–20%.

Switching from Colorado River impacts to hydrologic impacts elsewhere in the LC Region, Ellis et al. (2008) used downscaled GCM temperature and precipitation changes as inputs to a water balance model for Arizona's

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[19] 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.

[20] 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.

Salt and Verde River basins to assess runoff at mid-century; the Salt River is a tributary to the Colorado River. Using a variety of 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.

Such future impacts on hydrology have been shown to have implications for water resources management. Chapter 4 of SAP 4.3 focuses on water resources effects and suggests that management of Western United States reservoir systems is very likely to become more challenging as net annual runoff decreases and interannual patterns continue to change as the result of climate change (Lettenmaier et al. 2008). Numerous studies have focused on the Colorado River Basin (Nash and Gleick 1991 and 1993; Christensen et al. 2004; and Christensen and Lettenmaier 2007). These studies are similar in that they portray potential operations impacts on the Colorado River system associated with different scenarios of projected future climate and hydrology, as summarized in Reclamation (2007). 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 (Reclamation 2007). 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, three other water management impacts studies on the Colorado River Basin were conducted, relating historical and projected climate and hydrology to system impacts (McCabe and Wolock 2007; Barnett and Pierce 2008; and Rajagopalan et al. 2009). 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 1490–1997. Rajagopalan et al. (2009) predicted similar impacts to that of McCabe and Wolock (2007). Barnett and Pierce (2008) reported more severe potential operations impacts, but this study was later revised (Barnett and Pierce 2009a), modifiying several original assessment assumptions (Barsugli et al. 2009) and leading to results more consistent with Rajagopalan et al. (2009). For both studies, the shortage risk on the whole system increases greatly in the 2020s and beyond. However, Barnett and Pierce (2009a) still insist that the whole upper basin is already in a deficit of 1 million acre-feet a year because a) climate change has already robbed the basin of several hundred thousand acre-feet annually, and b) the 20th century average is “wet” compared to the longer-term flows in the basin, and one should expect a reversion to a lower mean flow.

Although system impacts are not analyzed as in the studies discussed in the previous paragraph, Cayan et al. (2010) predict significant future Colorado River Basin impacts in terms of drought (runoff, SWE, and soil moisture). Predictions are based on the output from combined GCM and hydrologic models showing increased drought conditions (severity and duration) during the 21st century—especially so during the second half of the century. Dai (2010) calculated projections of the self-calibrated PDSI, which integrates precipitation and temperature, using the 22-model GCM ensemble from the IPCC Fourth Assessment Report, and demonstrated increasing drought severity across the Lower Colorado Region during the span of the 21st century.

Other studies have focused on water management impacts in portions of the LC Region not involving mainstem Colorado River operations. Gober et al. (2010) used 50 statistically downscaled CMIP3 climate model-scenario combinations as input to Ellis et al.’s water balance model; they then ran the results in conjunction with a variety of population estimates and management scenarios for the Phoenix metro area, using a dynamic simulation system model, WaterSim. According to Gober et al. (2010), results of the simulation experiments suggest that “(1) current levels of per capita water consumption cannot be supported without unsustainable groundwater use under most climate model scenarios, (2) feasible reductions in residential water consumption allow the region to weather the most pessimistic of the climate projections, (3) delaying actions, such as the reduction of consumption to decrease groundwater drawdown, reduces the long-term sustainability of groundwater resources (under some scenarios), and (4) adaptive policy with appropriate monitoring to track groundwater provides warning that the need for use restrictions is approaching and avoids the need for drastic, ad hoc actions.” 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%. Harou et al. (2010) evaluated economically driven California water resources management and reservoir systems operations using a hydroeconomic model. As a proxy for climate change, their simulations where driven by hydrology reflecting extreme drought from the paleorecord. The authors synthesized a 72-year drought with half of mean historical inflows (1921–1991) using random sampling of historical dry years. Model results include time series of optimized monthly operations and water allocations to maximize statewide net economic benefits that predict impacts to be expensive but not catastrophic for the overall economy; however, severe burdens would be imposed on the agricultural sector and environmental water use.

Switching 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 Climate Change Impacts on Environmental Resources

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.[21] Predicted impacts are primarily associated with projected increases in air and water temperatures and include species range shifts poleward, adjustment of migratory species arrival and departure, amphibian population declines, and effects on pests and pathogens in ecosystems. Climate change also has affected forest insect species range and abundance through changes in insect survival rates, increases in life cycle development rates, facilitation of range expansion, and effect on host plant capacity to resist attack (Ryan et al. 2008). Cayan et al. (2001) document earlier blooming of lilacs and honeysuckles correlated to increasing spring temperatures.

Chapter 2 of SAP 4.3 discusses the effects of climate change on agriculture and water resources (Hatfield et al. 2008). It addresses the many issues associated with future agricultural water demands and discusses that only a few studies have attempted to predict climate change impacts on irrigation demands. These limited study findings suggest significant irrigation requirement increases for corn and alfalfa due to increased temperatures and CO_2 and reduced precipitation. 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 and assuming that farming practices could adapt to this opportunity by planting more crop cycles per growing season. This possibility is based on studies suggesting that the average

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[21] Ansu and McCarney (2008) offer a categorized bibliography of articles related to climate change and environmental resources impacts. Readers are encouraged to review this bibliography for additional articles relevant to their specific interests.

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) 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. Christidis et al. (2007) point out that increases in growing season length also have ramifications for phenological events, with possible cascading impacts related to water storage, peak flows, and pollinators. The International Panel on Climate Change Technical Paper on Climate Change and Water includes similar discussions (Bates et al. 2008) on the above issues and noting that only a few studies have attempted to predict climate change impacts on irrigation demands.

Increased air temperatures could increase aquatic temperatures and affect fisheries habitat. In general, studies of climate change impacts on freshwater ecosystems are more straightforward with streams and rivers, which are typically well mixed and track air temperature closely, as opposed to lakes and reservoirs, where thermal stratification and depth affect habitat (Allan et al. 2005). Ficke et al. (2007) present an extensive synthesis and bibliography of literature on climate change impacts on freshwater fisheries. Fang et al. (2004a and 2004b) predicted changes to cold water fisheries habitat in terms of water temperature and dissolved oxygen under a doubled CO_2 climate change regional warming scenario for 27 lake types in the United States, including Western United States lakes. They report an overall decrease in the average length of good-growth periods and the area for which lakes cannot support cold water fish would extend significantly further north. Luce and Holden (2009) discuss the potential for fish and wildlife impacts if observed streamflow reductions trends continue into the future. 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. Williams et al. (2009) predict future adverse impacts to several species of cutthroat trout due to increased summer temperatures, uncharacteristic winter flooding, and increased wildfires resulting from climate change. Haak et al. (2010) present similar predictions for various salmonid species of the inland Western United States.

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). Burkett and Kusler (2000) discuss potential impacts to wetlands caused by climate change. Potential impacts to five different types of wetlands are discussed as well as how impacts may vary by region. Allan et al. (2005) suggest that, although freshwater ecosystems will adapt to climate change as they have to land use changes, acid rain, habitat degradation, pollution, etc., the adaptation likely will entail a diminishment of native biodiversity.

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.

Switching to nonaquatic species and ecosystem impacts, Ray et al. (2010) present a synthesis of existing climate change prediction data sets adjusted and downscaled to support efforts to determine the need of listing the American Pika under the Endangered Species Act. Significant increasing temperature trends and earlier snowmelt implications to Pika habitat are presented. Beever et al. (2010) report study findings associated with potential climate change impacts to the American Pika that include results of testing alternative models of climate-mediated extirpations. Beever et al. (2010) point out that, during 1945–2006, sites of Pika extirpations have experienced approximately a 10% increase in the number of days above 28 °C, whereas this number has decreased slightly where Pika have persisted. 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. Kirkpatrick et al. (2009) studied bird abundance in Arizona riparian woodlands and found that riparian areas contained 68% more species than adjacent uplands, regardless of whether the population consisted of breeding or nonbreeding bird communities. More important, they noted that relative abundance and richness of bird species were positively associated with surface water extent, mediated by aerial arthropod abundance (i.e., wetter areas produce more arthropods—a key source of avian food). They noted that should long-term drought conditions persist to the degree that surface water flows are reduced or eliminated then many populations of breeding birds are likely to decline. Wiens et al. (2009) used the NCAR CCSM3 and GFDL CM2.1 models in projections of bird species richness in California, and noted that, in the future, most of the portion of California in the Lower Colorado Region will have lower species richness. Their work also points to low similarity between current and future bird assemblages in southern California, which has important implications for wildlife management. Projected declines in winter precipitation in the LC Region surely will 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). Another potential effect of climate change impacts on ecosystems and watershed hydrology involves changes in vegetation disturbances due to wildfires and forest dieback. In the Western United States, increases in spring-summer temperatures lead to attenuated snow melt, reduced soil moisture, and reduced fuel moisture conditions. This, in turn, affects wildland fire activity. Such effects are discussed in chapter 3 of SAP 4.3 (Ryan et al. 2008) and also Westerling et al. (2006), which documents large increases in fire season duration and fire frequency, especially at mid-elevations, in the Western United States. Coincident with trends toward warmer and drier climate in the Western United States over the past two decades (1990–2009), forest fires have grown larger and more frequent. Both the frequency of large wildfires and fire season length increased substantially since 1985, and these changes were closely linked with advances in the timing of spring snowmelt. Hot and dry weather also allows fires to grow exponentially, covering more acreage (Lettenmaier et al. 2008).

Several studies have focused on potential future forest impacts under climate change spawned by disturbances involving forest fire or pest invasions. Westerling et al. (2006) document large increases in fire season duration and fire frequency, especially at mid-elevations. Brown et al. (2004) evaluated future (2006–2099) Western United States wildfire potential based on climate change scenarios relative to current climate conditions and current wildfire potential quantified using the Forest Service National Fire Rating System. The study predicts increased potential for large wildfires throughout most of the Western United States with the exception of the Pacific Northwest and with the greatest increase in the northern Rockies, Great Basin, and the Southwest. 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. These authors also discuss how some plant and animal species that are sensitive to fire may decline, whereas the distribution and abundance of species favored by fire may be enhanced due to increased wildfires resulting from climate change. Westerling and Bryant (2008) projected California wildfire risks for A2 and B1 SRES scenarios, using the NCAR PCM and GFDL models; the majority of the Lower Colorado Region is shown in their analysis. They found that “On average, however, the results presented here indicate that increasing temperatures would likely result in a substantial increase in the risk of large wildfires in energy-limited wildfire regimes, while the effects in moisture-limited fire regimes will be sensitive to changes in both temperature and precipitation.” They also noted that “while higher temperatures tended to promote fire risk overall, reductions in moisture due to lower precipitation and higher temperatures led to reduced fire risk in dry areas that appear to have moisture-limited fire regimes.” Low moisture reduced fine fuel production in their model experiments, which outweighed increased fuel flammability in low elevation grasslands and shrublands in much of southern California and western Arizona. Even without fire as an intermediary, increasing temperatures, increasing CO_2, and longer growing seasons can have direct effects on the establishment of invasive vegetation species (DeFalco et al. 2007; Wolkovich and Cleland 2010). Wolkovich and Cleland (2010) note that many invasive grasses, including cheatgrass (*Bromus tectorum*), annual grasses in California perennial grasslands, and perennials in California’s Mohave Desert, benefit from “seasonal priority effects” (i.e., their ability to establish earlier in the season than native vegetation, due to, for example, earlier onset of spring season). 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). Robinson et al. (2008) describe and compare several ecological models that estimate vegetation development (productivity or vegetation type) under climate change. Beukema et al. (2007) discuss the potential for increased fire risk and insect and pathogen impacts to pinyon-juniper forest ecosystems resulting from climate change. 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) and colonized ecosystems that have no history of adaptation to fire (Ryan et al. 2008).

Climate changes also can 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, evapotranspirational demand, chronic water stress, and carbon starvation (via reduced gas exchange) are a key factor in conifer species die-off in western North America (Breshears et al. 2005; Weiss et al. 2009; Adams et al. 2010; McDowell et al. 2010). 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). Ryan et al. (2008) report that several large insect outbreaks have recently occurred or are occurring in the United States, and increased temperature and drought likely influenced these outbreaks.[22] Climate change has affected forest insect species range and abundance through changes in insect survival rates, increases in life cycle development rates, facilitation of range expansion, and effect on host plant capacity to resist attack. 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 and runoff rates—as dust is transported from disturbed areas to distant mountains (Painter et al.

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[22] Numerous articles on invasive bark beetle topics are available at http://wwa.colorado.edu/ecology/beetle/references.html.

2007; Painter et al. 2010). Several large insect outbreaks have recently occurred or are occurring in the United States, and increased temperature and drought likely influenced these outbreaks (Ryan et al. 2008).

2.4 Upper Colorado Region

Numerous studies have been conducted on the potential consequences of climate change for water resources in Reclamation's Upper Colorado (UC) Region. This section summarizes findings from recent studies (1994–2010 demonstrating evidence of regional climate change during the 20th century and exploring water and environmental resources impacts associated with various climate change scenarios.[23]

2.4.1 Historical Climate and Hydrology

Over the course of the 20th century, it appears that all areas of the UC Region became warmer, but precipitation trends are less evident. Cayan et al. (2001) report that Western United States spring temperatures increased 1–3 °C (1.8–5.4 °F) between 1970 and 1998. Based on data available from the Western Climate Mapping Initiative,[24] the change in the 11-year mean during the 20th century is roughly +1.2 °C (+2.2 °F) for the Upper Colorado River Basin and +1.7 °C (+3.1 °F) for the Lower Colorado River Basin.[25] Rangwala and Miller (2010) report trends in surface air temperature for the San Juan Mountains of the UC Region from 1895 to 2005. Results show a net warming of 1 °C between 1895 and 2005 with most warming during 1990–2005.

Temperature data for UC Region locations show a warming period during the early 20th century followed by a flat, or even decreasing, period from the 1940s to the 1970s and then warming from the 1970s to present. Hence the magnitude of analyzed temperature trends varies from study to study depending on the period of analysis and trends at individual locations may differ from the regional average. Changes in annual total precipitation for UC Region locations can be found in the data, but the observed changes are small compared to the variability, making

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[23] 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 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.

[24] http://www.cefa.dri.edu/Westmap/. This Website provides a plotting interface for analysis of PRISM (http://www.prism.oregonstate.edu/) monthly temperature data.

[25] 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).

statistical detection of trends difficult. It is significant to note that annual total precipitation trends are not statistically significant at most locations in the UC Region.

Investigations for 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 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." Guentchev et al. (2010) analyzed homogeneity of three gridded precipitation datasets that have been used in studies of the Colorado River Basin. They report that all three datasets show breakpoints in 1977 and 1978 and suggest that these may be due to an anomalously rapid shift in the Pacific Decadal Oscillation. They note that, for 1950–1999, the data are sufficiently homogeneous for analyses of precipitation variability, when aggregated on a subregional scale. The authors noted that care must be taken to assure the statistical homogeneity of gridded observational precipitation datasets, and that for the Colorado River Basin, Precipitation Regression on Independent Slopes Method (PRISM) (for 1916–2006), and Maurer et al. 2002 (for 1950–1999) performed adequately.

Villarini et al. (2009) analyzed annual peak discharge records from 50 stations in the United States with 100 years of record and attempted to document reduced stationarity. However, their results were equivocal, due to evidence of human modifications affecting runoff generation (e.g., changes in land use and land cover), fluvial transportation (e.g., construction of dams and pools), and changes in measurements, all of which can induce nonclimatic nonstationarity. Consequently, they reported that they were "not able to assess whether the observed variations in annual maximum instantaneous peak discharge were due to natural climate variability or anthropogenic climate change."

Focusing on changes in precipitation extremes, the former U.S. Climate Change Science Program issued SAP 3.3 (CCSP 2008), wherein chapter 3 focuses on mechanisms for observed changes in extremes and and reports heavy precipitation events averaged over North America have increased over the past 50 years (Gutowski et al. 2008). Kunkel (2003) presents an analysis of extreme precipitation events and indicates there has been an increase in their frequency since the 1920s/1930s in the United States, although very small trends (1931–1996) were shown for the climate divisions of the UC Region; and Figdor (2007) evaluated 1948–2006 trends in extreme precipitation events for each State using the method of Kunkel et al. (1998) and report similar findings.

Painter et al. (2010) discuss the role of dust deposition on snowmelt timing and runoff amount. The relevance to climate change is that the impact of warming on runoff timing is less for dusty snow because a greater fraction of the energy needed for snowmelt comes from sunlight, not air-temperature. Also, dust can impact even relatively cold, high-elevation snowpack. Dust-on-snow is very prevalent in the Upper Colorado River Basin, with a likely origin due to human-caused land disturbance on the Colorado Plateau. Understanding the role of dust is important for interpreting the historical record since it is important not to attribute all the changes in runoff timing to warmer temperatures.

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; Woodhouse et al. 2009; Cook et al. 2010). The upshot of work examining historical and paleo-drought, is that drought and precipitation in the UC Region is primarily dominated by interannual and multidecade variations related to ocean-atmosphere interactions. This 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. Woodhouse et al. (2009) examined signatures of atmospheric circulation associated with North American drought and found two primary modes: one related to ENSO, and one related to high latitude Northern Hemisphere circulation, such as the Northern Annular Mode (Arctic Oscillation). The ENSO mode plays a key, but not exclusive, role in UCR drought and wet periods; Woodhouse et al. (2009) note that the early 20th century pluvial, which coincided with the signing of the Colorado River Compact, was characterized by a strength and persistence of both atmospheric circulation modes that was unprecedented back to the 1400s. They also note that the Medieval drought, associated with the most persistent low flows in the Colorado River Basin, was kicked off by the ENSO mode, but other factors influenced the drought after the mid-1100s.

Recent work by Ben Cook and colleagues (Cook et al. 2010) demonstrates that the Pacific Ocean is the primary driver of drought in the Upper Colorado Region, and while the direct influence of the Atlantic on drought is relatively weak, it may significantly amplify forcing from the Pacific. Cook et al. (2010) also note that land surface factors can amplify drought, such as in the Dust Bowl drought of the 1930s. This insight resonates with Painter ’s (2010) finding that a five-fold increase in dust loading, from anthropogenically disturbed soils in the Southwest, decreased snow albedo and shortened the duration of snow cover by several weeks during the last 100 years. They attribute a loss of 5% of annual average Colorado River flow, measured at Lees Ferry, to increased dust loading on snow, generating early runoff, and increased evapotranspiration from vegetation and exposed soils.

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 long-term droughts has likely been amplified by local greenhouse gas warming in recent decades." Cayan et al. (2010) used combined GCM and hydrologic models to conclude that the early 21st century Colorado River Basin drought has been the most extreme in over a century. This study defines extreme drought years as those when the area-averaged soil moisture falls below the 10th percentile for the 1951–1999 period and there were 11 such years during 1916–2008, including 2002, 2007, and 2008. Cayan et al. (2010) used combined GCM and hydrologic models to conclude that the early 21st century Colorado River Basin drought has been the most extreme in over a century. This study defines extreme drought years as those when the area-averaged soil moisture falls below the 10th percentile for the 1951–1999 period and there were 11 such years during 1916–2008, including 2002, 2007 and 2008. Matter et al. (2010) report on the application of a new methodology to characterize historical time series of UC Region temperature, precipitation, and streamflow.

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. Rangwala and Miller (2010) report trends in surface air temperature for the San Juan Mountains of the UC Region from 1895 to 2005. Results show a net warming of 1 ºC between 1895 and 2005 with most warming during 1990–2005.

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 United States stations (Knowles et al. 2007). Regonda et al. (2005) report monthly SWE trends during 1950–1999 and suggests that there were statistically significant declines in monthly SWE over roughly half of the Western United States sites evaluated for 1970–1998. Among those sites, there was no regional consensus among SWE trends over southern Montana to Colorado. One of the main results of Regonda et al. (2005) is the dependence of the results on elevation (and hence average temperature). Basins above about 2,500 meters showed little change in peak streamflow or in monthly SWE (at least for March1 and April1, and May 1 does show a signal up to about 3,000 meters).

Moreover, Stewart (2009) examined global snowpack and melt responses and noted that the greatest responses have been observed for areas that remain close to freezing throughout the winter season.

Studies that document decreasing snowpack and earlier runoff in the Colorado River Basin include Clow (2010), 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.

On explaining historical trends in regional climate and hydrology, chapter 4 of the U.S. Climate Change Science Program SAP 4.3 discusses several studies that indicate most observed trends for SWE, soil moisture and runoff in the Western United States are the result of increasing temperatures rather than precipitation effects (Lettenmaier et al. 2008). This assertion is supported by a collection of journal articles that targeted 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 naturally originating climate variations explaining observed trends. Barnett et al. (2008) performed a multiple variable formal detection and attribution study and showed how the changes in Tmin, SWE, precipitation and CT for 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, Hidalgo et al. (2009) for streamflow timing changes, and Das et al. (2009) for temperature, snow/rain days ratio, SWE, and 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. 2009).

While the trends in Western United States river flow, winter air temperature, and snow pack might be partially explained by anthropogenic influences on climate, Hoerling et al. (2010) show that it remains difficult to attribute historical precipitation variability to anthropogenic forcings. They evaluated regional precipitation data from around the world (observed and modeled) for 1977–2006. They suggest that the relationship between sea temperatures and rainfall changes are generally not symptomatic of human-induced emissions of greenhouse gases and aerosols. Rather, their results suggest that trends during this period are consistent with atmospheric response to observed sea surface temperature variability. Shin and Sardeshmukh (2010) show that the 20th century trends in PDSI are consistent with forcing by tropical sea-surface temperature trends and discuss that the sea surface temperature trends are due to a combination of natural and anthropogenic forcing. These two studies reinforce the fact that tropical SSTs can act as a “middleman” for anthropogenic climate change in the West. McAfee and Russell (2008) examined connections between the observed poleward migration of the Northern Hemisphere storm track (a global warming response suggested by current climate projections, sometimes referred to as Hadley Cell expansion [Seager et al. 2007]), atmospheric circulation over North America, and precipitation and temperature responses in the Western United States. They found that during the transition to spring, following a Northern Annular Mode (also called Arctic Oscillation) high-index winter, which is associated with poleward storm track shifts, there is a weakening of the storm track over the northeastern Pacific, resulting in warmer and drier conditions west of the Rocky Mountains. They note that these results are consistent with observations of early spring onset in the Western United States.

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 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 cause reduced snowpack development during winter, more runoff during the winter season, and earlier spring peak flows associated with an earlier snowmelt.

2.4.2 Climate Change Impacts on Hydrology and Water Resources

Several studies have been conducted to relate potential future climate scenarios to UC Region runoff and water resources management impacts. A recent paper by the Congressional Budget Office (CBO 2009) presents an overview of the current understanding of the impacts of climate change in the United States, including that warming will tend to be greater at high latitudes and in the interiors of the United States. CBO 2009 suggests that future climate conditions will feature less snowfall and more rainfall, less snowpack development, and earlier snowmelt runoff. The report also suggests that warming will lead to more intense and heavy rainfall that will tend to be interspersed with longer relatively dry periods. Lundquist et al. (2009) report similar findings.

On future temperature and precipitation projections over the Colorado River Basin and UC Region, there is greater agreement reported between model projections, and thus higher confidence, in future temperature change.[26] There is much less agreement in the sign of change and, thus, less confidence in projections for precipitation change for the Upper Colorado River Basin (Dai

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[26] Note that some researchers caution that agreement between models is not a sufficient metric for judging projection credibility (Pirtle et al. 2010), noting that the modeling community has yet to demonstrate sufficient independence between models that can be similarly flawed or biased as a result of sharing code or parameterizations.

2006). The UC Region lies between the subtropics, for which there is substantial, but not complete, model agreement on drying and the subpolar region where there is near universal model agreement on increased precipitation. The amount of consensus on sign of precipitation change also varies geographically from 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; Cayan et al. 2010; Seager and Vecchi 2010), there is little consensus among projections on whether mean-annual precipitation will increase or decrease over the northern 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).

Other notable studies on future climate projections over UC Region include Rauscher et al. (2008), which used a high-resolution, nested climate model to investigate future changes in snowmelt-driven runoff over the Western United States. Results include that runoff could occur as much as 2 months earlier than present, particularly in the Northwest; and earlier runoff timing of at least 15 days in early-, middle-, and late-season flow is projected for almost all mountainous areas where runoff is snowmelt driven. Focusing on the Rio Grande portion of the UC Region, D'Antonio (2006) reports that the projected mean-annual temperatures over New Mexico would increase by 3.3 °C (about 6 °F) in 2061–2090 compared to the 1971–2000 average, based on the multimodel average from 18 of the CMIP3 models.

Switching focus to extreme precipitation events, chapter 3 of SAP 3.3 (CCSP 2008) comments on projected future changes in extremes (Gutowski et al. 2008), suggesting 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. Sun et al. (2007) report that under 21st century modeled emissions scenarios B1 (low), A1B (medium), and A2 (high), all models consistently show a trend towards more intense and extreme precipitation for the globe as a whole and over various regions.

Several studies have assessed hydrologic impacts under projected climate conditions over the UC Region. Many of these studies have focused on the Colorado River Basin, including 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, which tend 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). 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. Third, the choice of GCMs and emissions scenarios used in the aforementioned studies also had some effect on the projected Colorado River Basin changes (Lettenmaier et al. 2008). A systematic comparison of these studies (Hoerling et al. 2009) yields some interesting insights into hydrology models, input data, and likely levels of Colorado River runoff decline. First, Hoerling and Eischeid (2007) now believe that their estimate of a 45-percent runoff reduction overstates potential Colorado River losses. Using different but equally valid downscaling methods, VIC model projections of future runoff changed from a 5% reduction by 2050 (Christensen and Lettenmaier 2007) to a 10% reduction. A key difference between hydrology models used in Colorado River runoff projections is the runoff sensitivity to temperature changes; Hoerling et al. (2010) found that sensitivity ranged from 2–9% runoff reduction per degree Celsius increase in temperature—which implies a large range of runoff reductions, 4-18% by 2050. Based on their assessment of these and other factors, Hoerling et al. estimate 2050 Colorado River flow declines of 5–20%.

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 3.5–13.7% in 2030 and 8.3–28.7% 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 under a 3 °C (5.4 ºF) temperature increase for the Rio Grande Basin and reported respective April and May runoff increases of 158 and 89% and decreases for all other months based on 1983 conditions. D'Antonio (2006) reports that drastic reductions in Rio Grande spring runoff by the end of the century likely are based on evaluation of an 18-GCM average relative to a 1971–2000 average baseline.

On extreme hydrologic events, Gutzler and Robbins (2010) note that projected trends in PDSI imply that higher evaporation rates, associated with positive temperature trends, exacerbate drought severity and extent such that "the projected trend towared warmer temperatures inhibit recovery from droughts caused by decade-scale precipitation deficits." Switching focus from droughts to floods, some studies suggest that change in extreme precipitation and runoff could present flood control challenges to varying degrees at many locations, but possibly to lesser degrees in snowmelt dominated basins. Hamlet and Lettenmaier (2007) cite decreasing flood quantiles in snowmelt dominated systems due to lower spring snowpack. It should be noted that this is an area where the existence of dust-on-snow complicates matters, since this phenomenon can lead to rapid snowmelt. Raff et al. 2009 introduced a framework for estimating flood frequency in the context of climate projection information. The framework was applied to a set of four diverse basins in the Western United States (i.e., the Boise River above Lucky Peak Dam, the San Joaquin River above Friant Dam, the James River above Jamestown Dam, and the Gunnison River above Blue Mesa Dam). Results for three of the four basins (Boise, San Joaquin, and James) showed that, under current climate projection information, probability distributions of annual maximum discharge would feature greater flow rates at all quantiles. For the fourth basin (Gunnison), greater flow rates were projected for roughly the upper third of quantiles. Granted, this study represents a preliminary effort, focused on introducing a framework for estimating flood frequency in a changing climate. Results are limited by various uncertainties, including how the climate projection information used in the analysis did not reflect potential changes in storm frequency and duration (only changes in storm intensity relative to historical storm events)

Such future impacts on hydrology have been shown to have implications for water resources management. Chapter 4 of SAP 4.3 focuses on water resources effects and suggests that management of Western United States reservoir systems is very likely to become more challenging as net annual runoff decreases and interannual patterns continue to change as the result of climate change (Lettenmaier et al. 2008). Numerous studies have focused on the Colorado River Basin (Nash and Gleick 1991 and 1993; Christensen et al. 2004; Christensen and Lettenmaier 2007). These studies are similar in that they portray potential operations impacts on the Colorado River system associated with different scenarios of projected future climate and hydrology, as summarized in Reclamation (2007). 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 (Reclamation 2007). 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, three other water management impacts studies on the Colorado River Basin were conducted, relating historical and projected climate and hydrology to system impacts (McCabe and Wolock 2007; Barnett and Pierce 2008; Rajagopalan et al. 2009). 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 1490–1997. Rajagopalan et al. (2009) predicted similar impacts as to McCabe and Wolock (2007). Barnett and Pierce (2008) reported more severe potential operations impacts, but this study was later revised (Barnett and Pierce 2009a), modifiying several original assessment assumptions (Barsugli et al. 2009) and leading to results more consistent with Rajagopalan et al. (2009). For both studies, the risk of shortage on the whole system increases greatly in the 2020s and beyond. However, Barnett and Pierce (2009a) still insist that the whole upper basin is already in a deficit of 1 million acre-feet a year because a) climate change has already robbed the basin of several hundred thousand acre-feet annually and b) that the 20th century average is “wet” compared to the longer-term flows in the basin, and one should expect a reversion to a lower mean flow.

Although system impacts are not analyzed as in the studies discussed in the previous paragraph, Cayan et al. (2010) predict significant future Colorado River Basin impacts in terms of drought (runoff, SWE, and soil moisture). Predictions are based on the output from combined GCM and hydrologic models showing increased drought conditions (severity and duration) during the 21st century—especially so during the second half of the century.

Switching to demand impacts, Ramirez and Finnerty (1996) evaluated the effects of increased air temperatures and atmospheric CO_2 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 Climate Change Impacts on Environmental Resources

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.[27] Predicted impacts are primarily associated with projected increases in air and water temperatures and include species range shifts poleward, adjustment of migratory species arrival and departure, amphibian population declines, and effects on pests, and pathogens in ecosystems. Climate change also has affected forest insect species range and abundance through changes in insect survival rates, increases in life cycle development rates, facilitation of range expansion, and the effect on host plant capacity to resist attack (Ryan et al. 2008). Cayan et al. (2001) document earlier blooming of lilacs and honeysuckles correlated to increasing spring temperatures.

Chapter 2 of SAP 4.3 discusses the effects of climate change on agriculture and water resources (Hatfield et al. 2008). It addresses the many issues associated with future agricultural water demands and discusses that only a few studies have attempted to predict climate change impacts on irrigation demands. These limited study findings suggest significant irrigation requirement increases for corn and alfalfa due to increased temperatures and CO_2 and reduced precipitation. 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 and assuming that farming practices could adapt to this opportunity by planting more crop cycles per growing season. 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). Christidis et al. (2007) point out that increases in growing season length also have ramifications for phenological events, with possible cascading impacts related to water storage, peak flows, and pollinators. The International Panel on Climate Change Technical Paper on Climate Change and Water includes similar discussions (Bates et al. 2008) on the above issues and noting that only a few studies have attempted to predict climate change impacts on irrigation demands.

Increased air temperatures could increase aquatic temperatures and affect fisheries habitat. In general, studies of climate change impacts on freshwater ecosystems are more straightforward with streams and rivers, which are typically well mixed and track air temperature closely, as opposed to lakes and reservoirs, where thermal stratification and depth affect habitat (Allan et al. 2005). Ficke et al.

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[27] Ansu and McCarney (2008) offer a categorized bibliography of articles related to climate change and environmental resources impacts. Readers are encouraged to review this bibliography for additional articles relevant to their specific interests.

(2007) present an extensive synthesis and bibliography of literature on climate change impacts on freshwater fisheries. Fang et al. (2004a and 2004b) predicted changes to cold water fisheries habitat in terms of water temperature and dissolved oxygen under a doubled CO_2 climate change regional warming scenario for 27 lake types in the United States, including Western United States lakes. They report an overall decrease in the average length of good-growth periods and the area for which lakes cannot support cold water fish would extend significantly further north. Luce and Holden (2009) discuss the potential for fish and wildlife impacts if observed streamflow reductions trends continue into the future. Williams et al. (2009) predict future adverse impacts to several species of cutthroat trout due to increased summer temperatures, uncharacteristic winter flooding, and increased wildfires resulting from climate change. Haak et al. (2010) present similar predictions for various salmonid species of the inland western United States.

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). Burkett and Kusler (2000) discuss potential impacts to wetlands caused by climate change. Potential impacts to five different types of wetlands are discussed as well as how impacts may vary by region. Allan et al. (2005) suggest that, although freshwater ecosystems will adapt to climate change as they have to land use changes, acid rain, habitat degradation, pollution, etc., the adaptation likely will entail a diminishment of native biodiversity.

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 also could 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.

Switching to nonaquatic species and ecosystem impacts, Ray et al. (2010) present a synthesis of existing climate change prediction data sets adjusted and downscaled to support efforts to determine the need of listing the American Pika under the Endangered Species Act. Significant increasing temperature trends and earlier snowmelt implications to Pika habitat are presented. Beever et al. (2010) report study findings associated with potential climate change impacts to the American Pika that include results of testing alternative models of climate-mediated extirpations.

Another potential effect of climate change impacts on ecosystems and watershed hydrology involves changes in vegetation disturbances due to wildfires and forest dieback. In the Western United States, increases in spring-summer temperatures lead to attenuated snow melt, reduced soil moisture, and reduced fuel moisture conditions. This, in turn, affects wildland fire activity. Such effects are discussed in chapter 3 of SAP 4.3 (Ryan et al. 2008) and also Westerling et al. (2006), which document large increases in fire season duration and fire frequency, especially at mid-elevations, in the Western United States. Coincident with trends toward warmer and drier climate in the Western United States over the past two decades (1990–2009), forest fires have grown larger and more frequent. Both the frequency of large wildfires and fire season length increased substantially since 1985, and these changes were closely linked with advances in the timing of spring snowmelt. Hot and dry weather also allows fires to grow exponentially, covering more acreage (Lettenmaier et al. 2008).

Several studies have focused on potential future forest impacts under climate change spawned by disturbances involving forest fire or pest invasions. Westerling et al. (2006) document large increases in fire season duration and fire frequency, especially at mid-elevations. Brown et al. (2004) evaluated future (2006–2099) Western United States wildfire potential based on climate change scenarios relative to current climate conditions and current wildfire potential quantified using the Forest Service National Fire Rating System. The study predicts increased potential for large wildfires throughout most of the Western United States with the exception of the Pacific Northwest and with the greatest increase in the northern Rockies, Great Basin, and the Southwest United States. 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. These authors also discuss how some plant and animal species that are sensitive to fire may decline, whereas the distribution and abundance of species favored by fire may be enhanced due to increased wildfires resulting from climate change. Robinson et al. (2008) describe and compare several ecological models that estimate vegetation development (productivity or vegetation type) under climate change. Beukema et al. (2007) discuss the potential for increased fire risk and insect and pathogen impacts to pinyon-juniper and spruce-fir forest ecosystems resulting from climate change.

Climate changes also can 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). For example, Ryan et al. (2008) report that several large insect outbreaks recently have occurred or are occurring in the United States, and increased temperature and drought likely influenced these outbreaks.[28] Climate change has affected forest insect species range and abundance through changes in insect survival rates, increases in life

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[28] Numerous articles on invasive bark beetle topics are available at http://wwa.colorado.edu/ecology/beetle/references.html.

cycle development rates, facilitation of range expansion, and effect on host plant capacity to resist attack. 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.

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

Numerous studies have been conducted on the potential consequences of climate change for water resources in Reclamation's Great Plains (GP) Region. This section summarizes findings from recent studies (1994–2010) demonstrating evidence of regional climate change during the 20th century and exploring water and environmental resources impacts associated with various climate change scenarios.[29]

2.5.1 Historical Climate and Hydrology

Over the course of the 20th century, it appears that all areas of the GP Region became warmer, and some areas received more winter precipitation during the 20th century. Cayan et al. (2001) report that Western United States 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 Great Plains to approximately 0.63 °F (0.35 °C) in the southern Great Plains between 1901 and 2008.[30] That dataset also reveals an increase in annual precipitation of more than 4% in the northern Great Plains and 10% in the southern Great Plains over the same period. The trend was more consistent in the

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[29] Relative to Reclamation's other four regions, a limited number of studies have been conducted on the potential consequences of climate change for water resources that are specific to Reclamation's 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.

[30] 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).

southern Great Plains. Regonda et al. (2005) report increased winter precipitation trends during 1950–1999 at many Western United States sites, including numerous sites in the western GP Region, but a consistent region-wide Great Plains 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 snowfall to winter precipitation ratios from 1949–2005 also are indicated in the northern GP Region by Feng and Hu (2007). Reduced snowpack and snowfall ratios are indicated by analyses of 1948–2001 SWE measurements at 173 Western United States stations (Knowles et al. 2007). Regonda et al. (2005) report monthly SWE trends during 1950–1999 and suggest that there were statistically significant declines in monthly SWE over roughly half of the Western United States sites evaluated for 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. Similarly, Clow (2010) evaluated 1978–2007 SWE and runoff data for the Colorado mountains and found strong, pervasive trends in streamflow timing shifting earlier by about 2–3 weeks, and April 1 and maximum SWE declined 3.6 and 4.1 cm per decade, respectively. Stewart (2009) examined global snowpack and melt responses and noted that the greatest responses have been observed for areas that remain close to freezing throughout the winter season.

Villarini et al. (2009) analyzed annual peak discharge records from 50 stations in the United States with 100 years of record and attempted to document reduced stationarity. However, their results were equivocal, due to evidence of human modifications affecting runoff generation (e.g., changes in land use and land cover), fluvial transportation (e.g., construction of dams and pools), and changes in measurements, all of which can induce nonclimatic nonstationarity. Consequently, they reported that they were "not able to assess whether the observed variations in annual maximum instantaneous peak discharge were due to natural climate variability or anthropogenic climate change."

Focusing on changes in precipitation extremes, the former U.S. Climate Change Science Program issued SAP 3.3 (CCSP 2008), wherein chapter 3 focuses on mechanisms for observed changes in extremes and and reports heavy precipitation events averaged over North America have increased over the past 50 years (Gutowski et al. 2008). Kunkel (2003) presents an analysis of extreme precipitation events and indicates that there has been an increase in their frequency since the 1920s/1930s in the United States, although very small trends (1931–1996) were shown for the climate divisions of the GP Region. Madsen and Figdor (2007) evaluated 1948–2006 trends in extreme precipitation events for each State using the method of Kunkel et al. (1998).

Painter et al. (2010) discuss the role of dust deposition on snowmelt timing and runoff amount. The relevance to climate change is that the impact of warming on runoff timing is less for dusty snow because a greater fraction of the energy needed for snowmelt comes from sunlight, not air-temperature. Also, dust can impact even relatively cold, high-elevation snowpack. Dust-on-snow is very prevalent in the Upper Colorado River Basin, with a likely origin due to human-caused land disturbance on the Colorado Plateau. Understanding the role of dust is important for interpreting the historical record since it is important not to attribute all the changes in runoff timing to warmer temperatures.

On explaining historical trends in regional climate and hydrology, chapter 4 of the U.S. Climate Change Science Program SAP 4.3 discusses several studies that indicate most observed trends for SWE, soil moisture, and runoff in the Western United States are the result of increasing temperatures rather than precipitation effects (Lettenmaier et al. 2008). This assertion is supported by a collection of journal articles that targeted 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 naturally originating climate variations explaining observed trends. Barnett et al. (2008) performed a multiple variable formal detection and attribution study and showed how the changes in Tmin, SWE, precipitation and CT for 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, Hidalgo et al. (2009) for streamflow timing changes, and Das et al. (2009) for temperature, snow/rain days ratio, SWE, and 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. 2009).

While the trends in Western United States river flow, winter air temperature, and snow pack might be partially explained by anthropogenic influences on climate, Hoerling et al. (2010) show that it remains difficult to attribute historical precipitation variability to anthropogenic forcing. They evaluated regional precipitation data from around the world (observed and modeled) for 1977–2006. They suggest that the relationship between SSTs and rainfall changes are generally not symptomatic of human-induced emissions of greenhouse gases and aerosols. Rather, their results suggest that trends during this period are consistent with atmospheric response to observed SST variability. Shin and Sardeshmukh (2010) show that the 20th century trends in PDSI are consistent with forcing by tropical SST trends and discuss that the SST trends are due to a combination of natural and anthropogenic forcing. These two studies reinforce the fact that tropical SSTs can act as a “middleman” for anthropogenic climate change in the

West. McAfee and Russell (2008) examined connections between the observed poleward migration of the Northern Hemisphere storm track (a global warming response suggested by current climate projections, sometimes referred to as Hadley Cell expansion [Seager et al. 2007]), atmospheric circulation over North America, and precipitation and temperature responses in the Western United States. They found that, during the transition to spring, following a Northern Annular Mode (also called Arctic Oscillation) high-index winter, which is associated with poleward storm track shifts, there is a weakening of the storm track over the northeastern Pacific, resulting in warmer and drier conditions west of the Rocky Mountains. They note that these results are consistent with observations of early spring onset in the Western United States.

Other research has suggested that warming-induced increases in thunderstorm activity of the GP Region (and most of the contiguous United States) (Changnon 2001) has led to an increase in heavy precipitation events since 1900 (Groisman 2004). Garbrecht et al. (2004) found similar patterns of increasing annual streamflow in watersheds in the central Great Plains through 2001 from various starting points before 1950, particularly during spring and winter. They also found that modest changes in precipitation (+12%) led to relatively larger increases in streamflow (64%) but lesser increases in evapotranspiration (5%). Most of the increases in streamflow had occurred by about 1990, and the trends had reversed in some watersheds through 2001.

Mauget (2004) evaluated data from 42 Hydro Climatic Data Network stations across the Great Plains and Midwest for 1939–1998. Generally, higher flow periods occurred at the end of the period, which resulted in positive streamflow trends. Analysis of daily streamflow data indicates negative trends in the number of drought events and positive trends in the number of surplus days.

Kunkel et al. (2007) urged caution in interpreting temporal variations in SWE studies using data from the Cooperative Observer Program (COOP) network due to inhomogeneities in observational practices. There was less concern for studies in the Western United States than for the eastern GP Region. In a followup study using stations with a long-term homogenous record, Kunkel et al. (2009) found snowfall declines from 1920–21 to 2006–07 in the central Great Plains and large percentage increases in the lee of the Rocky Mountains and parts of the north-central Great Plains. This study notes that snowfall is an important climate variable since it is the primary process for the replenishment of snow cover and the SWE of the snowpack. Additionally, Dyer and Mote (2006) note that changes in depth of the snowpack over North America will have impacts on regional hydrological systems through changes in runoff.

These findings are significant for regional water resources management and reservoir operations in the western and northern Great Plains 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 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.

2.5.2 Climate Change Impacts on Hydrology and Water Resources

Several studies have been conducted to relate potential future climate scenarios to GP Region runoff and water resources management impacts. A recent paper by the Congressional Budget Office (CBO 2009) presents an overview of the current understanding of the impacts of climate change in the United States. Their findings indicate that warming will tend to be greater at high latitudes and in the interiors of the United States. CBO 2009 suggests that future climate conditions will feature less snowfall and more rainfall, less snowpack development, and earlier snowmelt runoff. The report also suggests that warming will lead to more intense and heavy rainfall that will tend to be interspersed with longer relatively dry periods. Lundquist et al. (2009) report similar findings. Such studies are particularly relevant to the western Great Plains headwaters and the central to northern High Plains.

For the GP Region east of the High Plains, and especially in the southern Great Plains, 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. Future projections of precipitation for the southern GP Region are further complicated by the limitations on the ability of climate models to portray the frequency and intensity of warm-season convection events or tropical storm systems tracking into the region.[31]

On future temperature and precipitation projections over the GP Region, there is greater agreement reported between model projections and, thus, higher confidence in future temperature change.[32] There is much less agreement in the sign of change and, thus, less confidence, in projections for precipitation change for *middle latitude* regions (Dai 2006). The amount of consensus on sign of precipitation change also varies geographically from northern to southern portions of the GP Region, with the northern limits of the region having a projection consensus toward wetter conditions and the southwestern limits having consensus toward drier conditions (appendix B).

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[31] See http://www.isp.ucar.edu/water and http://www.nar.ucar.edu/2008/ESSL/sp2/#03.

[32] Note that some researchers caution that agreement between models is not a sufficient metric for judging projection credibility (Pirtle et al. 2010), noting that the modeling community has yet to demonstrate sufficient independence between models that can be similarly flawed or biased as a result of sharing code or parameterizations.

Other notable studies on future climate projections over the GP Region include Rauscher et al. (2008), who used a high-resolution, nested climate model to investigate future changes in snowmelt-driven runoff over the Western United States. Results include that runoff could occur as much as 2 months earlier than present, particularly in the Northwest; and earlier runoff timing of at least 15 days in early-, middle-, and late-season flow is projected for almost all mountainous areas where runoff is snowmelt driven.

Switching focus to extreme precipitation events, chapter 3 of SAP 3.3 (CCSP 2008) comments on projected future changes in extremes (Gutowski et al. 2008), suggesting 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. Sun et al. (2007) report that, under 21st century modeled emissions scenarios B1 (low), A1B (medium), and A2 (high), all models consistently show a trend toward more intense and extreme precipitation for the globe as a whole and over various regions.

Several studies have assessed hydrologic impacts under projected climate conditions. The findings of six case studies on the sensitivity of water resources to climate change are reported by Lettenmaier 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. Rosenberg et al. (1999) report 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. On extreme hydrologic events, Raff et al. (2009) introduced a framework for estimating flood frequency in the context of climate projection information. The framework was applied to a set of four diverse basins in the Western United States (i.e., the Boise River above Lucky Peak Dam, the San Joaquin River above Friant Dam, the James River above Jamestown Dam, and the Gunnison River above Blue Mesa Dam). Results for three of the four basins (Boise, San Joaquin, and James) showed that, under current climate projection information, probability distributions of annual maximum discharge would feature greater flow rates at all quantiles. For the fourth basin (Gunnison), greater flow rates were projected for roughly the upper third of quantiles. Granted, this study represents a preliminary effort, focused on introducing a framework for estimating flood frequency in a changing climate. Results are limited by various uncertainties, including how the climate projection information used in the analysis did not reflect potential changes in storm frequency and duration (only changes in storm intensity relative to historical storm events).

Such future impacts on hydrology have been shown to have implications for water resources management. Chapter 4 of SAP 4.3 focuses on water resources effects and suggests that management of Western United States reservoir systems is very likely to become more challenging as net annual runoff decreases and interannual patterns continue to change as the result of climate change (Lettenmaier et al. 2008). 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. On managing for system flood risk, Lettenmaier 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. Changes in extreme precipitation and runoff could present flood control challenges to varying degrees at many locations, but possibly to lesser degrees in snowmelt dominated basins. Hamlet and Lettenmaier (2007) cite decreasing flood quantiles in snowmelt dominated systems due to lower spring snowpack. It should be noted that this is an area where the existence of dust-on-snow complicates matters, since this phenomenon can lead to rapid snowmelt. Their findings also 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. Trapp et al. (2007) looked at future changes in deep convection (i.e., severe thunderstorms) due to a warming climate and found increases in the number of days with suitable conditions for warm-season severe storms for most of the GP Region, particularly in the summer months. The associated increase in heavy precipitation events inherent with deep convection could bring increased flood risk.

Switching to water demands, 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.

2.5.3 Climate Change Impacts on Environmental Resources

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.[33] Predicted impacts are primarily associated with projected increases in air and water temperatures and include species range shifts poleward, adjustment of migratory species arrival and departure, amphibian population declines, and effects on pests and pathogens in ecosystems. Climate change also has affected forest insect species range and abundance through changes in insect survival rates, increases in life cycle development rates, facilitation of range expansion, and effect on host plant capacity to resist attack (Ryan et al. 2008). Cayan et al. (2001) document earlier blooming of lilacs and honeysuckles correlated to increasing spring temperatures.

Chapter 2 of SAP 4.3 discusses the effects of climate change on agriculture and water resources (Hatfield et al. 2008). It addresses the many issues associated with future agricultural water demands and that only a few studies have attempted to predict climate change impacts on irrigation demands. These limited study findings suggest significant irrigation requirement increases for corn and alfalfa due to increased temperatures and CO_2 and reduced precipitation. 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 and, assuming that farming practices could adapt to this opportunity, by planting more crop cycles per growing season. 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). Christidis et al. (2007) point out that increases in growing season length also have ramifications for phenological events, with possible cascading impacts related to water storage, peak flows, and pollinators. The International Panel on Climate Change Technical Paper on Climate Change and Water includes similar discussions (Bates et al. 2008), offering similar discussions on the above issues and noting that only a few studies have attempted to predict climate change impacts on irrigation demands.

Increased air temperatures could increase aquatic temperatures and affect fisheries habitat. In general, studies of climate change impacts on freshwater ecosystems are more straightforward with streams and rivers, which are typically well mixed and track air temperature closely, as opposed to lakes and reservoirs, where

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[33] Ansu and McCarney (2008) offer a categorized bibliography of articles related to climate change and environmental resources impacts. Readers are encouraged to review this bibliography for additional articles relevant to their specific interests.

thermal stratification and depth affect habitat (Allan et al. 2005). Ficke et al. (2007) present an extensive synthesis and bibliography of literature on climate change impacts on freshwater fisheries. Fang et al. (2004a and 2004b) predicted changes to cold water fisheries habitat in terms of water temperature and dissolved oxygen under a doubled CO_2 climate change regional warming scenario for 27 lake types in the United States, including Western United States lakes. They report an overall decrease in the average length of good-growth periods and the area for which lakes cannot support cold water fish would extend significantly further north. Williams et al. (2009) predict future adverse impacts to several species of cutthroat trout due to increased summer temperatures, uncharacteristic winter flooding, and increased wildfires resulting from climate change. Haak et al. (2010) present similar predictions for various salmonid species of the inland Western United States.

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). Allan et al. (2005) suggest that, although freshwater ecosystems will adapt to climate change as they have to land use changes, acid rain, habitat degradation, pollution, etc., the adaptation likely will entail a diminishment of native biodiversity. McCarty (2001) report night time temperature increases in northeastern Colorado resulting in a significant decline in the dominant native grass.

Covich et al. (1997) summarize 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). Johnson et al. (2005) used a wetland simulation model to predict significant climate change impacts to the northern pothole prairie region. Mathews (2008) reports on climate change-related impacts to playa lakes of the High Plains. 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. Burkett and Kusler (2000) discuss potential impacts to wetlands caused by climate change. Potential impacts to five different types of wetlands are discussed as well as how impacts may vary by region.

Climate change impacts on Great Plains pothole wetland areas and playa lakes have been studied (Johnson et al. 2005, Mathews 2008 and Scanlon et al. 2007), 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 pest 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.

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 also could 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.

Switching to nonaquatic species and ecosystem impacts, Ray et al. (2010) present a synthesis of existing climate change prediction data sets adjusted and downscaled to support efforts to determine the need of listing the American Pika under the Endangered Species Act. Significant increasing temperature trends and earlier snowmelt implications to Pika habitat are presented. Beever et al. (2010) report study findings associated with potential climate change impacts to the American Pika that include results of testing alternative models of climate-mediated extirpations. 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.

Another potential effect of climate change impacts on ecosystems and watershed hydrology involves changes in vegetation disturbances due to wildfires and forest dieback. In the Western United States, increases in spring-summer temperatures lead to attenuated snow melt, reduced soil moisture, and reduced fuel moisture conditions. This, in turn, affects wildland fire activity. Such effects are discussed in chapter 3 of SAP 4.3 (Ryan et al. 2008) and also Westerling et al. (2006), which document large increases in fire season duration and fire frequency, especially at mid-elevations, in the Western United States. Coincident with trends toward warmer and drier climate in the Western United States over the past two decades (1990–2009), forest fires have grown larger and more frequent. Both the frequency of large wildfires and fire season length increased substantially since 1985, and these changes were closely linked with advances in the timing of spring snowmelt. Hot and dry weather also allows fires to grow exponentially, covering more acreage (Lettenmaier et al. 2008).

Several studies have focused on potential future forest impacts under climate change spawned by disturbances involving forest fire or pest invasions. Westerling et al. (2006) document large increases in fire season duration and fire frequency, especially at mid-elevations. Brown et al. (2004) evaluated future (2006–2099) Western United States wildfire potential based on climate change scenarios relative to current climate conditions and current wildfire potential quantified using the Forest Service National Fire Rating System. The study predicts increased potential for large wildfires throughout most of the Western United States with the exception of the Pacific Northwest and with the greatest increase in the northern Rockies, Great Basin, and the Southwest United States. McKenzie et al. (2004) project increases in the number of days with high fire danger and acres burned, respectively, because of increasing temperatures and related climate changes. These authors also discuss how some plant and animal species that are sensitive to fire may decline, whereas the distribution and abundance of species favored by fire may be enhanced due to increased wildfires resulting from climate change. Robinson et al. (2008) describe and compare several ecological models that estimate vegetation development (productivity or vegetation type) under climate change. Beukema et al. (2007) discuss the potential for increased fire risk and insect and pathogen impacts to pinyon-juniper forest ecosystems in the mountainous western border of the Great Plains Region resulting from climate change.

Climate changes also can 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 effects 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). For example, Ryan et al. (2008) report that several large insect outbreaks have recently occurred or are occurring in the United States, and increased temperature and drought likely influenced these outbreaks.[34] Climate change has affected forest insect species range and abundance through changes in insect survival rates, increases in life cycle development rates, facilitation of range expansion, and effect on host plant capacity to resist attack. 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.

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[34] Numerous articles on invasive bark beetle topics are available at http://wwa.colorado.edu/ecology/beetle/references.html.

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 and wildlife, 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, hydropower, and environmental resources. 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 “Western United States” 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

3.1.1 Runoff and Surface Water Supplies

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 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 (Lettenmaier et al. 1999; Hamlet and Lettenmaier 1999; Payne et al. 2004; Elsner et al. 2010). Projected reductions in spring and summer snowmelt runoff largely are balanced by increases in winter runoff as more precipitation 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 (Payne et al. 2004). Based on current reservoir operations constraints (e.g., capacity, flood control rules), it appears that such runoff shifts would lead to reduced water supplies under current system and operating conditions. This follows the understanding that storage opportunities during winter runoff season currently are limited by flood control considerations at many reservoirs and that increased winter runoff under climate change won’t necessarily translate into increased storage of water leading into the spring season. Conversely, storage capture of snowmelt runoff traditionally has occurred during the late spring and early summer seasons. Reductions in runoff during this season likely would translate into reductions in storage capture and, likewise, reductions in water supply for warm season delivery.

3.1.2 Flood Control

In Western United States reservoir systems with flood control objectives in currently snowmelt-dominated basins, warming without precipitation change 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. 2009b; Lee 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) that may further affect dry season water supplies (e.g., spring refill beginning with less winter carryover storage).

3.1.3 Hydropower

Hydroelectric generation is highly sensitive to climate change effects on precipitation and river discharge. SAP 4.5 (Bull et al. 2007) indicates that hydropower operations also are 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 4.5 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. Net effects of on total energy demand are projected to be modest (±5% per 1 °C). 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 climate change impacts for individual species and ecosystems. Projected climate changes are likely to have an array of interrelated and cascading ecosystem impacts. At present, most predicted impacts are primarily associated with projected increases in air and water temperatures and include increased stress on fisheries that are sensitive to a warming aquatic habitat, potentially improved habitat for quagga mussels bearing implications for maintenance of hydraulic structures, and increased risk of watershed vegetation disturbances due to increased fire potential. Other warming-related impacts include poleward shifts in the geographic range of various species, impacts on the arrival and departure of migratory species, amphibian population declines, and effects on pests and pathogens in ecosystems. Climate change also can trigger synergistic effects in ecosystems and exacerbate invasive species problems.

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 natural groundwater recharge are sensitive to climate warming. Additionally, 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

Potential climate change-related impacts to agricultural, municipal and industrial, and instream water demands are difficult to predict; and existing information on the subject is limited. It is widely accepted in the literature that water demand impacts will occur due to increased air temperatures and atmospheric CO_2 levels and changes in precipitation, winds, humidity, and atmospheric aerosol and ozone levels. Further, these impacts must be considered in combination with socioeconomic impacts including future changes in infrastructure, land use, technology, and human behavior.

Agricultural water demands include those associated with crop irrigation and livestock consumption. The predominant water demand in the Western United States is for agricultural irrigation. Approximately 85% of the consumptive use water demand in the 17 Western States is for irrigation (Frederick 1997). Given that the atmosphere’s moisture holding capacity increases when air temperature increases, it seems intuitive that plant water consumption and surface water evaporation associated with agricultural demands will increase in a warming climate. However, it’s understood that crop water needs respond to not only temperature and precipitation conditions but also atmospheric CO_2, ozone, and potential evapotranspiration (which, in turn, is affected by solar radiation, humidity, and wind speed). Uncertainties in projecting climate change impacts on these connditions lead to uncertainties in future irrigation demands.

On the matter of joint changes in climate and CO_2, Baldocchi and Wong (2006) and Bloom (2010) report that, to varying degrees, plants respond to increased CO_2 by closing their stomata. This stomal closure results in a net reduction in plant transpiration and water consumption. Additionally, Baldocchi and Wong (2006) found that increasing CO_2 concentrations tend to, at least initially, increase plant growth and vigor. Larger plants growing more vigorously should use more water. Although increased temperatures may result in increased growth, when temperatures exceed the optimal range for various plant types, growth is diminished. As an example, increased winter temperatures due to climate warming in California’s Central Valley may eventually preclude growing certain fruit crops that require a certain amount of chilling hours prior to flowering (Baldocchi and Wong 2006).

On evaporation potential, 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 and wind speed) that are not congruous with the notion of increasing air temperatures. Historical potential evapotranspiration data typically are limited and inconsistent; however, Hidalgo et al. (2005) report no appreciable trends in their review of California Irrigation Management Information System (CIMIS) data for 1990–2002. Consequently, there is uncertainty about how physically driven agricultural water demands may change under climate change.

Besides potential direct influences from changes in climate, CO_2, and potential evapotranspiration, 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 become longer and assuming that farming practices could adapt to this opportunity by planting more crop cycles per growing season. 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). Gunther et al. (2006) predict significant increases in 21st century irrigation demands for North America based on combined GCM and socioeconomic scenarios. Some studies predict that agricultural lands requiring irrigation may increase by up to 40% due to climate change, and livestock water demands will increase significantly (Pacific Institute 2009).

Although changes in water demands associated with natural processes may be difficult to quantify, municipal and industrial consumption increases associated with population growth will occur. Domestic water use is not very sensitive to changes in temperature and precipitation (Frederick 1997), and water conservation measures may offset potential increases in per capita water usage. Although the use of new water efficient appliances and fixtures will increase through institutional measures and mandates, socioeconomic factors will impact water conservation.

Nonbeneficial consumptive uses associated with agricultural demands (reservoir evaporation and conveyance and onfarm application losses) are significant. Reservoir evaporation may increase if warming temperatures override other factors, but other agricultural losses may be reduced in the future with more efficient application methods and conveyance improvements.

Water demands for industrial cooling and thermoelectric power production likely will increase with warmer air and water temperatures (Frederick 1997). Although demands may not increase, certain industries are extremely reliant on reliable water supplies (semiconductor, beverage, pharmaceutical, etc.).

Potential instream water demand increases resulting from climate change could include ecosystem demands, hydropower and thermoelectric power production, industrial cooling, and navigation and recreational uses. Water demands for endangered species and other fish and wildlife could increase with ecosystem impacts due to warmer air and water temperatures and resulting hydrologic impacts (i.e., runoff timing). Diversions and consumptive use by thermoelectric power production and industrial cooling facilities are predicted to increase since these processes will function less efficiently with warmer air and water temperatures. The timing of these diversions and those for hydropower production could also be a factor in ecosystem demands and navigation and recreational water uses.

As climate change might affect water supplies and reservoir operations, the resultant effects on 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

3.2.1 Runoff and Surface Water Supplies

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 (Van Rheenan et al. 2004; Anderson et al. 2008; Brekke et al. 2009b; Null et al. 2010). 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 a 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.

This seasonal timing shift in runoff could present challenges in managing increasing winter streamflow and decreasing late spring and early summer streamflow. Based on current reservoir operations constraints (e.g., capacity, flood control rules), it appears that such runoff shifts would lead to reduced water supplies under current system and operating conditions. This follows the understanding that storage opportunities during winter runoff season currently are limited by flood control considerations at many reservoirs, and that increased winter runoff under climate change won't necessarily translate into increased storage of water leading into the spring season. Conversely, storage capture of snowmelt runoff traditionally has occurred during the late spring and early summer seasons. Reductions in runoff during this season likely would translate into reductions in storage capture and, likewise, reductions in water supply for warm season delivery.

3.2.2 Flood Control

In Western United States reservoir systems with flood control objectives in currently snowmelt-dominated basins, warming without precipitation change 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. 2009b and Lee 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) that may further affect dry season water supplies (e.g., spring refill beginning with less winter carryover storage).

3.2.3 Hydropower

Hydroelectric generation is highly sensitive to climate change effects on precipitation and river discharge. SAP 4.5 (Bull et al. 2007) indicates that hydropower operations also are 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 4.5 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. Net effects of on total energy demand are projected to be modest (±5% per 1 °C). 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).

Harou et al. (2010) evaluated California economic and water supply systems operations impacts using a hydroeconomic model based on a paleorecord data based drought scenario rather than downscaled GCM results. The authors report a predicted 60% reduction in hydropower generation under the modeled 70-year drought scenario. Null et al. (2010) predict that the most valuable western-slope Sierra Nevada watersheds with regard to hydropower are the most vulnerable to changes in runoff timing and hydropower production impacts. These predictions are based on the results of a rainfall-runoff model with 2, 4, and 6 °C air temperature increases with no precipitation change.

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 climate change impacts for individual species and ecosystems. Projected climate changes are likely to have an array of interrelated and cascading ecosystem impacts. At present, most predicted impacts are primarily associated with projected increases in air and water temperatures and include increased stress on fisheries that are sensitive to a warming aquatic habitat, potentially improved habitat for quagga mussels bearing implications for maintenance of hydraulic structures, and increased risk of watershed vegetation disturbances due to increased fire potential. Other warming-related impacts include poleward shifts in the geographic range of various species, impacts on the arrival and departure of migratory species, amphibian population declines, and effects on pests and pathogens in ecosystems. Climate change also can trigger synergistic effects in ecosystems and exacerbate invasive species problems.

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.

Dettinger and Cayan (2003) studied the relationship between San Francisco Bay estuary salinity levels and interseasonal inflows from the eight major river basins that flush the bay. Monthly reconstructions of full natural flow quantities for 1906-1992 were analyzed, and distinct ‘modes’ of seasonal flow and runoff variability were characterized. The study findings underscore the need to predict future runoff conditions to manage estuary salinity and especially for in the central middle-altitude river basins that are most susceptible to climate change impacts. Knowles and Cayan (2004) evaluated GCM-based projected runoff conditions for the western Sierra Nevada river basins and found that the shift of water in mid-elevations of the Sacramento River basin from snowmelt to rainfall runoff is the dominant cause of projected changes in San Francisco Bay estuarine inflows and salinity.

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 natural groundwater recharge are sensitive to climate warming. Additionally, 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

Potential climate change-related impacts to agricultural, municipal and industrial, and instream water demands are difficult to predict and existing information on the subject is limited. It is widely accepted in the literature that water demand impacts will occur due to increased air temperatures and atmospheric CO_2 levels and changes in precipitation, winds, humidity, and atmospheric aerosol and ozone levels. Further, these impacts must be considered in combination with socioeconomic impacts including future changes in infrastructure, land use, technology, and human behavior.

Agricultural water demands include those associated with crop irrigation and livestock consumption. The predominant water demand in the Western United States is for agricultural irrigation. Approximately 85% of the consumptive use water demand in the 17 Western States is for irrigation (Frederick 1997). Given that the atmosphere’s moisture holding capacity increases when air temperature increases, it seems intuitive that plant water consumption and surface water evaporation associated with agricultural demands will increase in a warming climate. However, it’s understood that crop water needs respond to not only temperature and precipitation conditions but also atmospheric CO_2, ozone, and potential evapotranspiration (which, in turn, is affected by solar radiation, humidity, and wind speed). Uncertainties in projecting climate change impacts on these connditions lead to uncertainties in future irrigation demands.

On the matter of joint changes in climate and CO_2, Baldocchi and Wong (2006) and Bloom (2010) report that, to varying degrees, plants respond to increased CO_2 by closing their stomata. This stomal closure results in a net reduction in plant transpiration and water consumption. Additionally, Baldocchi and Wong (2006) found that increasing CO_2 concentrations tend to, at least initially, increase plant growth and vigor. Larger plants growing more vigorously should use more water. Although increased temperatures may result in increased growth, when temperatures exceed the optimal range for various plant types, growth is diminished. As an example, increased winter temperatures due to climate warming in California’s

Central Valley may eventually preclude growing certain fruit crops which require a certain amount of chilling hours prior to flowering (Baldocchi and Wong 2006).

On evaporation potential, 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 and wind speed) that are not congruous with the notion of increasing air temperatures. Historical potential evapotranspiration data typically are limited and inconsistent; however, Hidalgo et al. (2005) report no appreciable trends in their review of CIMIS data for 1990–2002. Consequently, there is uncertainty about how physically driven agricultural water demands may change under climate change.

Besides potential direct influences from changes in climate, CO_2, and potential evapotranspiration, 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 become longer and assuming that farming practices could adapt to this opportunity by planting more crop cycles per growing season. 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). Gunther et al. (2006) predict significant increases in 21st century irrigation demands for North America based on combined GCM and socioeconomic scenarios. Some studies predict that agricultural lands requiring irrigation may increase by up to 40% due to climate change, and livestock water demands will increase significantly (Pacific Institute 2009).

Although changes in water demands associated with natural processes may be difficult to quantify, municipal and industrial consumption increases associated with population growth will occur. Domestic water use is not very sensitive to changes in temperature and precipitation (Frederick 1997), and water conservation measures may offset potential increases in per capita water usage. Although the use of new water efficient appliances and fixtures will increase through institutional measures and mandates, socioeconomic factors will impact water conservation.

Nonbeneficial consumptive uses associated with agricultural demands (reservoir evaporation and conveyance and onfarm application losses) are significant. Reservoir evaporation may increase if warming temperatures override other factors, but other agricultural losses may be reduced in the future with more efficient application methods and conveyance improvements.

Water demands for industrial cooling and thermoelectric power production likely will increase with warmer air and water temperatures (Frederick 1997). Although demands may not increase, certain industries are extremely reliant on reliable water supplies (semiconductor, beverage, pharmaceutical, etc.).

Potential instream water demand increases resulting from climate change could include ecosystem demands, hydropower and thermoelectric power production, industrial cooling, and navigation and recreational uses. Water demands for endangered species and other fish and wildlife could increase with ecosystem impacts due to warmer air and water temperatures and resulting hydrologic impacts (i.e., runoff timing). Diversions and consumptive use by thermoelectric power production and industrial cooling facilities are predicted to increase since these processes will function less efficiently with warmer air and water temperatures. The timing of these diversions and those for hydropower production could also be a factor in ecosystem demands and navigation and recreational water uses.

As climate change might affect water supplies and reservoir operations, the resultant effects on 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

3.3.1 Runoff and Surface Water Supplies

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.

Warming could also lead to shifts in the seasonal timing of runoff with increased winter runoff and decreased summer runoff. This shift in timing could present challenges in managing increasing winter streamflow and decreasing late spring and early summer streamflow. Based on current reservoir operations constraints (e.g., capacity, flood control rules), it appears that such runoff shifts would lead to reduced water supplies under current system and operating conditions. This follows the understanding that storage opportunities during winter runoff season currently are limited by flood control considerations at many reservoirs and that increased winter runoff under climate change won't necessarily translate into increased storage of water leading into the spring season. Conversely, storage capture of snowmelt runoff traditionally has occurred during the late spring and early summer seasons. Reductions in runoff during this season likely would translate into reductions in storage capture and, likewise, reductions in water supply for warm season delivery.

3.3.2 Flood Control

In Western United States reservoir systems with flood control objectives in currently snowmelt-dominated basins, warming without precipitation change 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. 2009b; Lee 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) that 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

Hydroelectric generation is highly sensitive to climate change effects on precipitation and river discharge. SAP 4.5 (Bull et al. 2007) indicates that hydropower operations also are 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 4.5 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. Net effects of on total energy demand are projected to be modest (±5% per 1 °C). 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).

Harou et al. (2010) evaluated California economic and water supply systems operations impacts using a hydroeconomic model based on a paleorecord data based drought scenario rather than downscaled GCM results. The authors report a predicted 60% reduction in hydropower generation under the modeled 70-year drought scenario.

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 climate change impacts for individual species and ecosystems. Projected climate changes are likely to have an array of interrelated and cascading ecosystem impacts. At present, most predicted impacts are primarily associated with projected increases in air and water temperatures and include increased stress on fisheries that are sensitive to a warming aquatic habitat, potentially improved habitat for quagga mussels bearing implications for maintenance of hydraulic structures, and increased risk of watershed vegetation disturbances due to increased fire potential. Other warming-related impacts include poleward shifts in the geographic range of various species, impacts on the arrival and departure of migratory species, amphibian population declines, and effects on pests and pathogens in ecosystems. Climate change also can trigger synergistic effects in ecosystems and exacerbate invasive species problems.

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 natural groundwater recharge are sensitive to climate warming. Additionally, 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

Potential climate change-related impacts to agricultural, municipal and industrial, and instream water demands are difficult to predict and existing information on the subject is limited. It is widely accepted in the literature that water demand impacts will occur due to increased air temperatures and atmospheric CO_2 levels and changes in precipitation, winds, humidity, and atmospheric aerosol and ozone levels. Further, these impacts must be considered in combination with socioeconomic impacts including future changes in infrastructure, land use, technology, and human behavior.

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On evaporation potential, 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 and wind speed) that are not congruous with the notion of increasing air temperatures. Historical potential evapotranspiration data typically are limited and inconsistent; however, Hidalgo et al. (2005) report no appreciable trends in their review of CIMIS data for 1990–2002. Consequently, there is uncertainty about how physically driven agricultural water demands may change under climate change.

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Bark et al. (2009) discuss 21st century climate change impacts on water demands for Arizona skiing industry snowmaking that are based on downscaled ECHAM5 and HadCM3 projections.

Although changes in water demands associated with natural processes may be difficult to quantify, municipal and industrial consumption increases associated with population growth will occur. Domestic water use is not very sensitive to changes in temperature and precipitation (Frederick 1997), and water conservation measures may offset potential increases in per capita water usage. Although the use of new water efficient appliances and fixtures will increase through institutional measures and mandates, socioeconomic factors will impact water conservation.

Nonbeneficial consumptive uses associated with agricultural demands (reservoir evaporation and conveyance and on-arm application losses) are significant. Reservoir evaporation may increase if warming temperatures override other factors, but other agricultural losses may be reduced in the future with more efficient application methods and conveyance improvements.

Water demands for industrial cooling and thermoelectric power production likely will increase with warmer air and water temperatures (Frederick 1997). Although demands may not increase, certain industries are extremely reliant on reliable water supplies (semiconductor, beverage, pharmaceutical, etc.).

Potential instream water demand increases resulting from climate change could include ecosystem demands, hydropower and thermoelectric power production, industrial cooling, and navigation and recreational uses. Water demands for endangered species and other fish and wildlife could increase with ecosystem impacts due to warmer air and water temperatures and resulting hydrologic impacts (i.e., runoff timing). Diversions and consumptive use by thermoelectric power production and industrial cooling facilities are predicted to increase since these processes will function less efficiently with warmer air and water temperatures. The timing of these diversions and those for hydropower production could also be a factor in ecosystem demands and navigation and recreational water uses.

As climate change might affect water supplies and reservoir operations, the resultant effects on 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. Demands for field-scale irrigation water supplies might increase further to the extent that existing demands partially are satisfied by precipitation and that precipitation is projected to decrease gradually over the LC Region.

3.4 Upper Colorado Region

3.4.1 Runoff and Surface Water Supplies

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 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).

This seasonal timing shift in runoff could present challenges in managing increasing winter streamflow and decreasing late spring and early summer streamflow. Based on current reservoir operations constraints (e.g., capacity, flood control rules), it appears that such runoff shifts would lead to reduced water supplies under current system and operating conditions. This follows the understanding that storage opportunities during winter runoff season currently are limited by flood control considerations at many reservoirs and that increased winter runoff under climate change won't necessarily translate into increased storage of water leading into the spring season. Conversely, storage capture of snowmelt runoff traditionally has occurred during the late spring and early summer seasons. Reductions in runoff during this season likely would translate into reductions in storage capture and, likewise, reductions in water supply for warm season delivery. It should be noted that these impacts may geographically vary within the UC Region. The high elevation headwaters of the UC Region are projected to see more modest declines in snowpack than lower-elevation mountain ranges elsewhere in the West (Christensen and Lettenmaier 2007) and increased attention is being paid to the role of dust-on-snow in the snowmelt process and in streamflow timing and annual runoff volume (Painter et al. 2010).

3.4.2 Flood Control

In Western United States reservoir systems with flood control objectives in currently snowmelt-dominated basins, warming without precipitation change 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. 2009b and Lee 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) that may further affect dry season water supplies (e.g., spring refill beginning with less winter carryover storage).

3.4.3 Hydropower

Hydroelectric generation is highly sensitive to climate change effects on precipitation and river discharge. SAP 4.5 (Bull et al. 2007) indicates that hydropower operations also are 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 4.5 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. Net effects of on total energy demand are projected to be modest (±5% per 1 °C). 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 climate change impacts for individual species and ecosystems. Projected climate changes are likely to have an array of interrelated and cascading ecosystem impacts. At present, most predicted impacts are primarily associated with projected increases in air and water temperatures and include increased stress on fisheries that are sensitive to a warming aquatic habitat, potentially improved habitat for quagga mussels bearing implications for maintenance of hydraulic structures, and increased risk of watershed vegetation disturbances due to increased fire potential. Other warming-related impacts include poleward shifts in the geographic range of various species, impacts on the arrival and departure of migratory species, amphibian population declines, and effects on pests and pathogens in ecosystems. Climate changes also can trigger synergistic effects in ecosystems and exacerbate invasive species problems.

3.4.5 Water Quality

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3.4.7 Water Demand

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On evaporation potential, 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 and wind speed) that are not congruous with the notion of increasing air temperatures. Historical potential evapotranspiration data typically are limited and inconsistent; however, Hidalgo et al. (2005) report no appreciable trends in their review of CIMIS data for 1990–2002. Consequently, there is uncertainty about how physically driven agricultural water demands may change under climate change.

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Water demands for industrial cooling and thermoelectric power production likely will increase with warmer air and water temperatures (Frederick 1997). Although demands may not increase, certain industries are extremely reliant on reliable water supplies (semiconductor, beverage, pharmaceutical, etc.).

Potential instream water demand increases resulting from climate change could include ecosystem demands, hydropower and thermoelectric power production, industrial cooling, and navigation and recreational uses. Water demands for endangered species and other fish and wildlife could increase with ecosystem impacts due to warmer air and water temperatures and resulting hydrologic impacts (i.e., runoff timing). Diversions and consumptive use by thermoelectric power production and industrial cooling facilities are predicted to increase since these processes will function less efficiently with warmer air and water temperatures. The timing of these diversions and those for hydropower production could also be a factor in ecosystem demands and navigation and recreational water uses.

As climate change might affect water supplies and reservoir operations, the resultant effects on 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.

3.5 Great Plains Region

3.5.1 Runoff and Surface Water Supplies

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 in the western and northern Great Plains and decreased runoff during summer in all areas of the Great Plains. 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 a minor change in dry season water supply (albeit, with significantly increased winter runoff to manage).

This seasonal timing shift in runoff could present challenges in managing increasing winter streamflow and decreasing late spring and early summer streamflow. Based on current reservoir operations constraints (e.g., capacity, flood control rules), it appears that such runoff shifts would lead to reduced water supplies under current system and operating conditions. This follows the understanding that storage opportunities during winter runoff season are currently limited by flood control considerations at many reservoirs, and that increased winter runoff under climate change won't necessarily translate into increased storage of water leading into the spring season. Conversely, storage capture of snowmelt runoff has traditionally occurred during the late spring and early summer seasons. Reductions in runoff during this season would likely translate into reductions in storage capture and likewise reductions in water supply for warm season delivery.

3.5.2 Flood Control

In Western United States reservoir systems with flood control objectives in currently snowmelt-dominated basins, warming without precipitation change 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. 2009b and Lee 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) that may further affect dry season water supplies (e.g., spring refill beginning with less winter carryover storage).

3.5.3 Hydropower

Hydroelectric generation is highly sensitive to climate change effects on precipitation and river discharge. SAP 4.5 (Bull et al. 2007) indicates that hydropower operations also are 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 4.5 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. Net effects of on total energy demand are projected to be modest (±5% per 1 °C). 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 climate change impacts for individual species and ecosystems. Projected climate changes are likely to have an array of interrelated and cascading ecosystem impacts. At present, most predicted impacts are primarily associated with projected increases in air and water temperatures and include increased stress on fisheries that are sensitive to a warming aquatic habitat, potentially improved habitat for quagga mussels bearing implications for maintenance of hydraulic structures, and increased risk of watershed vegegation disturbances due to increased fire potential. Other warming-related impacts include poleward shifts in the geographic range of various species, impacts on the arrival and departure of migratory species, amphibian population declines, and effects on pests and pathogens in ecosystems. Climate changes also can trigger synergistic effects in ecosystems and exacerbate invasive species problems.

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 natural groundwater recharge are sensitive to climate warming. Additionally, 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. In addition, 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

Potential climate change-related impacts to agricultural, municipal and industrial, and instream water demands are difficult to predict and existing information on the subject is limited. It is widely accepted in the literature that water demand impacts will occur due to increased air temperatures and atmospheric CO_2 levels and changes in precipitation, winds, humidity, and atmospheric aerosol and ozone levels. Further, these impacts must be considered in combination with socioeconomic impacts including future changes in infrastructure, land use, technology, and human behavior.

Agricultural water demands include those associated with crop irrigation and livestock consumption. The predominant water demand in the Western United States is for agricultural irrigation. Approximately 85% of the consumptive use water demand in the 17 Western States is for irrigation (Frederick 1997). Given that the atmosphere’s moisture-holding capacity increases when air temperature increases, it seems intuitive that plant water consumption and surface water evaporation associated with agricultural demands will increase in a warming climate. However, it’s understood that crop water needs respond to not only temperature and precipitation conditions but also atmospheric CO_2, ozone, and potential evapotranspiration (which is, in turn, affected by solar radiation, humidity, and wind speed). Uncertainties in projecting climate change impacts on these connditions lead to uncertainties in future irrigation demands.

On the matter of joint changes in climate and CO_2, Baldocchi and Wong (2006) and Bloom (2010) report that, to varying degrees, plants respond to increased CO_2 by closing their stomata. This stomal closure results in a net reduction in plant transpiration and water consumption. Additionally, Baldocchi and Wong (2006) found that increasing CO2 concentrations tend to, at least initially, increase plant growth and vigor. Larger plants growing more vigorously should use more water. Although increased temperatures may result in increased growth, when temperatures exceed the optimal range for various plant types, growth is diminished. As an example, increased winter temperatures due to climate warming in California’s Central Valley may eventually preclude growing certain fruit crops that require a certain amount of chilling hours prior to flowering (Baldocchi and Wong 2006).

On evaporation potential, 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 and wind speed) that are not congruous with the notion of increasing air temperatures. Historical potential evapotranspiration data typically are limited and inconsistent; however, Hidalgo et al. (2005) report no appreciable trends in their review of CIMIS data for 1990–2002. Consequently, there is uncertainty about how physically driven agricultural water demands may be altered under climate change.

Besides potential direct influences from changes in climate, CO_2, and potential evapotranspiration, 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 become longer and assuming that farming practices could adapt to this opportunity by planting more crop cycles per growing season. 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). Gunther et al. (2006) predict significant increases in 21st century irrigation demands for North America based on combined GCM and socioeconomic scenarios. Some studies predict that agricultural lands requiring irrigation may increase by up to 40% due to climate change, and livestock water demands will increase significantly (Pacific Institute 2009).

Although changes in water demands associated with natural processes may be difficult to quantify, municipal and industrial consumption increases associated with population growth will occur. Domestic water use is not very sensitive to changes in temperature and precipitation (Frederick 1997), and water conservation measures may offset potential increases in per capita water usage. Although the use of new water-efficient appliances and fixtures will increase through institutional measures and mandates, socioeconomic factors will impact water conservation.

Nonbeneficial consumptive uses associated with agricultural demands (reservoir evaporation and conveyance and onfarm application losses) are significant. Reservoir evaporation may increase if warming temperatures override other factors, but other agricultural losses may be reduced in the future with more efficient application methods and conveyance improvements.

Water demands for industrial cooling and thermoelectric power production likely will increase with warmer air and water temperatures (Frederick 1997). Although demands may not increase, certain industries are extremely reliant on reliable water supplies (semiconductor, beverage, pharmaceutical, etc.).

Potential instream water demand increases resulting from climate change could include ecosystem demands, hydropower and thermoelectric power production, industrial cooling, and navigation and recreational uses. Water demands for endangered species and other fish and wildlife could increase with ecosystem impacts due to warmer air and water temperatures and resulting hydrologic impacts (i.e., runoff timing). Diversions and consumptive use by thermoelectric power production and industrial cooling facilities are predicted to increase since these processes will function less efficiently with warmer air and water temperatures. The timing of these diversions and those for hydropower production could also be a factor in ecosystem demands and navigation and recreational water uses.

As climate change might affect water supplies and reservoir operations, the resultant effects on 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. 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 represented adequately 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),[35] which discusses rationale for the downscaling

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

technique used, its limitations,[36] 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).[37] 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 1950–2099 and at a spatial resolution of 1/8° (approximately [~]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 always are 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

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

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

year 1900 (sometimes from multiple initial conditions, leading to multiple historical "runs").[38] 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.[39] 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.

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

[39] 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 being 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 being 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 being 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 a 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

This appendix contains a tabulated summary of cited references and other references pertaining to the subject matter of this report and an associated comprehensive bibliography. The tables are subdivided into the categories of peer reviewed journal articles, peer reviewed synthesis documents and reports, and nonpeer reviewed documents. Information summarized in each table includes resource themes, time coverage, and geographic coverage.

Resource themes include: regional or local climate change, runoff and surface water supplies, sea level rise, flood control, hydropower, ecosystems, water quality, ground water, and water demand. Time coverage is historical and future. Geographic coverage is broken into the five Bureau of Reclamation (Reclamation) regions: Pacific Northwest (PN); Mid-Pacific (MP); Lower Colorado (LC); Upper Colorado (UC); and Great Plains (GP).

The summarized information is based on cursory reviews performed by the authors, and every effort has been made to ensure accuracy. However, given the large amount of information summarized and the potential for misinterpretations and errors, the reader should use the summary for a guide and verify all information before using or citing this report as a source.

Peer Reviewed Journal Articles

Journal Articles (Peer Reviewed)	Resource Theme(s)										Time Coverage		Geographic Coverage				
	Regional or Local Climate Change	Runoff and Surface Water Supplies	Sea Level Rise	Eco-systems	Water Quality	Ground-water	Water Demand	Reservoir System Operations	Flood Control	Hydro-power	Historical	Future	PN	MP	LC	UC	GP
Adams et al. 2009				X								x			X	X	
Allen 2007				X							X					X	
Allen et al. 2010				X							X	X	X	X	X	X	X
Ansu and McCarney 2008				X									X	X	X	X	X
Anderson et al. 2008				X												X	
Andreadis and Lettenmaier 2006	X	X									X		X	X	X	X	X
Bala et al. 2008	X										X	X	X	X	X	X	X
Baldocchi and Wong 2006				X			X					X		X	X		
Bark et al. 2009							X					X			X		
Barnett et al. 2008	X	X						X			X		X	X	X	X	X
Barnett and Pierce 2009a		X										X			X	X	
Barnett and Pierce 2009b	X	X					X	X			X	X			X	X	
Barnett and Pierce 2008		X										X			X	X	
Barsugli et al. 2009		X										X			X	X	
Battin et al. 2007	X			X								X	X				
Battles et al. 2008				X								X		X			
Beauchamp and Stromberg 2007				X											X	X	X
Beckley et al. 2007			X								X			X	X		
Beever et al. 2010				X							X	X	X	X	X	X	X
Bell and Sloan 2006									X			X					
Bell et al. 2004	X			X								X		X	X		
Bloom 2010				X			X				X	X	X	X	X	X	X
Bonfills et al. 2008	X	X									X		X	X	X	X	X
Bonfils et al. 2007	X										X			X	X		
Brekke et al. 2009a	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X
Brekke et al. 2009b		X						X				X		X			
Brekke et al. 2008	X	X										X	X	X	X	X	X
Brown et al. 2004	X			X								X	X	X	X	X	X

Peer Reviewed Journal Articles

Journal Articles (Peer Reviewed)	Resource Theme(s)										Time Coverage		Geographic Coverage				
	Regional or Local Climate Change	Runoff and Surface Water Supplies	Sea Level Rise	Eco-systems	Water Quality	Ground-water	Water Demand	Reservoir System Operations	Flood Control	Hydro-power	Historical	Future	PN	MP	LC	UC	GP
Burkett and Kusler 2000	X			X							X	X	X	X	X	X	X
Caldwell 2010	X											X		X	X		
Casola et al. 2009	X	X									X	X	X				
Cayan et al. 2010	X	X									X	X			X	X	
Cayan et al. 2008			X									X		X	X		
Cayan et al. 2001		X		X							X		X	X	X	X	X
Changnon 2001	X								X		X		X	X	X	X	X
Christidis et al. 2007				X			X				X	X	X	X	X	X	X
Christensen and Lettenmaier 2007		X										X			X	X	
Christensen et al. 2004		X										X			X	X	
Church and White 2006			X								X			X			
Clow 2010		X									X					X	X
Conley and Kemp 2001				X							X						X
Cook et al. 2010	X	X									X		X	X	X	X	X
Cook et al. 2004	X	X									X		X	X	X	X	X
Cooney et al. 2005				X								X					X
Covich et al. 1997				X								X				X	X
Crimmins et al. 2009				X							X		X	X	X	X	X
Dai et al. 2009		X									X		X	X	X	X	X
Dai 2006	X											X	X	X	X	X	X
Das et al. 2009		X									X		X	X	X	X	X
DeFalco et al. 2007				X								X			X		
Dettinger 2005	X											X		X	X		
Dettinger et al. 2004		X									X	X		X			
Dettinger and Cayan 2003		X		X	X						X			X			
Dettinger and Cayan 1995		X									X			X	X		
Diffenbaugh and Ashfaq 2010	X											X	X	X	X	X	X
Diffenbaugh et al. 2008	X											X	X	X	X	X	X

Peer Reviewed Journal Articles

Journal Articles (Peer Reviewed)	Resource Theme(s)										Time Coverage		Geographic Coverage				
	Regional or Local Climate Change	Runoff and Surface Water Supplies	Sea Level Rise	Eco-systems	Water Quality	Ground-water	Water Demand	Reservoir System Operations	Flood Control	Hydro-power	Historical	Future	PN	MP	LC	UC	GP
Diffenbaugh et al. 2005	X			X					X			X	X	X	X	X	X
Dominguez et al. 2010	X											X			X	X	
Dyer and Mote 2006	X	X									X		X	X	X	X	X
Easterling 2002	X										X		X	X	X	X	X
Eddy 1996	X										X					X	
Elgaali et al. 2007	X						X				X	X					X
Ellis et al. 2008		X										X			X		
Elsner et al. 2010	X	X										X	X				
Fang et al. 2004a				X								X	X	X	X	X	X
Fang et al. 2004b				X								X	X	X	X	X	X
Favre and Gershunov 2008	X										X	X	X	X	X	X	X
Feng and Hu 2007	X	X									X		X	X	X	X	X
Ficke et al. 2007				X								X	X	X	X	X	X
Garbrecht et al. 2004	X	X					X				X						X
Garfin et al. 2010	X											X			X	X	
Georgi and Mearns 2002	X											X	X	X	X	X	X
Gershunov et al. 2009	X											X		X	X		
Giorgi and Mearns 1991	X											X	X	X	X	X	X
Gleckler et al. 2008	X											X	X	X	X	X	X
Gober et al. 2010	X						X					X			X		
Groisman et al. 2004	X	X									X		X	X	X	X	X
Groismand and Knight 2008	X										X		X	X	X	X	X
Grotch and McCracken 1991	X											X	X	X	X	X	X
Guentchev et al. 2010	X										X				X	X	
Gunther et al. 2006							X					X	X	X	X	X	X
Gutzler et al. 2010	X	X									X	X	X	X	X	X	X
Gutzler et al. 2005	X										X	X	X	X	X	X	X
Hamlet and Lettenmaier 2007		X	X								X		X	X	X	X	X

Peer Reviewed Journal Articles

	Resource Theme(s)										Time Coverage		Geographic Coverage				
Journal Articles (Peer Reviewed)	Regional or Local Climate Change	Runoff and Surface Water Supplies	Sea Level Rise	Eco-systems	Water Quality	Ground-water	Water Demand	Reservoir System Operations	Flood Control	Hydro-power	Historical	Future	PN	MP	LC	UC	GP
Hamlet and Lettenmaier 1999		X						X				X	X				
Hamlet et al. 2007		X					X				X		X	X	X	X	X
Hamlet et al. 2005	X										X		X	X	X	X	X
Harou et al. 2010	X	X						X		X		X		X	X		
Hayhoe et al. 2004	X	X										X		X	X		
Hellmann et al. 2008				X								X	X	X	X	X	X
Hidalgo et al. 2009		X									X		X	X	X	X	X
Hidalgo et al. 2008a		X									X		X	X	X	X	X
Hidalgo et al. 2008b	X										X		X	X	X	X	X
Hidalgo et al. 2005							X				X				X	X	
Hoerling and Eischeid 2007	X	X										X			X	X	
Hoerling et al. 2010	X										X		X	X	X		
Hoerling et al. 2009		X										X			X	X	
Hotchkiss et al. 2000	X	X										X					X
Hurd and Conrood 2007		X		X			X					X				X	
Hughes and Diaz 2008	X			X							X	X	X	X	X	X	X
Johnson et al. 2005				X													X
Kalra et al. 2008		X											X	X	X	X	X
Kelly and Goulden 2008				X							X		X	X	X	X	X
Kennedy et al. 2009				X								X			X	X	X
Kittel et al. 1995				X								X	X	X	X	X	X
Knowles 2010			X									X		X			
Knowles and Cayan 2004		X		X	X							X		X			
Knowles et al. 2007	X										X		X	X	X	X	X
Kunkel 2003	X										X		X	X	X	X	X
Kunkel et al. 2009	X	X									X		X	X	X	X	X
Kunkel et al. 2007	X	X									X		X	X	X	X	X
Kunkel et al. 2003	X										X		X	X	X	X	X

Peer Reviewed Journal Articles

Journal Articles (Peer Reviewed)	Resource Theme(s)										Time Coverage		Geographic Coverage				
	Regional or Local Climate Change	Runoff and Surface Water Supplies	Sea Level Rise	Eco-systems	Water Quality	Ground-water	Water Demand	Reservoir System Operations	Flood Control	Hydro-power	Historical	Future	PN	MP	LC	UC	GP
Kunkel et al. 1998	X										X		X	X	X	X	X
Lee et al. 2009								X	X			X	X				
Lettenmaier 2004		X									X		X	X	X	X	X
Lettenmaier et al. 2008b				X			X				X	X	X	X	X	X	X
Lettenmaier et al. 1999		X										X	X				X
Leung et al. 2004	X											X	X	X	X	X	X
Lewis and Hathaway 2002		X									X					X	
Lin et al. 2008	X											X	X	X	X	X	X
Littell et al. 2009	X			X								X	X				
Loaiciga et al. 2000						X						X					X
Logan et al. 2003				X								X	X	X	X	X	X
Luce and Holden 2009		X		X							X	X	X				
Lundquist et al. 2009		X									X	X	X	X	X	X	X
MacDonald 2008	X	X									X				X		
MacDonald et al. 2008	X	X									X	X			X		
Madsen and Figdor 2007		X							X		X	X	X	X	X	X	X
Mauget 2004		X									X						X
Mantua et al. 2009	X			X								X	X				
Marinec and Rango 1989		X										X				X	
Matter et al. 2010		X					X				X					X	
Maurer 2007		X										X		X			
Maurer et al. 2010	X	X										X		X	X		
Maurer et al. 2007		X									X			X			
McAfee and Russell 2008	X	X									X	X	X	X	X	X	X
McCabe et al. 2004	X										X		X	X	X	X	X
McCabe and Wolock 2007		X										X			X	X	
McCarty 2001				X							X	X	X	X	X	X	X
McDowell et al. 2010				X							X	X	X	X	X	X	X
McKenzie et al. 2004				X								X	X	X	X	X	X
McKinney et al. 2008				X							X				X		

Peer Reviewed Journal Articles

Journal Articles (Peer Reviewed)	Resource Theme(s)										Time Coverage		Geographic Coverage				
	Regional or Local Climate Change	Runoff and Surface Water Supplies	Sea Level Rise	Eco-systems	Water Quality	Ground-water	Water Demand	Reservoir System Operations	Flood Control	Hydro-power	Historical	Future	PN	MP	LC	UC	GP
Meehl et al. 2004	X											X	X	X	X	X	X
Meko et al. 2007	X	X									X					X	
Miller and Schlegel 2006	X			X								X		X	X		
Milly et al. 2005		X										X	X	X	X	X	X
Minder 2010	X	X										X	X				
Mohensi et al. 2003				X								X	X	X	X	X	X
Moser et al. 2009	X	X	X	X							X	X		X	X		
Mote 2006		X									X		X	X	X	X	X
Mote and Salathe 2009	X		X									X	X				
Mote et al. 2008		X									X		X				
Mote et al. 2005		X									X		X	X	X	X	X
Mote et al. 2003		X		X								X	X				
Nash and Gleick 1993	X	X										X			X	X	
Nash and Gleick 1991	X	X										X			X	X	
Nozawa et al. 2007	X											X	X	X	X	X	X
Null et al. 2010		X								X		X		X	X		
Ojima et al. 1999		X		X			X					X					X
Pagano et al. 2004	X										X		X	X	X	X	X
Painter et al. 2010		X									X				X	X	X
Painter et al. 2007		X											X	X	X	X	X
Pan et al. 2004	X											X					X
Passell et al. 2004		X									X					X	
Payne et al. 2004		X										X	X				
Peterson et al. 2008		X									X			X	X		
Peierce et al. 2009	X											X	X	X	X	X	X
Pierce et al. 2008		X									X		X	X	X	X	X
Pirtle et al. 2010	X											X	X	X	X	X	X
Poiani and Johnson 1993				X								X					X
Purkey et al. 2008	X	X					X					X		X			
Raff et al. 2009									X			X	X	X		X	X

Peer Reviewed Journal Articles

Journal Articles (Peer Reviewed)	Resource Theme(s)										Time Coverage		Geographic Coverage				
	Regional or Local Climate Change	Runoff and Surface Water Supplies	Sea Level Rise	Eco-systems	Water Quality	Ground-water	Water Demand	Reservoir System Operations	Flood Control	Hydro-power	Historical	Future	PN	MP	LC	UC	GP
Rahel and Olden 2008				X								X	X	X	X	X	X
Rahmstorf 2007			X								X	X		X			
Rahel et al. 2008				X								X	X	X	X	X	X
Ramirez and Finnerty 1996							X					X				X	
Rajagopalan et al. 2009		X					X	X			X	X			X	X	
Rangwala and Miller 2010	X										X					X	
Rauscher et al. 2008		X										X	X	X	X	X	X
Ray et al. 2010				X							X	X	X	X	X	X	X
Reclamation 2009	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Reclamation 2007		X					X	X	X	X	X	X			X	X	
Regonda et al. 2005		X									X		X	X	X	X	X
Reichler and Kim 2008	X										X	X	X	X	X	X	X
Revelle and Waggoner 1983	X										X	X	X	X	X	X	X
Rosenweig et al. 2001				X							X	X					
Rosenberg et al. 2010	X	X									X	X	X				
Rosenberg et al. 1999		X				X	X					X					X
Scanlon et al. 2007				X							X						X
Seager and Vecchi 2010	X											X		X	X	X	X
Seager et al. 2007	X	X										X		X	X	X	X
Serrat-Capdevila et al. 2007	X	X										X			X		
Sheppard et al. 2002	X										X				X	X	X
Shin and Sardeshmukh 2010	X										X		X	X	X	X	X
Slaughter and Wiener 2007							X				X		X				
Stefan et al. 2001	X			X								X	X	X	X	X	X
Stewart 2009		X									X		X	X	X	X	X
Stewart et al. 2005	X	X									X		X	X	X	X	X
Stewart et al. 2004		X										X	X	X	X	X	X
Stine 1994	X										X			X			
Stoelinga et al. 2010	X	X									X		X				

Peer Reviewed Journal Articles																	
	Resource Theme(s)										Time Coverage		Geographic Coverage				
Journal Articles (Peer Reviewed)	Regional or Local Climate Change	Runoff and Surface Water Supplies	Sea Level Rise	Eco-systems	Water Quality	Ground-water	Water Demand	Reservoir System Operations	Flood Control	Hydro-power	Historical	Future	PN	MP	LC	UC	GP
Stromberg et al. 2007				X							X	X			X		
Sun et al. 2007	X	X										X	X	X	X	X	X
Tebaldi et al. 2006	X										X	X	X	X	X	X	X
Thompson et al. 2008			X								X			X	X		
Trapp et al. 2007	X	X							X			X	X	X	X	X	X
Van Rheenen et al. 2004	X	X						X				X		X			
Vano et al. 2009	X	X					X					X	X				
Vermeer and Rahmstorf			X								X	X		X			
Vicuna et al. 2010		X						X				X		X			
Villarini et al. 2009									X		x		X	X	X	X	X
Washington et al. 2000	X										X	X	X	X	X	X	X
Weiss and Overpeck 2005	X										X				X		
Weiss et al. 2009	X	X									X				X	X	
Westerling and Bryant 2008				X										X	X		
Westerling et al. 2006				X							X		X	X	X	X	X
Wiens et al. 2009				X								X	X	X	X	X	X
Wigley 2005	X		X									X	X	X	X	X	X
Williams et al. 2009				X								X				X	X
Williams et al. 2008				X							X	X			X		
Wolkovich and Cleland 2010				X								X	X	X	X	X	X
Wood et al. 2002	X										X	X	X	X	X	X	X
Woodhouse and Cook 2009	X	X									X		X	X	X	X	X
Woodhouse et al. 2006	X	X									X				X	X	
Yin et al. 2010			X									X		X	X		

Peer Reviewed Synthesis Documents and Reports

Synthesis Documents and Reports (Peer Reviewed)	Resource Theme(s)										Time Coverage		Geographic Coverage				
	Regional or Local Climate Change	Runoff and Surface Water Supplies	Sea Level Rise	Eco-systems	Water Quality	Ground-water	Water Demand	Reservoir System Operations	Flood Control	Hydro-power	Historical	Future	PN	MP	LC	UC	GP
Allan et al. 2005				X								X	X	X	X	X	X
Bates et al. 2008	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Beukema et al. 2007				X								X	X		X	X	X
Bindoff et al. 2007			X														
Breshears et al. 2005	X	X		X								X		X	X	X	X
Bull et al. 2007							X					X	X	X	X	X	X
CA DWR 2006	X	X	X	X	X	X	X		X	X		X		X	X		
CBO 2009	X	X		X		X						X	X	X	X	X	X
CCSP 2009				X								X	X	X	X	X	X
CCSP2008	X								X			X	X	X	X	X	X
Collins et al. 2007	X												X	X	X	X	X
Covich et al. 2003				X								X				X	X
Dai 2010	X										X	X	X	X	X	X	X
D'Antonio 2006	X	X		X			X		X		X	X				X	
Gutowski et al. 2008	X								X			X	X	X	X	X	X
Haak et al. 2010				X							X	X	X	X	X	X	X
Hatfield et al. 2008							X					X	X	X	X	X	X
IPCC 2007	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X
IPCC 2001	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X
IPCC 1996	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X
Janetos et al. 2008				X								X	X	X	X	X	X
Lettenmaier et al. 2008a		X		X			X				X	X	X	X	X	X	X
Mastin 2008		X										X	X				
Nakicenovic and Swart 2000	X											X	X	X	X	X	X
Reiners et al. 2003				X							X	X	X	X	X	X	X
Robinson et al. 2008				X								X	X	X	X	X	X
Ryan et al. 2008				X		X	X				X	X	X	X	X	X	X
Scott et al. 2007										X		X	X	X	X	X	X
Vicuna and Dracup 2007		X									X	X		X	X		

Nonpeer Reviewed Documents

Synthesis Documents, Reports and Other (Nonpeer Reviewed)	Resource Theme(s)									Time Coverage		Geographic Coverage				
	Regional or Local Climate Change	Runoff and Surface Water Supplies	Sea Level Rise	Flood Control	Hydro-power	Eco-systems	Water Quality	Ground-water	Water Demand	Historical	Future	PN	MP	LC	UC	GP
ASCE 1990									X	X	X	X	X	X	X	X
BRAC 2007	X	X	X			X			X	X	X				X	
CA DWR 2009	X	X									X		X	X		
CALFED ISB 2007			X								X		X	X		
Frederick 1997							X				X	X	X	X	X	X
Hann 2002		X										X	X	X	X	X
Hasumi and Emori 2002	X										X	X	X	X	X	X
IDSCU 2005		X							X			X	X	X	X	X
Kirkpatrick et al. 2009						X				X				X		
Mathews 2008						X				X	X					X
Pacific Institute 2009									X			X	X	X	X	X

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Appendix B. Graphical Resources – Downscaled Climate Changes Projected over Reclamation Regions

This appendix contains maps 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 the Bureau of Reclamation (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. The 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

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[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.

quotient of "incremental change of future period minus base period" divided by 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).

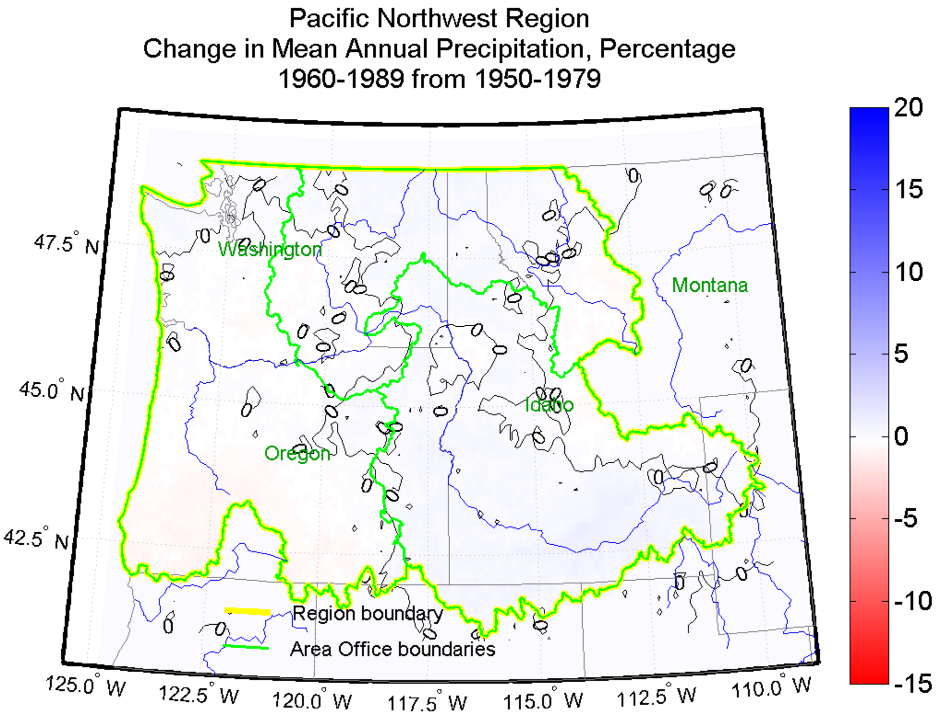
It is recommended that the maps be interpreted as follows:

- 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
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
20
15
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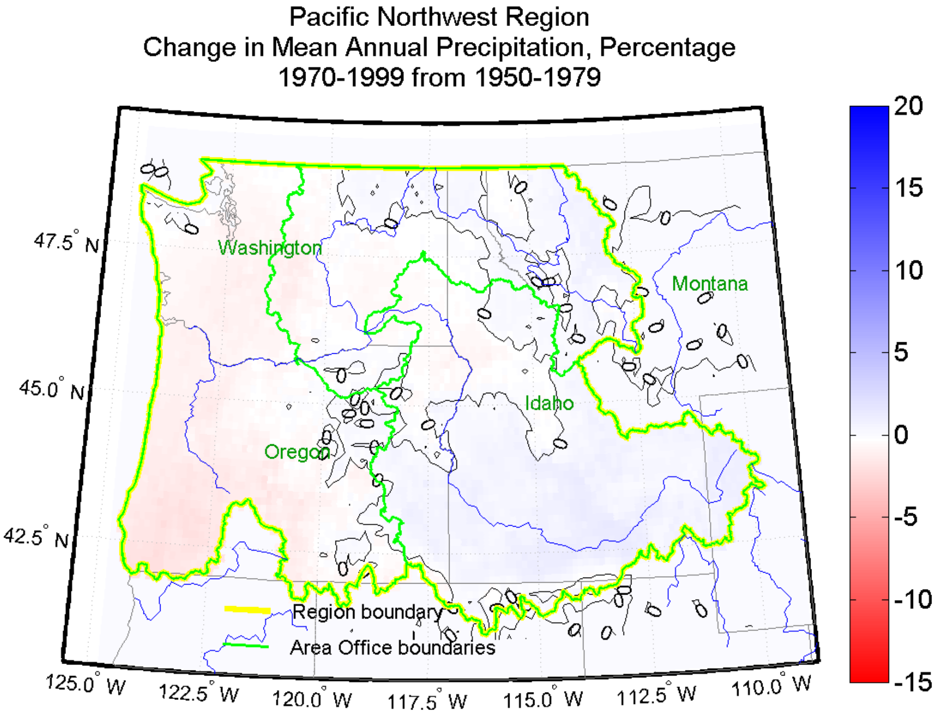
0
-5
-10
-15


Pacific Northwest Region
Change in Mean Annual Precipitation, Percentage
1970-1999 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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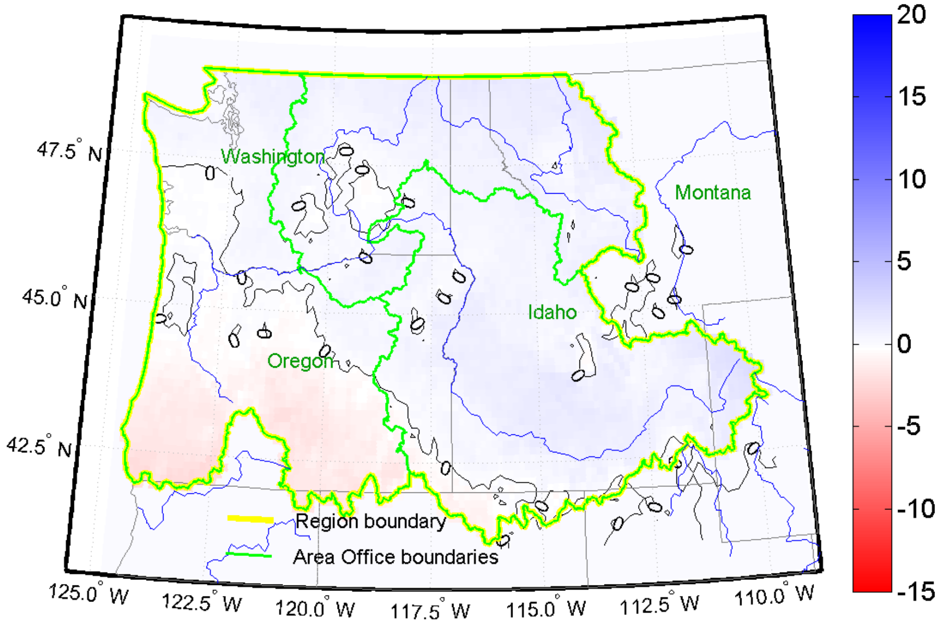
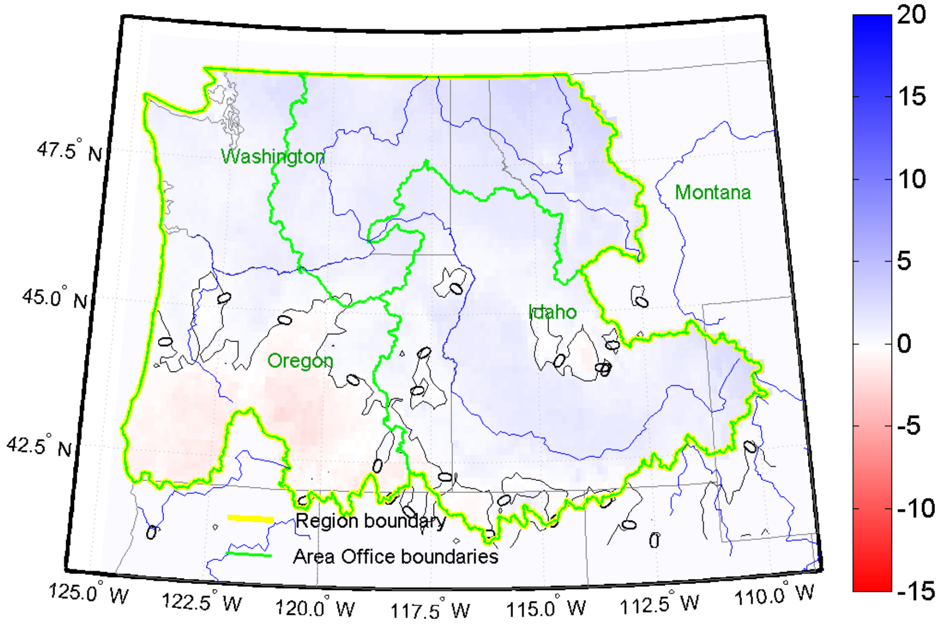
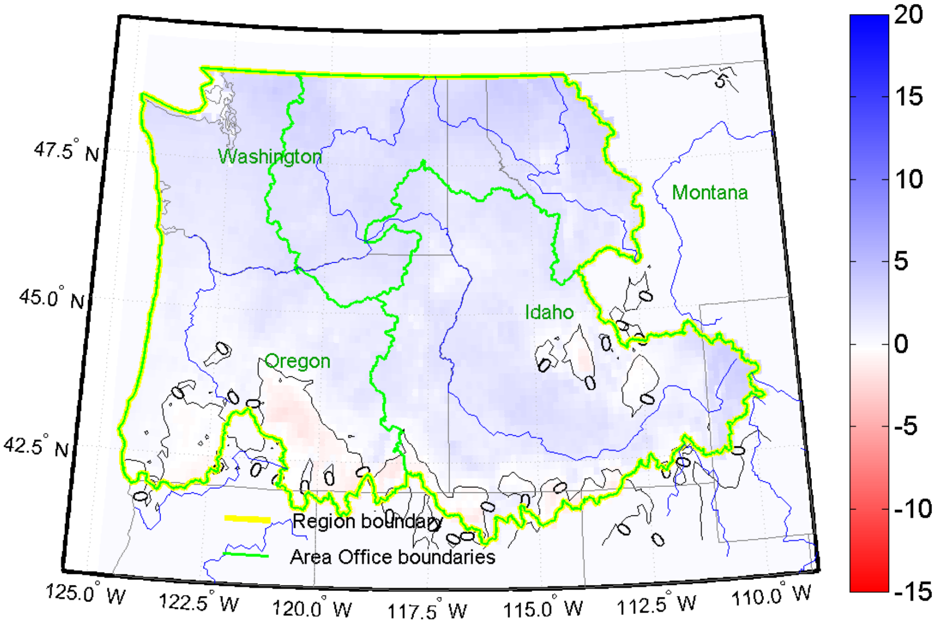
Pacific Northwest Region
Change in Mean Annual Precipitation, Percentage
1980-2009 from 1950-1979



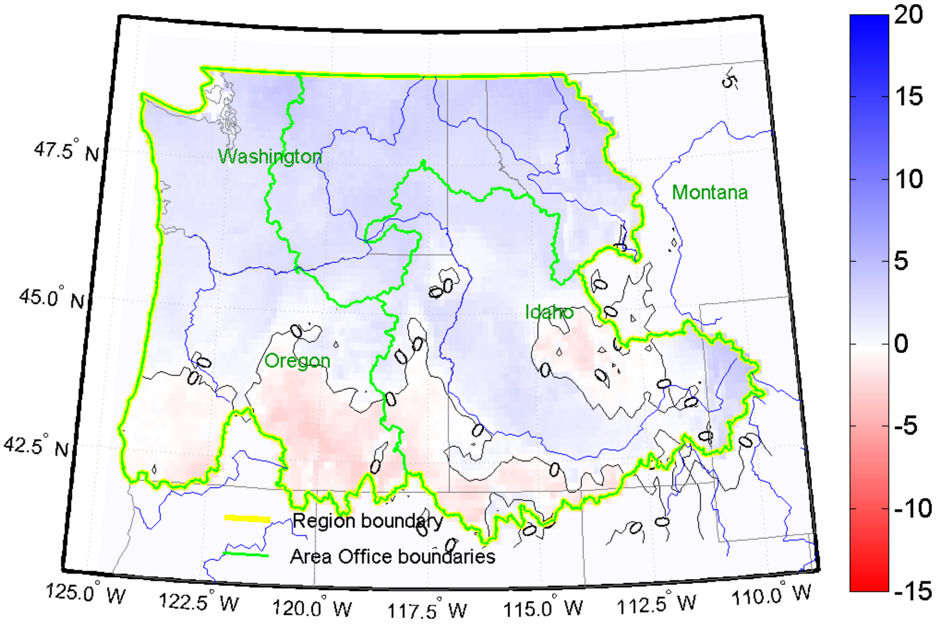
Pacific Northwest Region
Change in Mean Annual Precipitation, Percentage
1990-2019 from 1950-1979

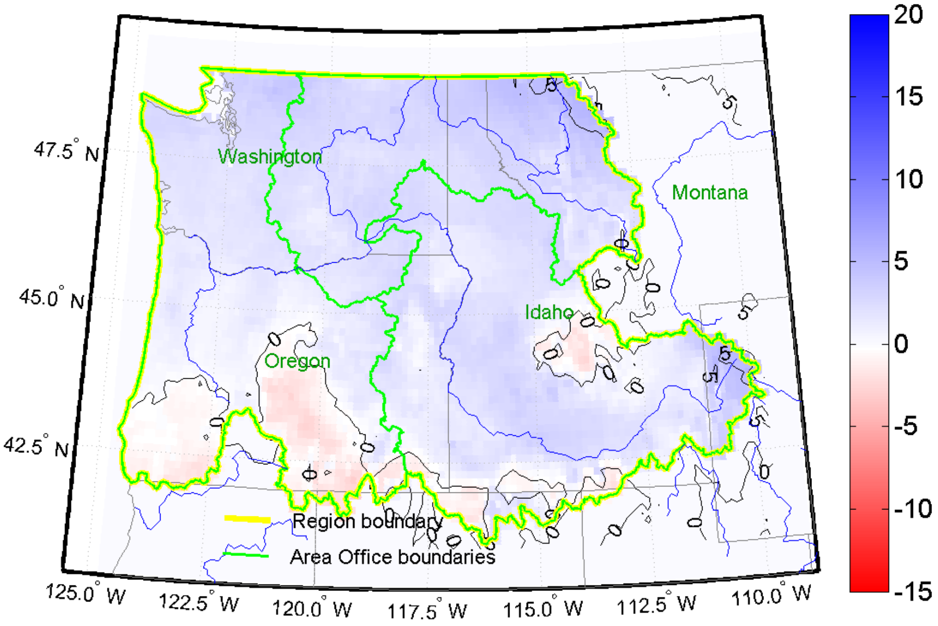


Pacific Northwest Region
Change in Mean Annual Precipitation, Percentage
2000-2029 from 1950-1979

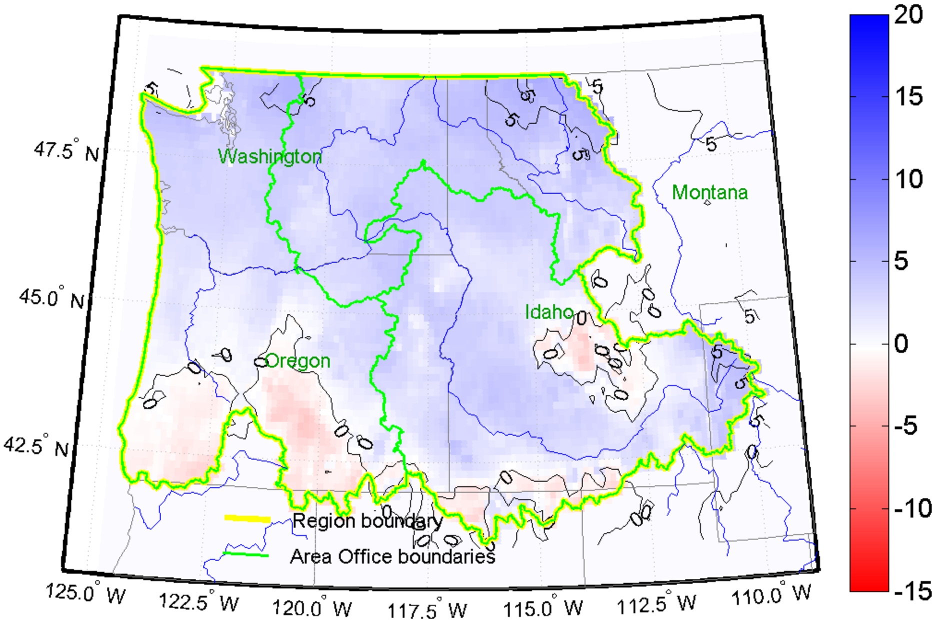


Pacific Northwest Region
Change in Mean Annual Precipitation, Percentage
2010-2039 from 1950-1979



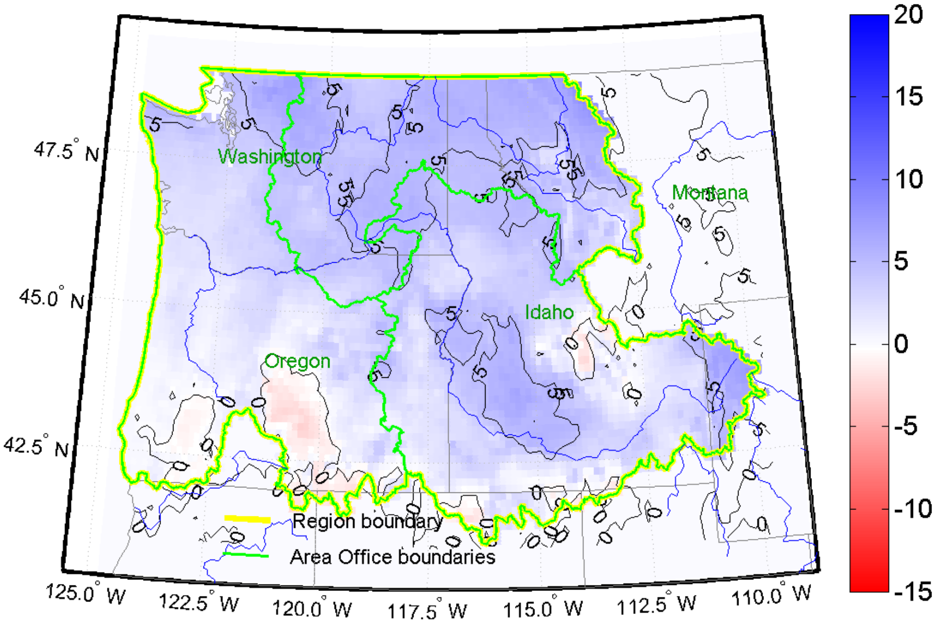


Pacific Northwest Region
Change in Mean Annual Precipitation, Percentage
2020-2049 from 1950-1979



Pacific Northwest Region
Change in Mean Annual Precipitation, Percentage
2030-2059 from 1950-1979

Pacific Northwest Region
Change in Mean Annual Precipitation, Percentage
2040-2069 from 1950-1979



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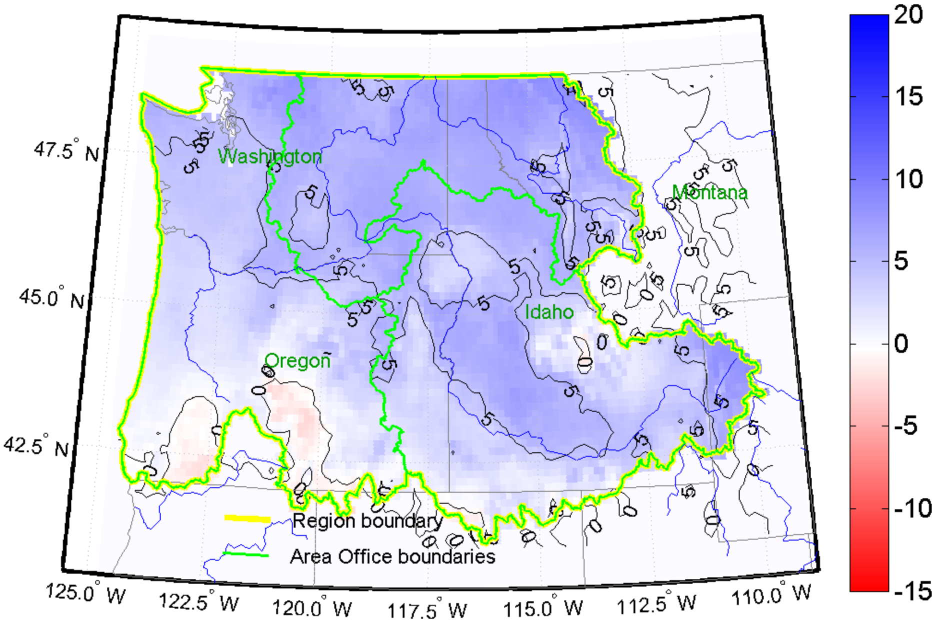
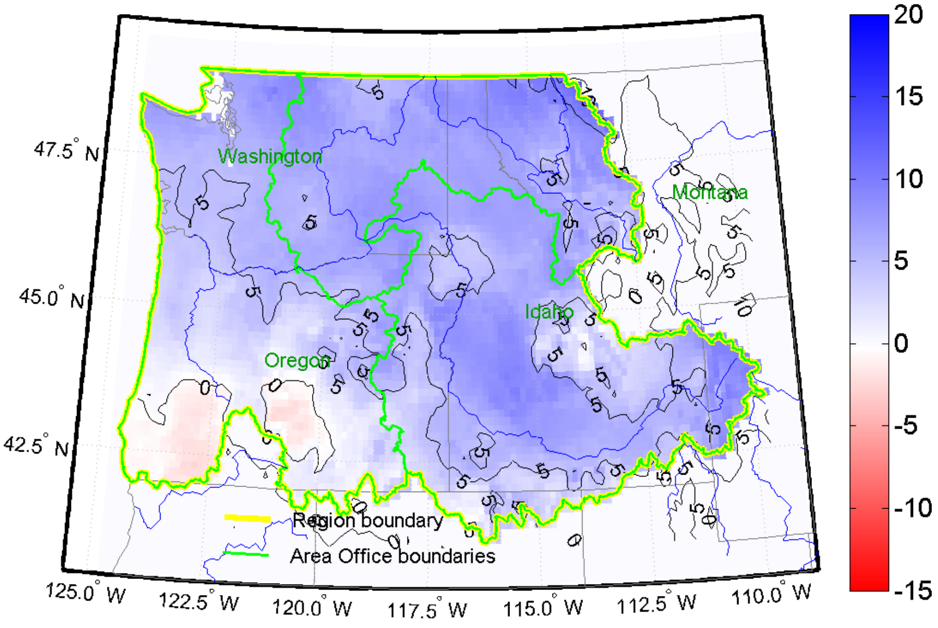
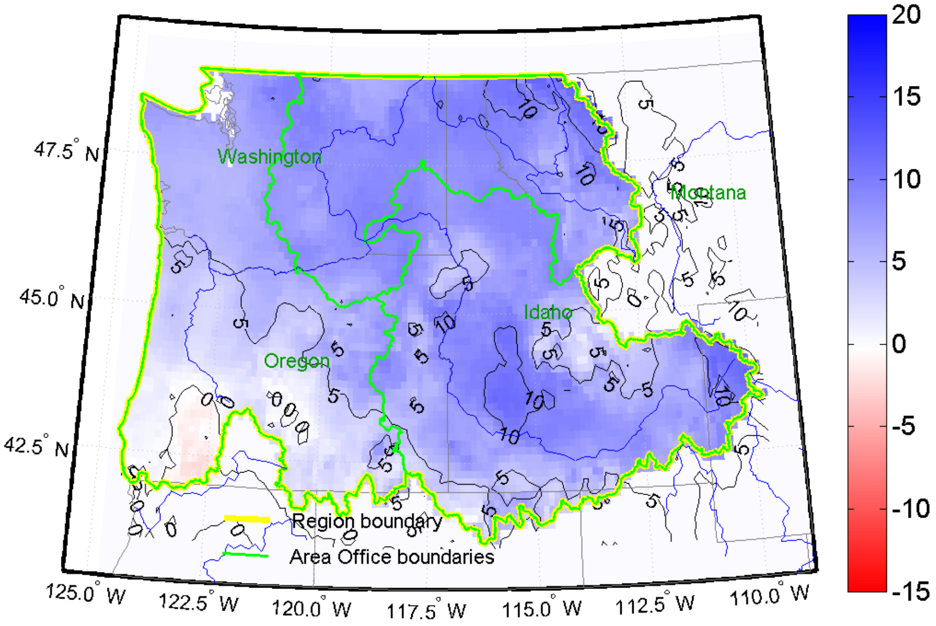
2050-2079 from 1950-1979



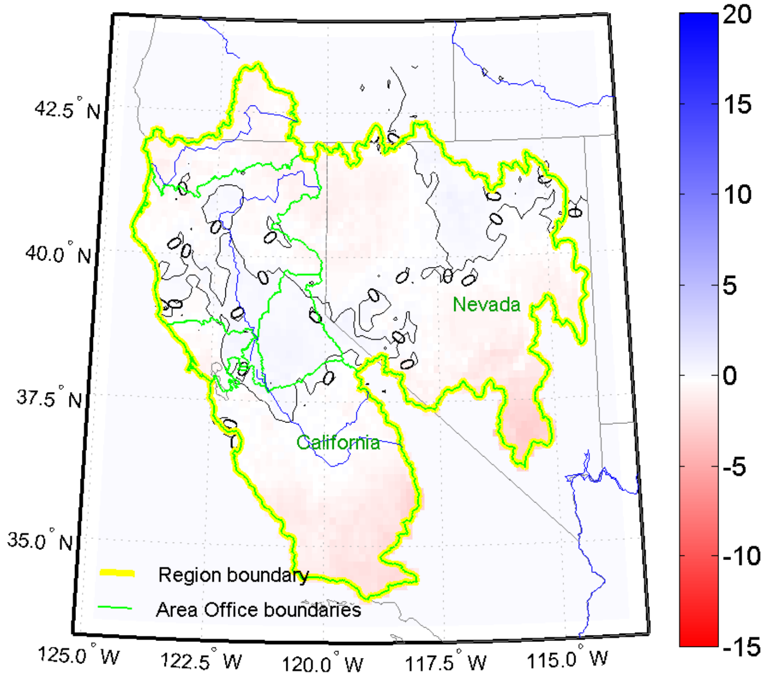


Pacific Northwest Region
Change in Mean Annual Precipitation, Percentage
2060-2089 from 1950-1979



Pacific Northwest Region
Change in Mean Annual Precipitation, Percentage
2070-2099 from 1950-1979

Mid-Pacific Region – Precipitation Change



Mid-Pacific Region
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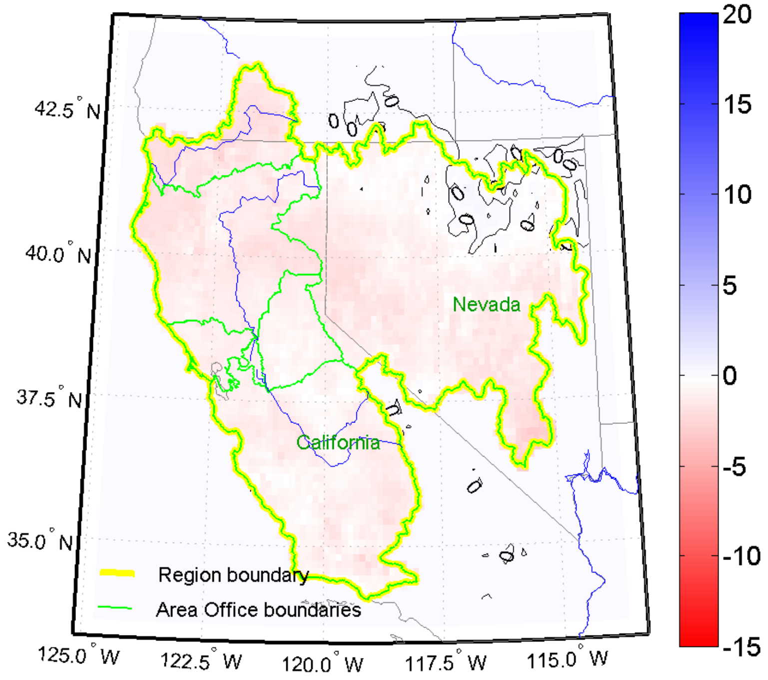
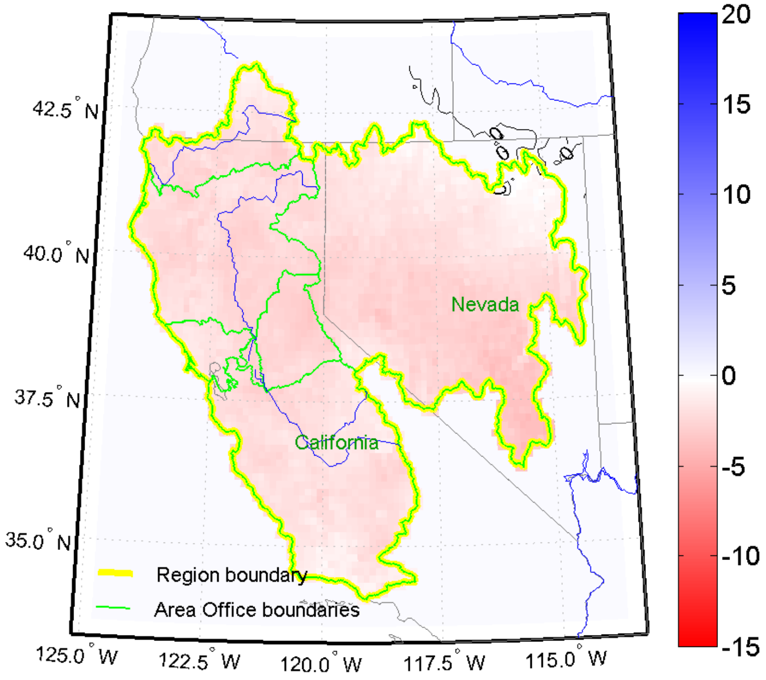
1960-1989 from 1950-1979

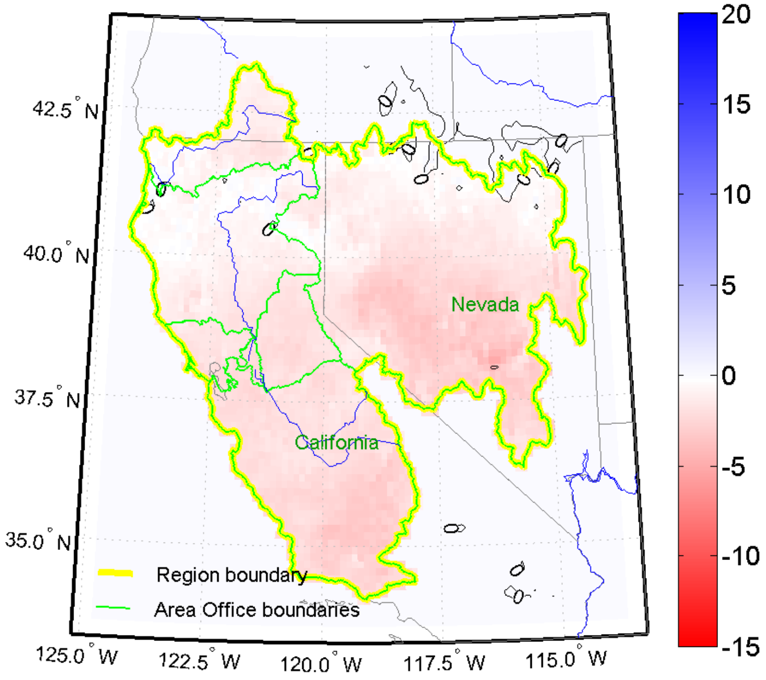


Mid-Pacific Region
Change in Mean Annual Precipitation, Percentage
1970-1999 from 1950-1979

Mid-Pacific Region
Change in Mean Annual Precipitation, Percentage
1980-2009 from 1950-1979



Mid-Pacific Region
Change in Mean Annual Precipitation, Percentage
1990-2019 from 1950-1979



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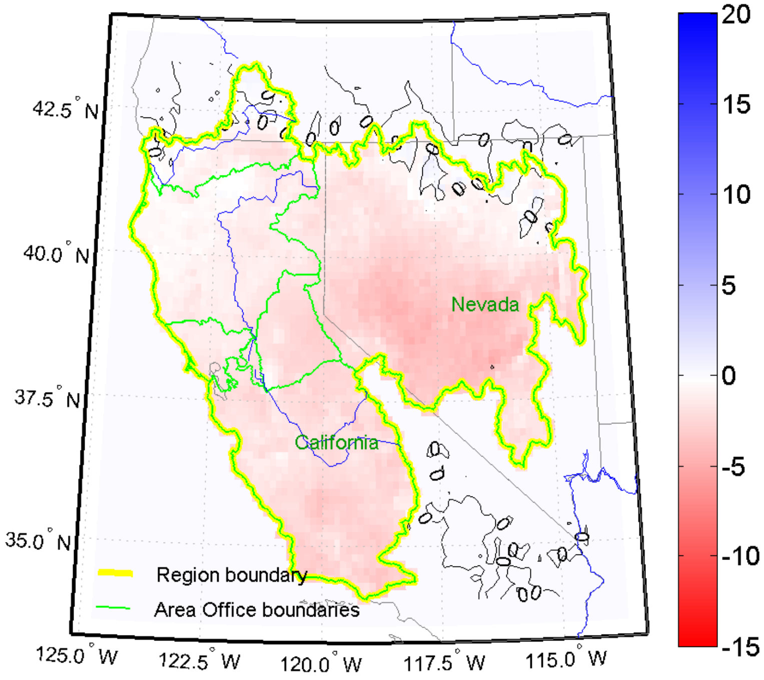
Change in Mean Annual Precipitation, Percentage
2000-2029 from 1950-1979



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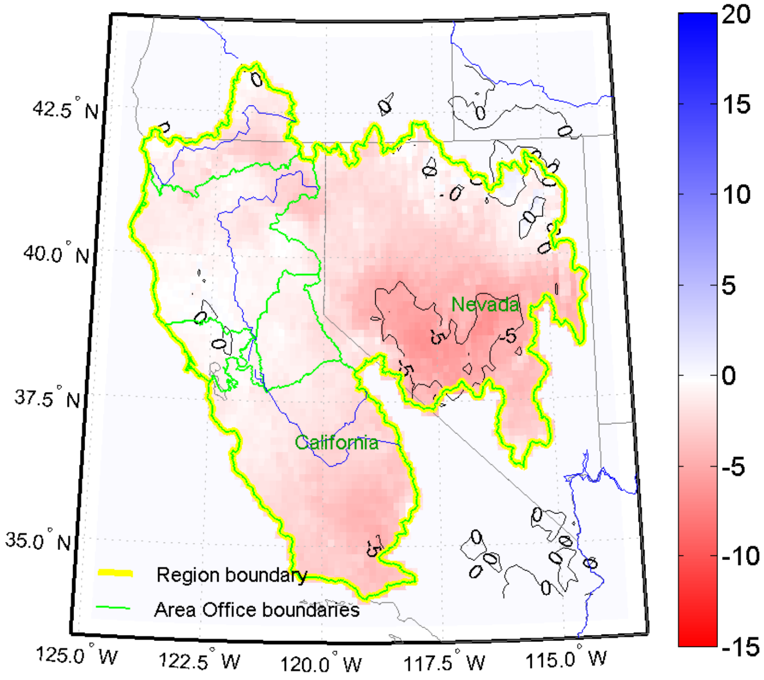
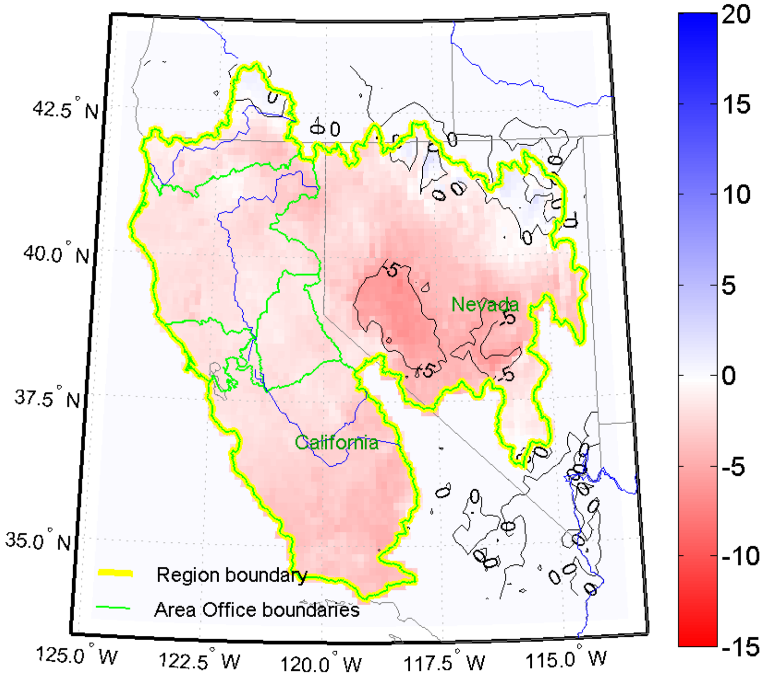
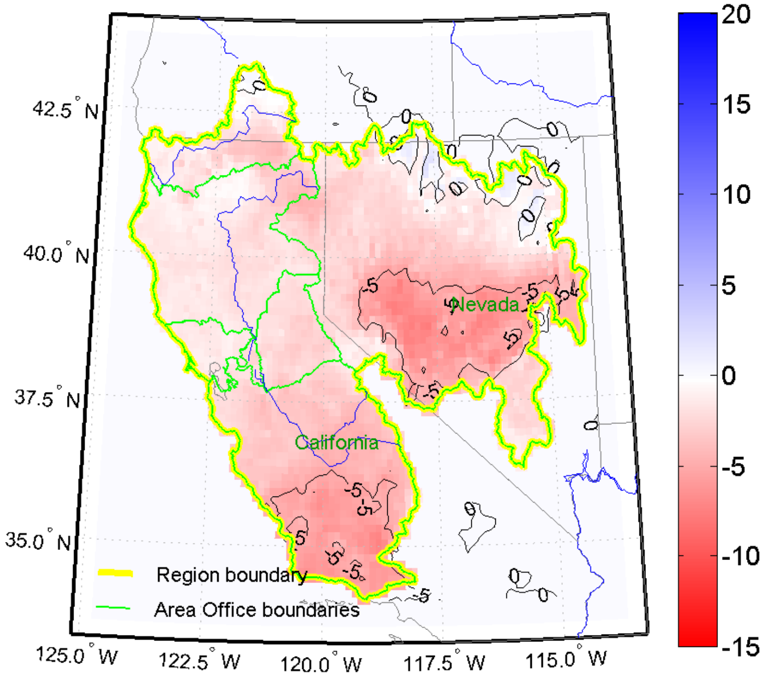
Change in Mean Annual Precipitation, Percentage
2010-2039 from 1950-1979



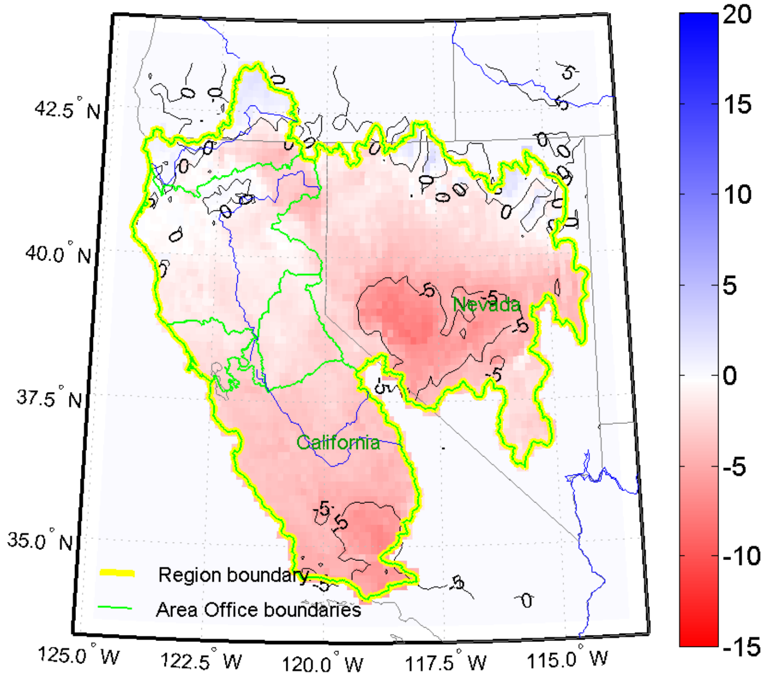
Mid-Pacific Region
Change in Mean Annual Precipitation, Percentage
2020-2049 from 1950-1979



Mid-Pacific Region
Change in Mean Annual Precipitation, Percentage
2030-2059 from 1950-1979



Mid-Pacific Region
Change in Mean Annual Precipitation, Percentage
2040-2069 from 1950-1979



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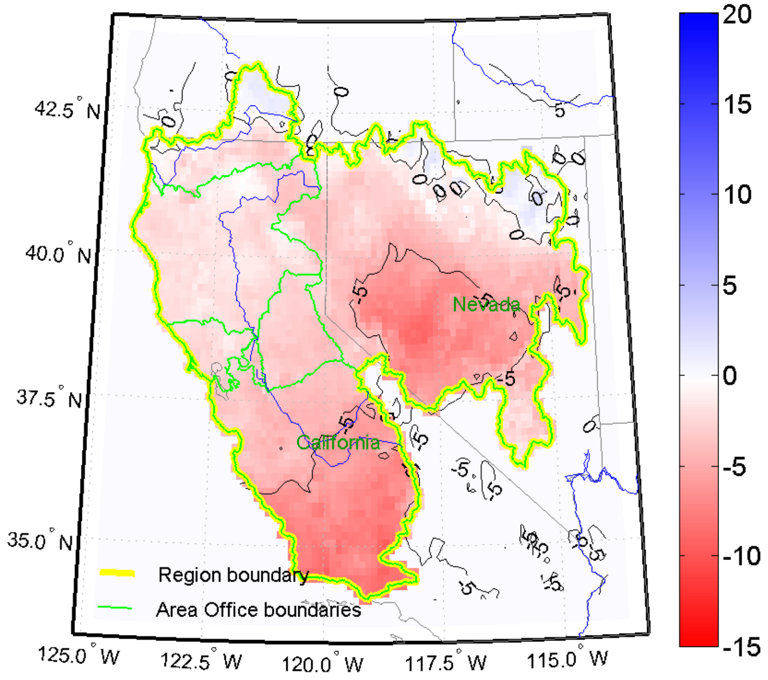
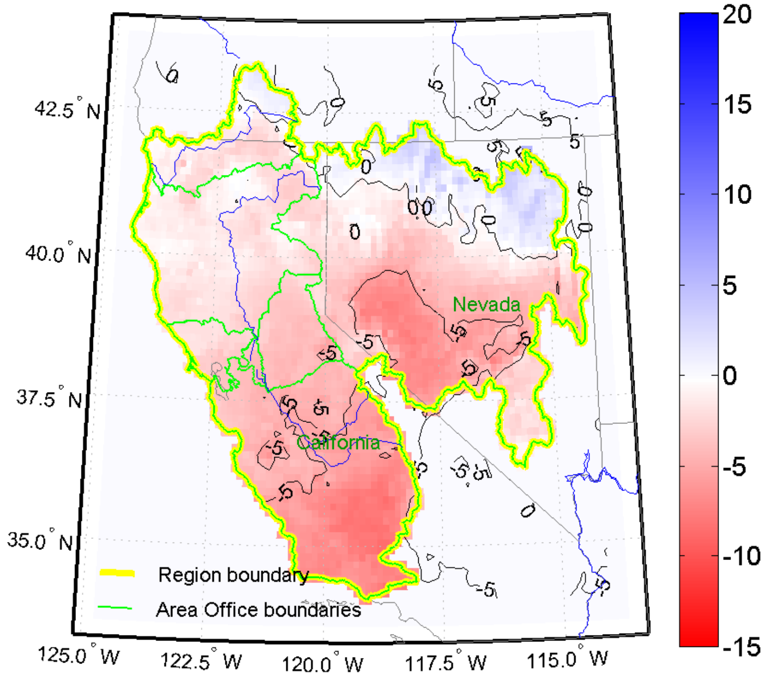
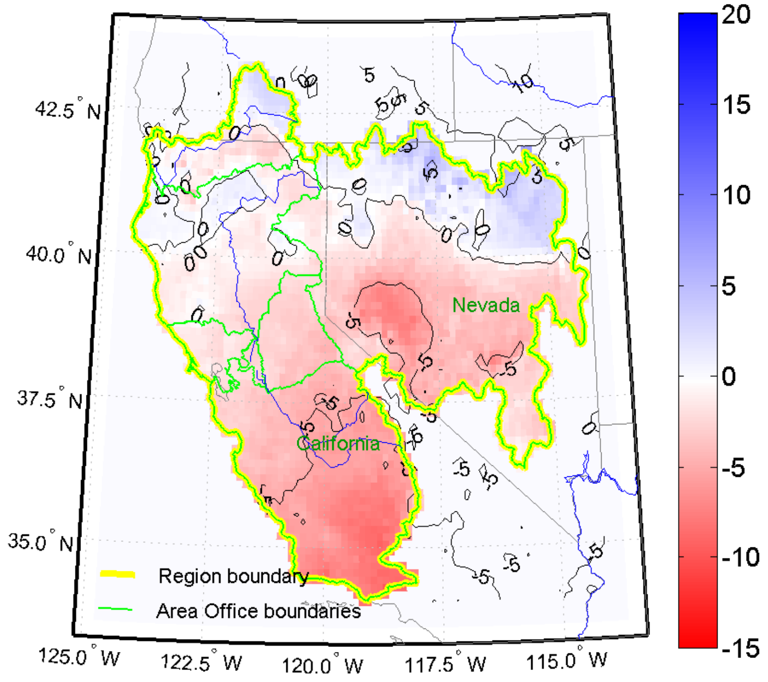
Change in Mean Annual Precipitation, Percentage
2050-2079 from 1950-1979

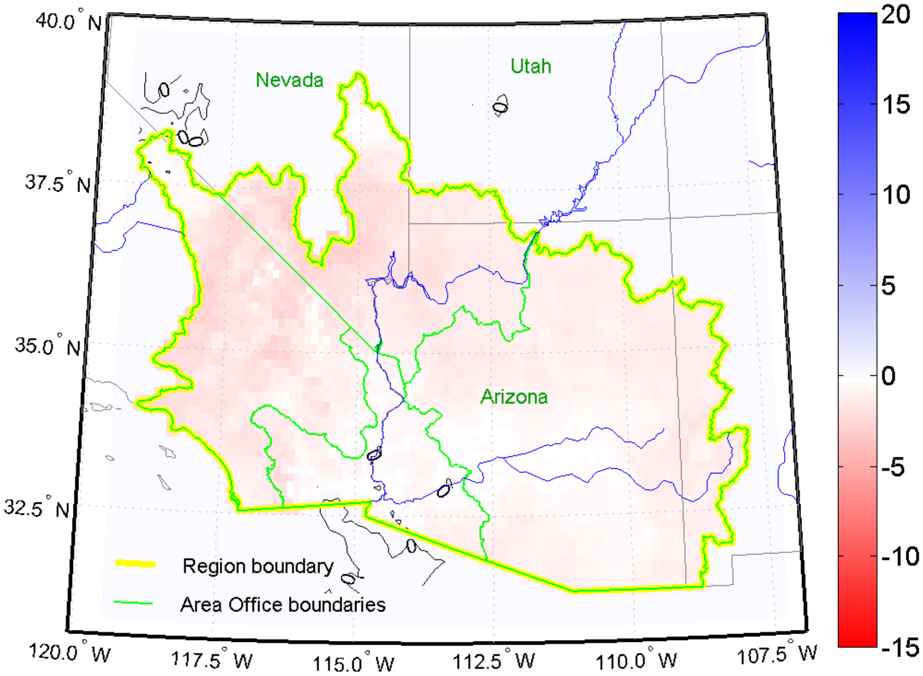



Mid-Pacific Region
Change in Mean Annual Precipitation, Percentage
2060-2089 from 1950-1979


Mid-Pacific Region
Change in Mean Annual Precipitation, Percentage
2070-2099 from 1950-1979

Lower Colorado Region – Precipitation Change

Lower Colorado Region
Change in Mean Annual Precipitation, Percentage
1960-1989 from 1950-1979



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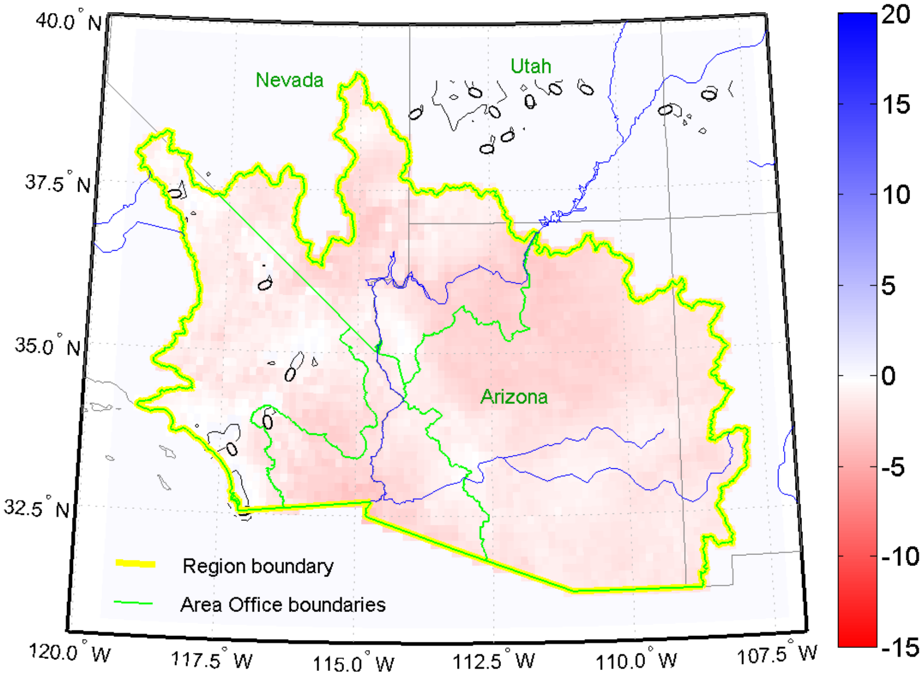
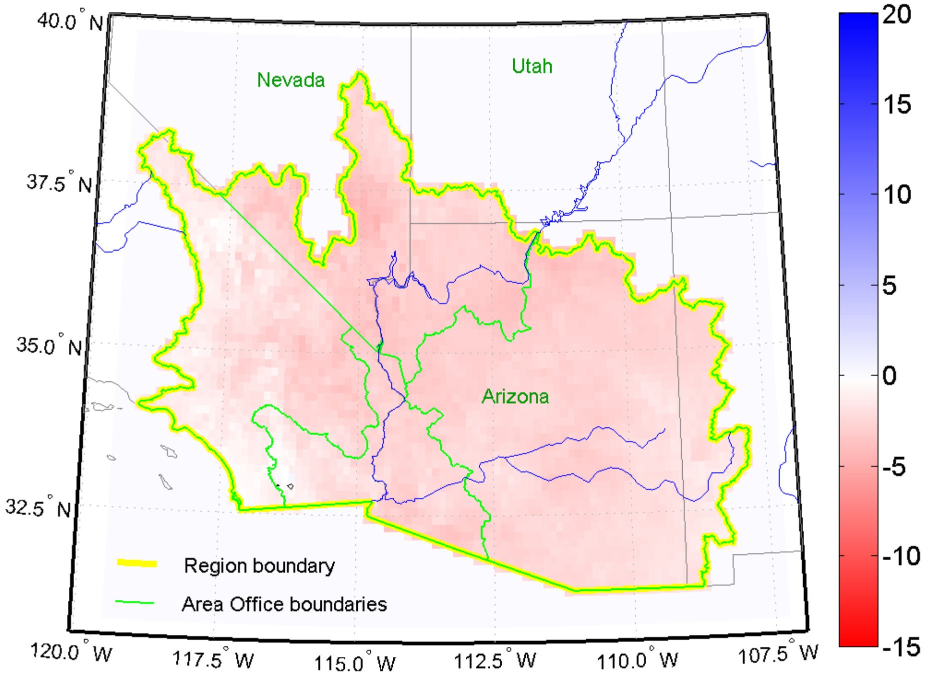
1970-1999 from 1950-1979



Lower Colorado Region
Change in Mean Annual Precipitation, Percentage
1980-2009 from 1950-1979



Lower Colorado Region
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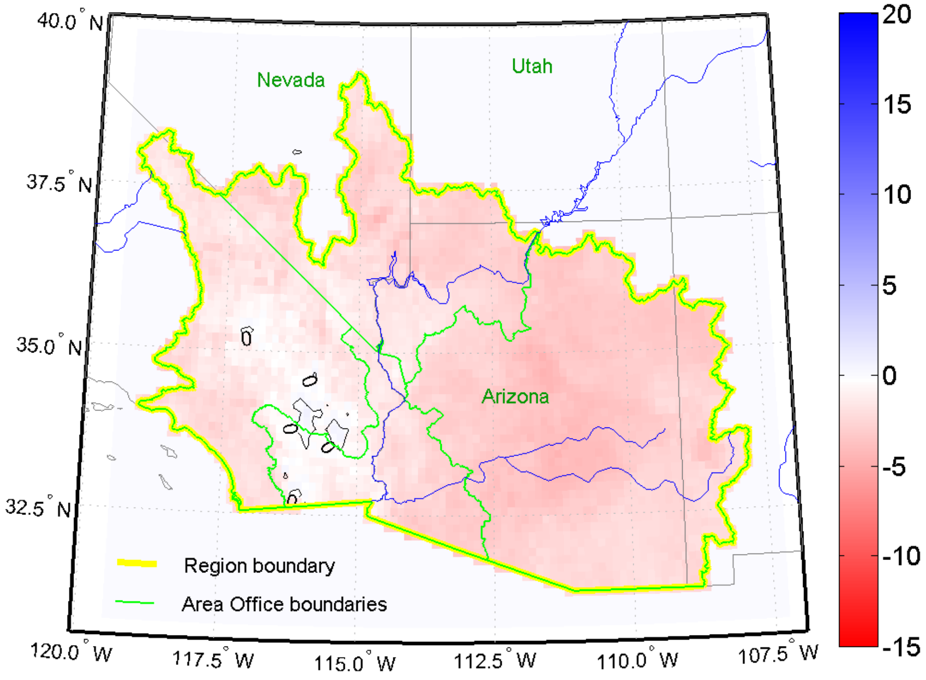
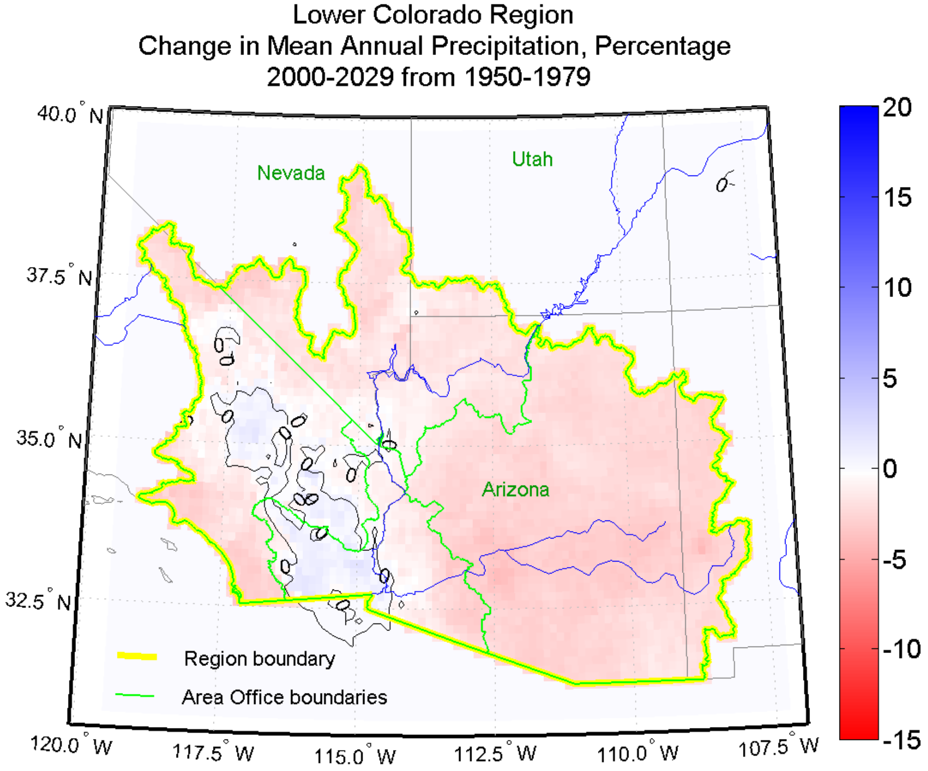
1990-2019 from 1950-1979




Lower Colorado Region
Change in Mean Annual Precipitation, Percentage
2000-2029 from 1950-1979
Nevada
Utah
Arizona
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
Region boundary
Area Office boundaries
20
15
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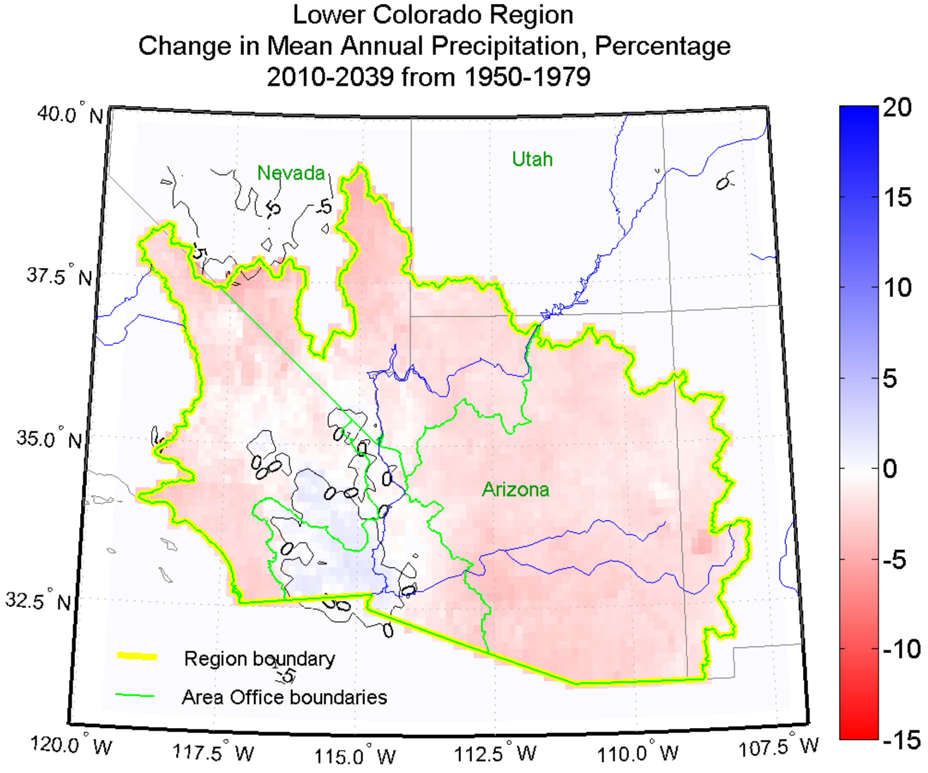
-5
-10
-15


Lower Colorado Region
Change in Mean Annual Precipitation, Percentage
2010-2039 from 1950-1979
Nevada
Utah
Arizona
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
Region boundary
Area Office boundaries
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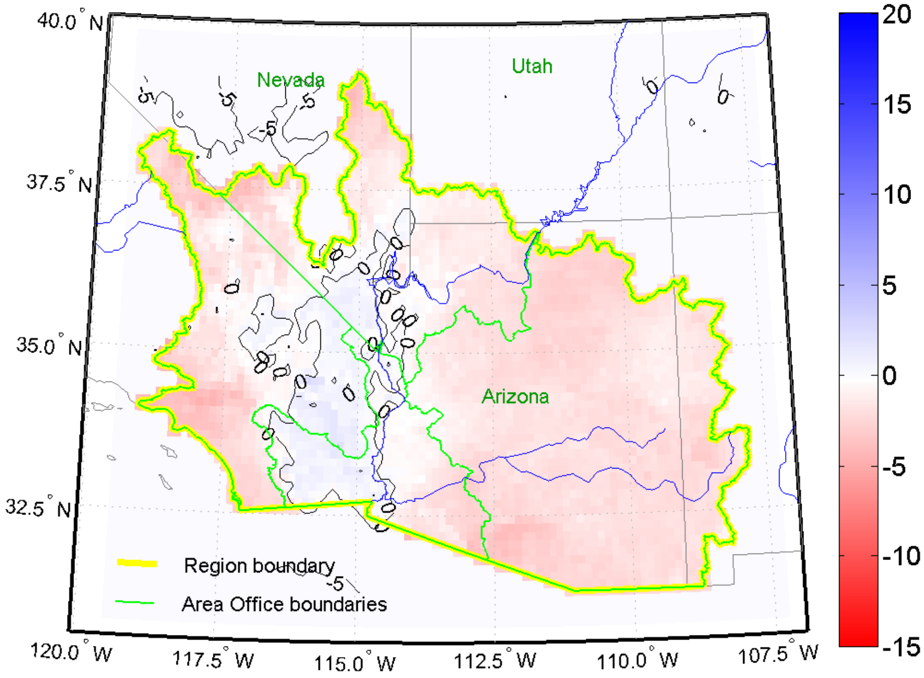
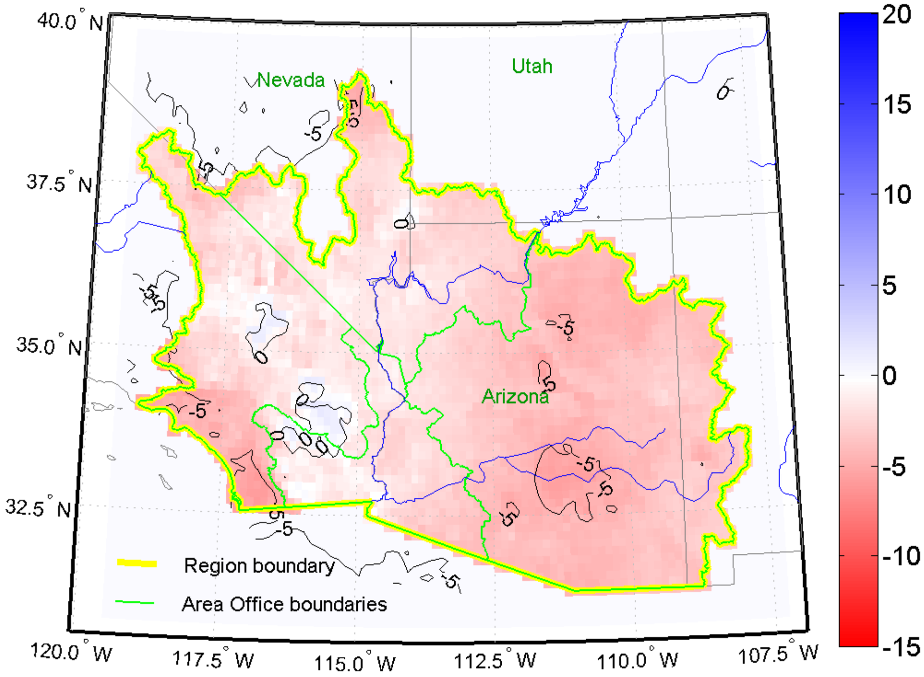
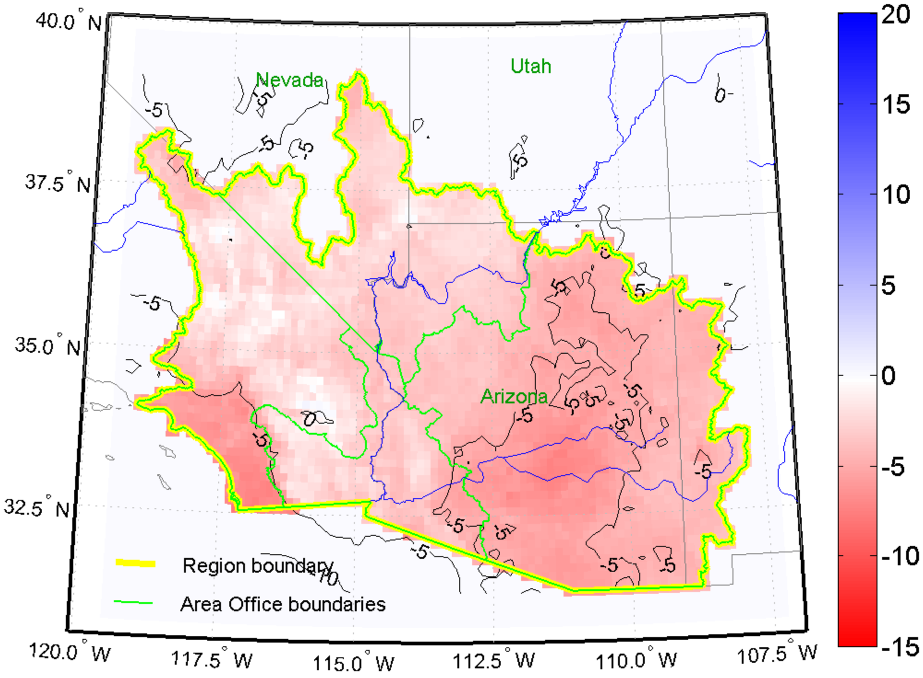
Lower Colorado Region
Change in Mean Annual Precipitation, Percentage
2020-2049 from 1950-1979



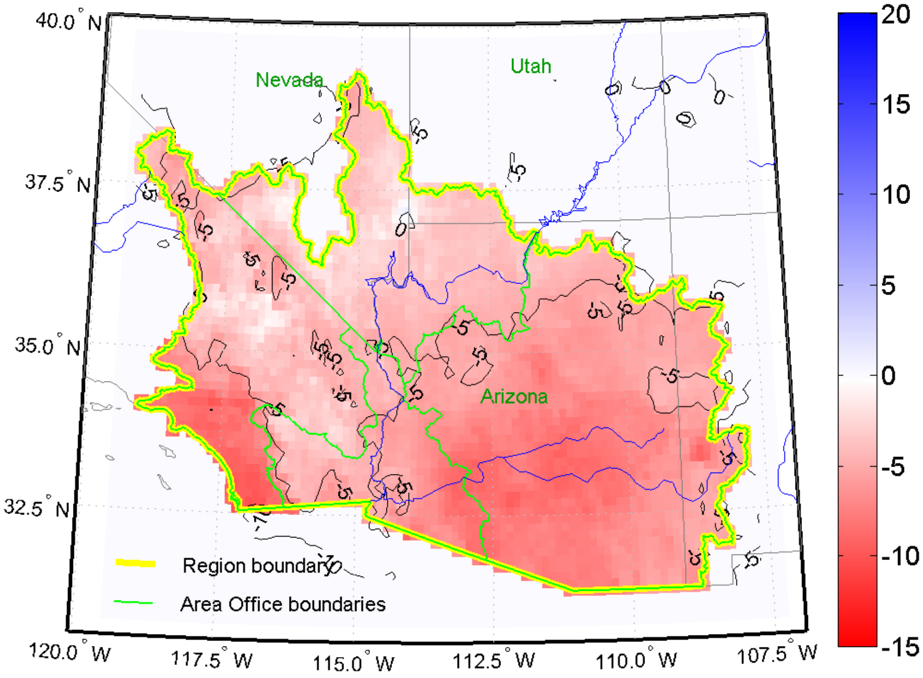
Lower Colorado Region
Change in Mean Annual Precipitation, Percentage
2030-2059 from 1950-1979



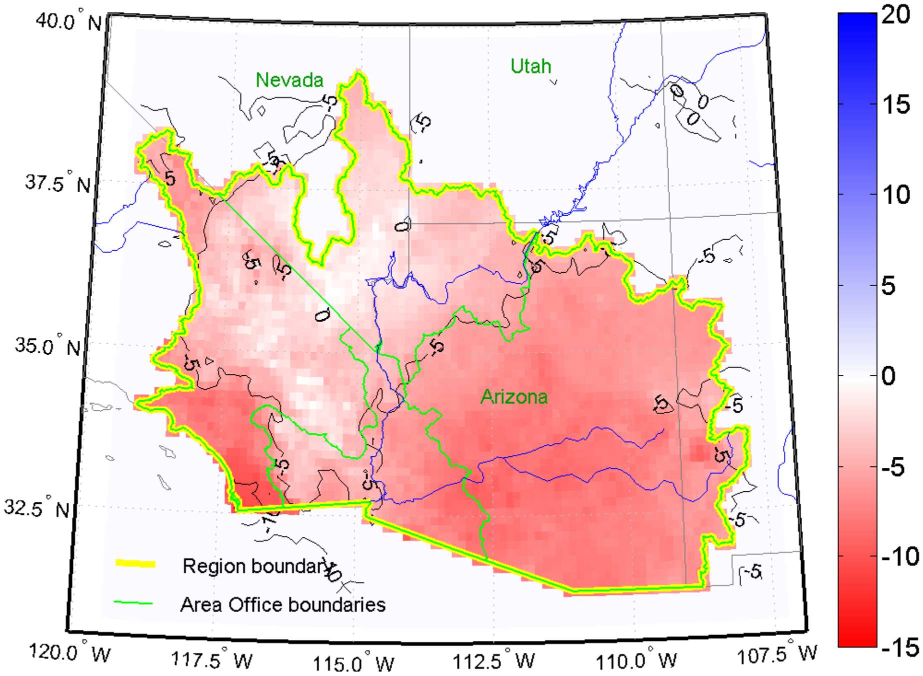
Lower Colorado Region
Change in Mean Annual Precipitation, Percentage
2040-2069 from 1950-1979



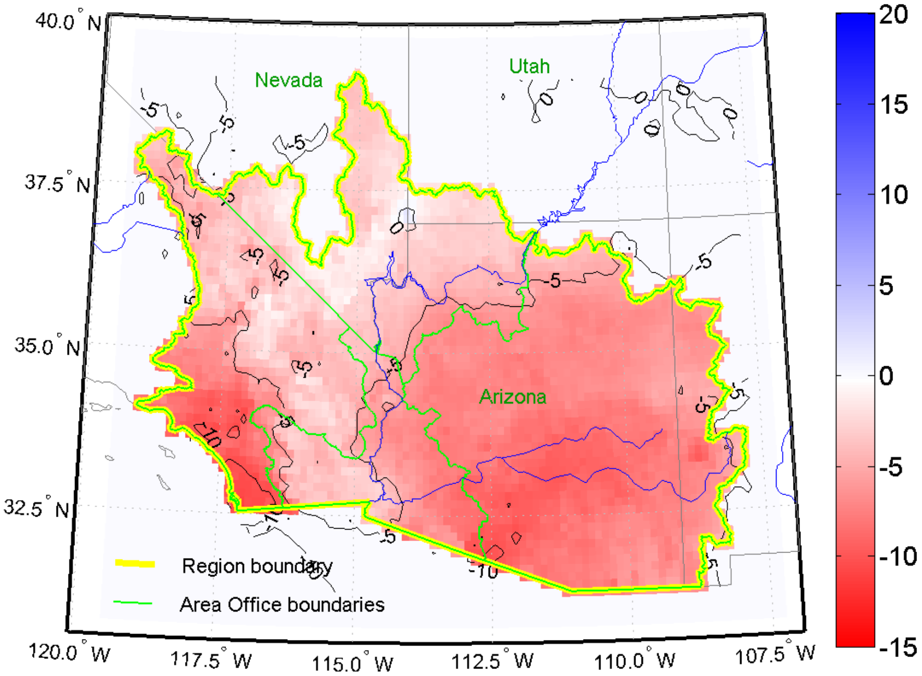
Lower Colorado Region
Change in Mean Annual Precipitation, Percentage
2050-2079 from 1950-1979



Lower Colorado Region
Change in Mean Annual Precipitation, Percentage
2060-2089 from 1950-1979

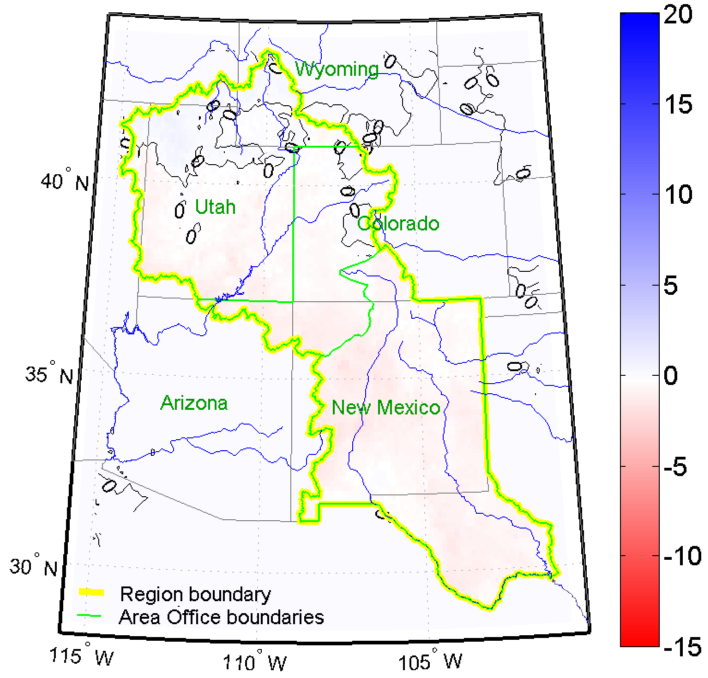


Lower Colorado Region
Change in Mean Annual Precipitation, Percentage
2070-2099 from 1950-1979

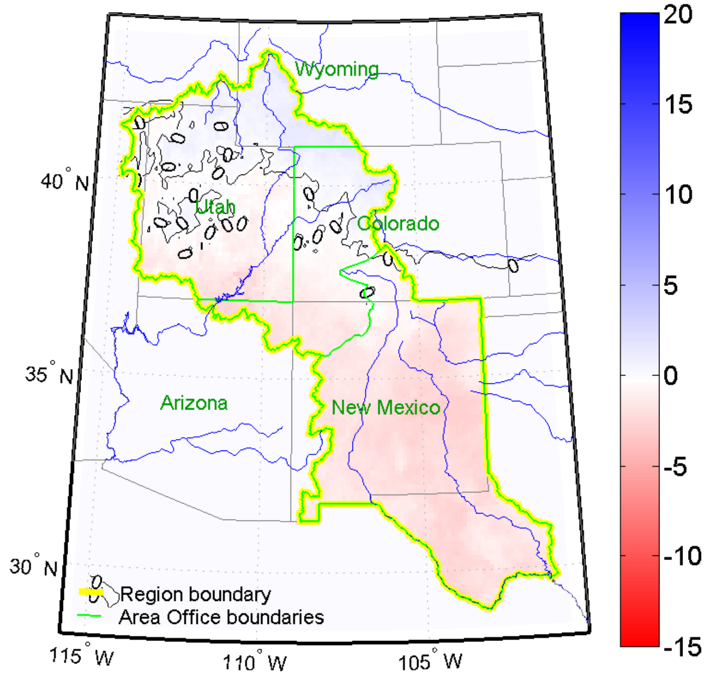


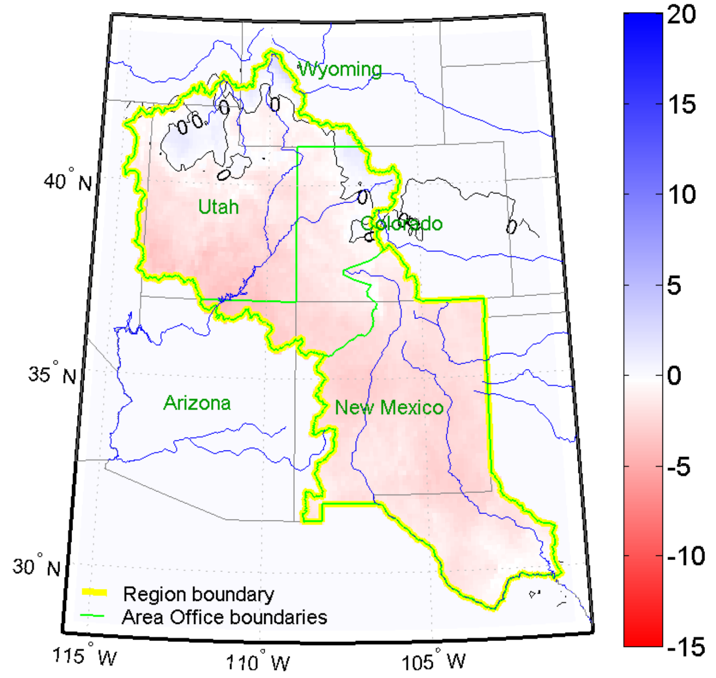
Upper Colorado Region – Precipitation Change

Upper Colorado Region
Change in Mean Annual Precipitation, Percentage
1960-1989 from 1950-1979

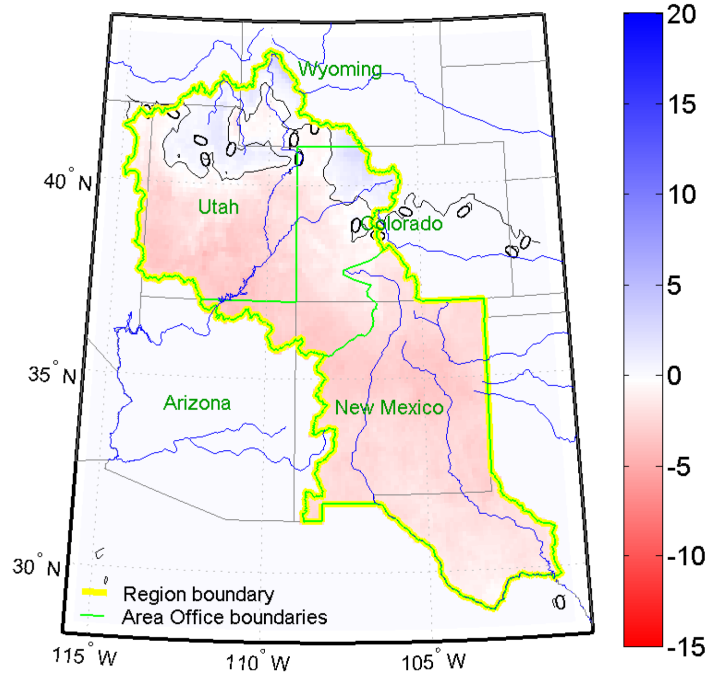


Upper Colorado Region
Change in Mean Annual Precipitation, Percentage
1970-1999 from 1950-1979



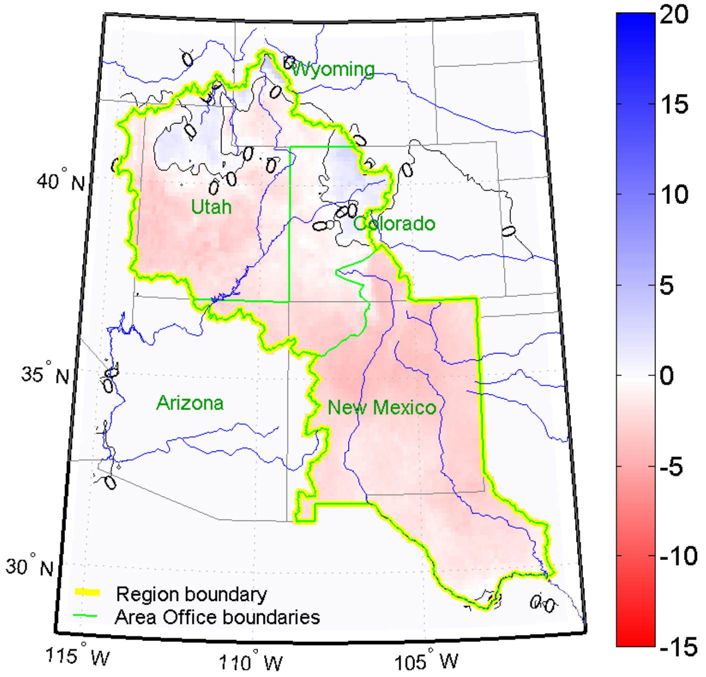


Upper Colorado Region
Change in Mean Annual Precipitation, Percentage
1980-2009 from 1950-1979

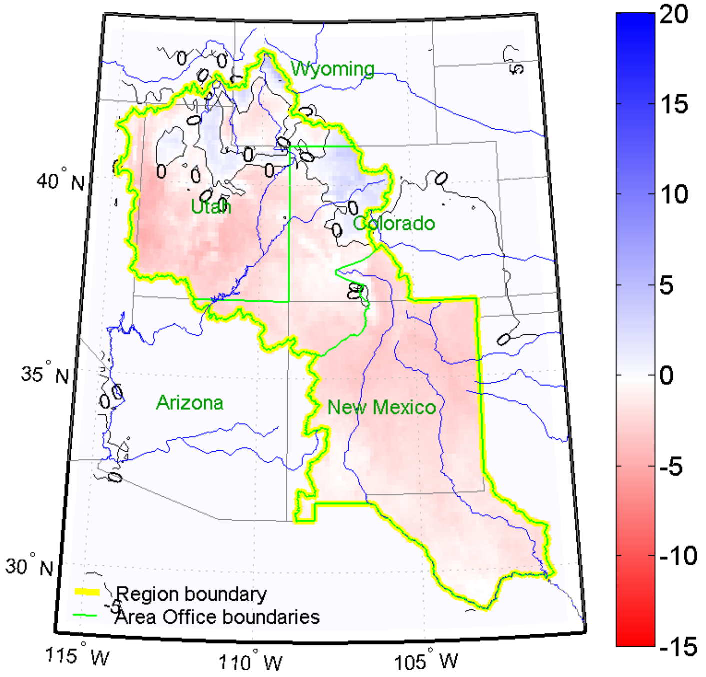


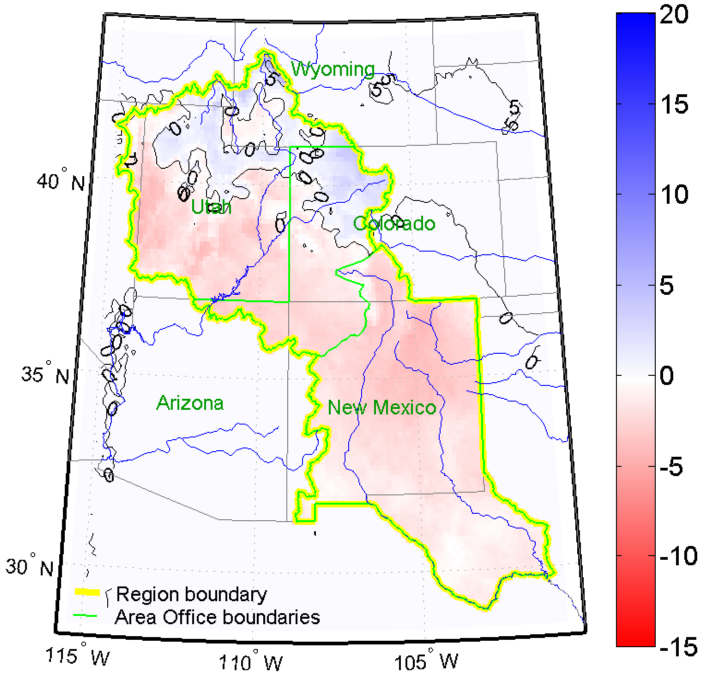
Upper Colorado Region
Change in Mean Annual Precipitation, Percentage
1990-2019 from 1950-1979

Upper Colorado Region
Change in Mean Annual Precipitation, Percentage
2000-2029 from 1950-1979

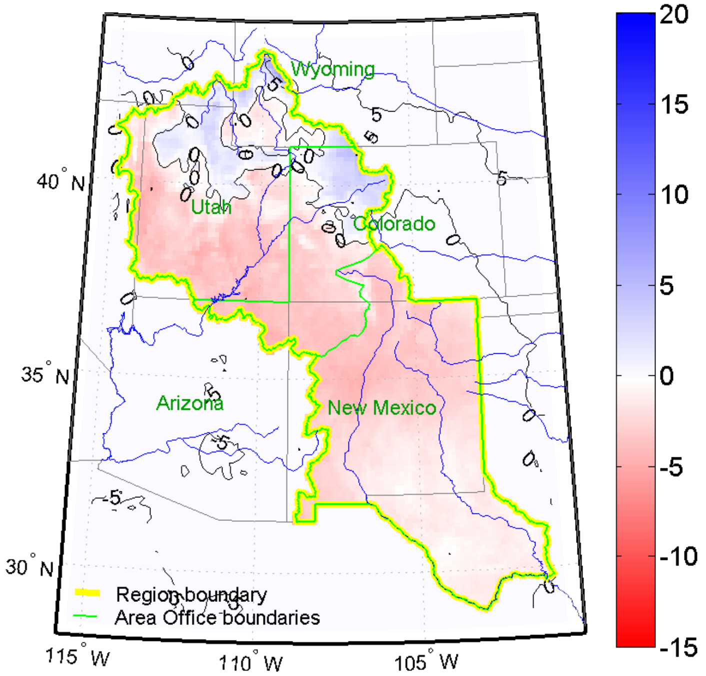


Upper Colorado Region
Change in Mean Annual Precipitation, Percentage
2010-2039 from 1950-1979



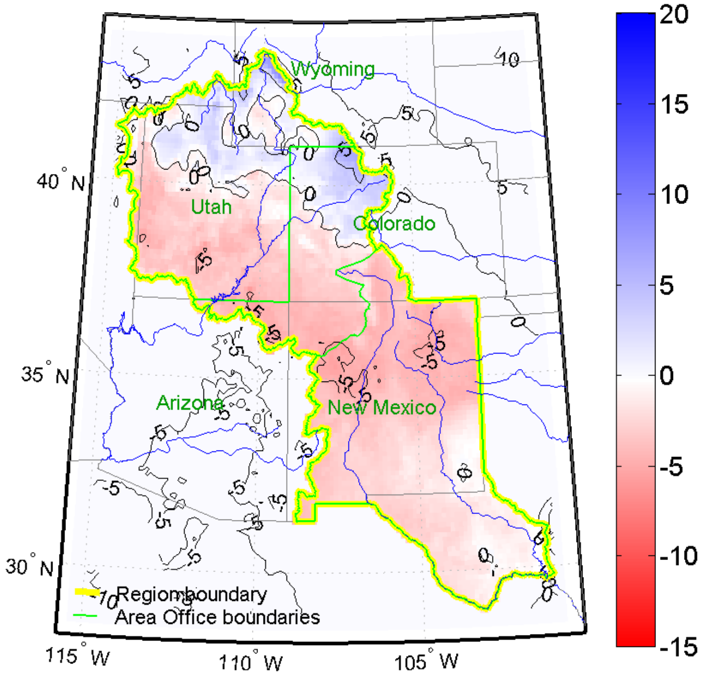


Upper Colorado Region
Change in Mean Annual Precipitation, Percentage
2020-2049 from 1950-1979

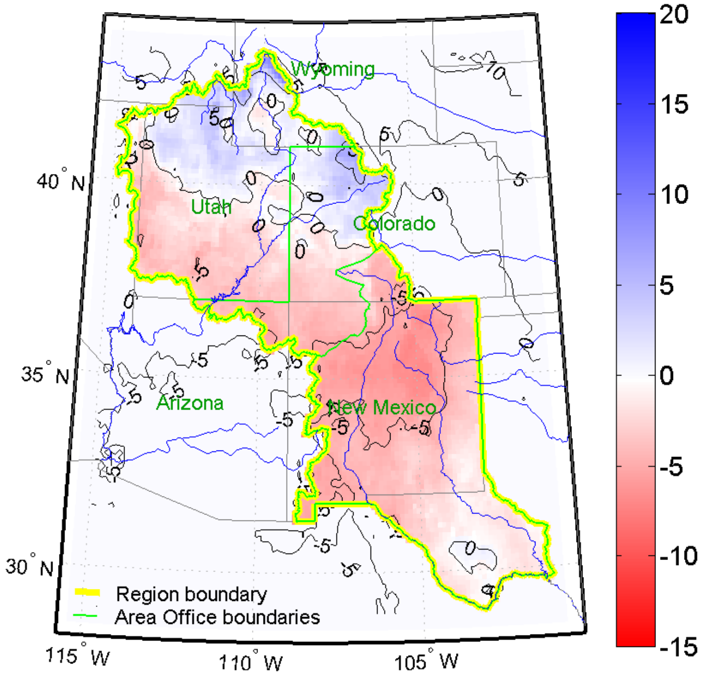


Upper Colorado Region
Change in Mean Annual Precipitation, Percentage
2030-2059 from 1950-1979

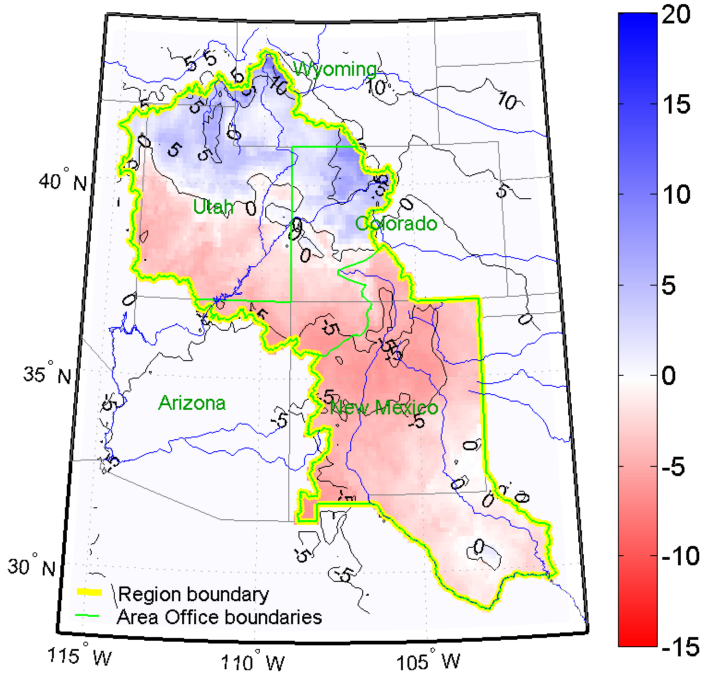
Upper Colorado Region
Change in Mean Annual Precipitation, Percentage
2040-2069 from 1950-1979



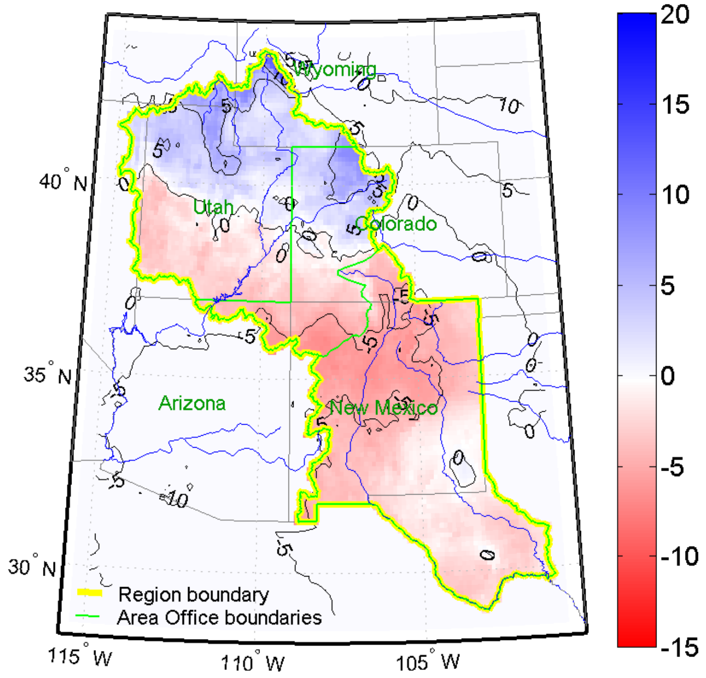
Upper Colorado Region
Change in Mean Annual Precipitation, Percentage
2050-2079 from 1950-1979



Upper Colorado Region
Change in Mean Annual Precipitation, Percentage
2060-2089 from 1950-1979

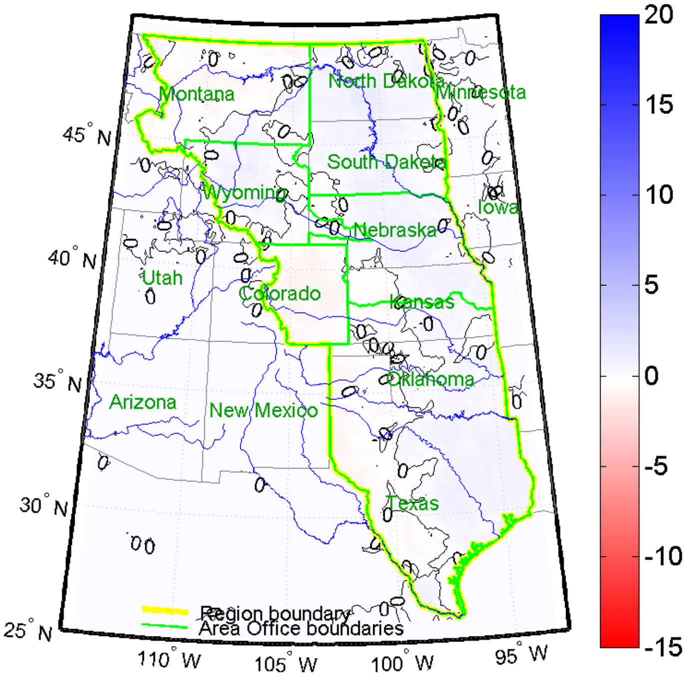


Upper Colorado Region
Change in Mean Annual Precipitation, Percentage
2070-2099 from 1950-1979

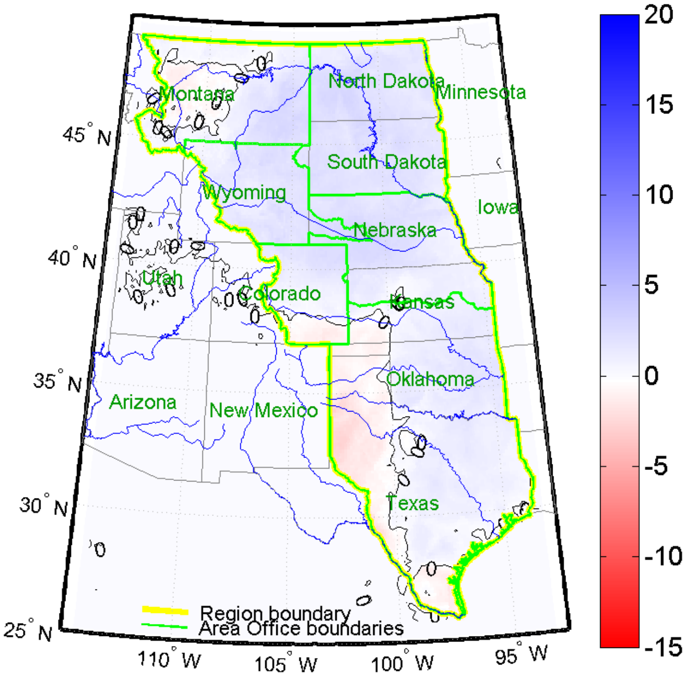


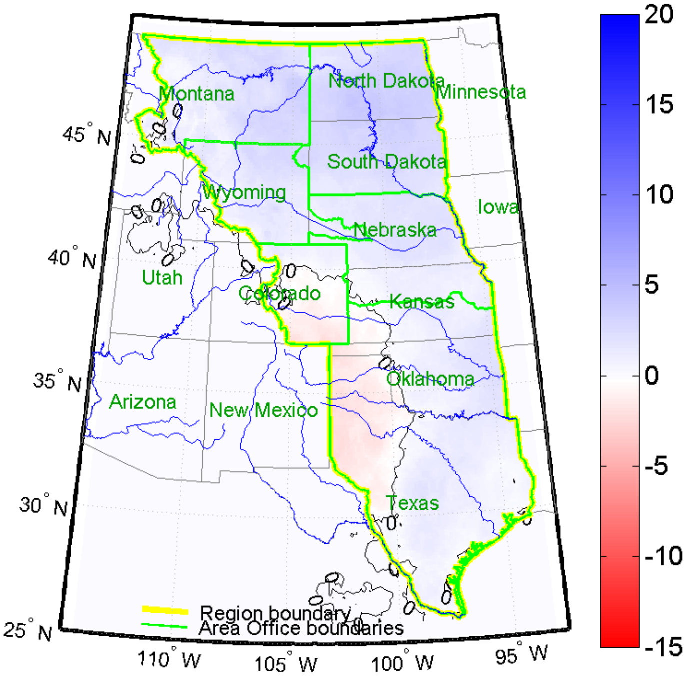
Great Plains Region – Precipitation Change

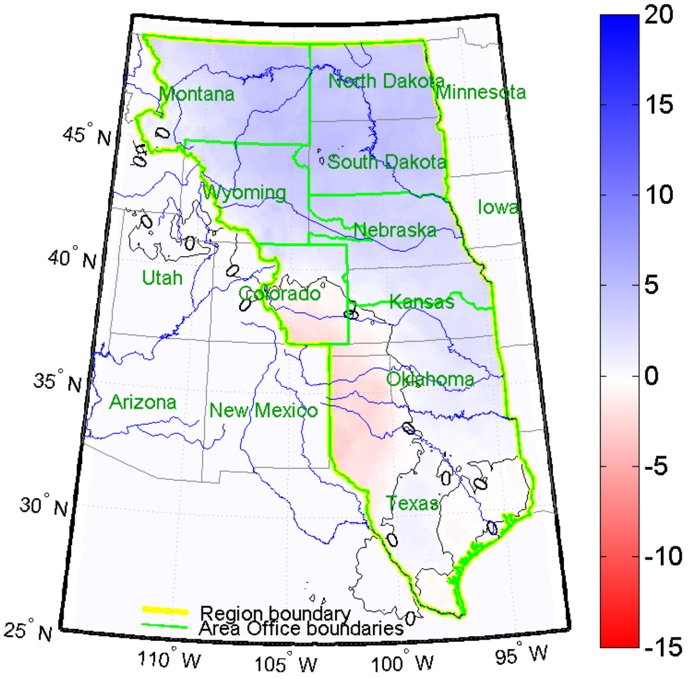
Great Plains Region
Change in Mean Annual Precipitation, Percentage
1960-1989 from 1950-1979

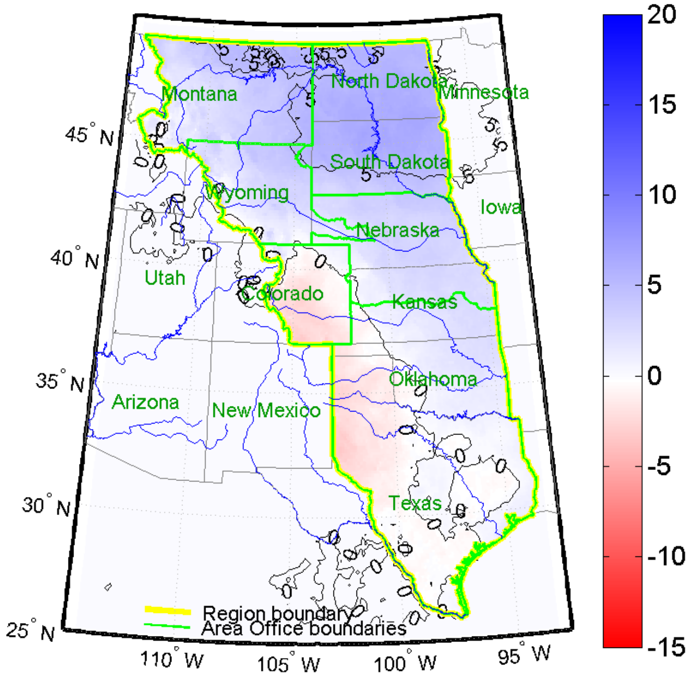


Great Plains Region
Change in Mean Annual Precipitation, Percentage
1970-1999 from 1950-1979

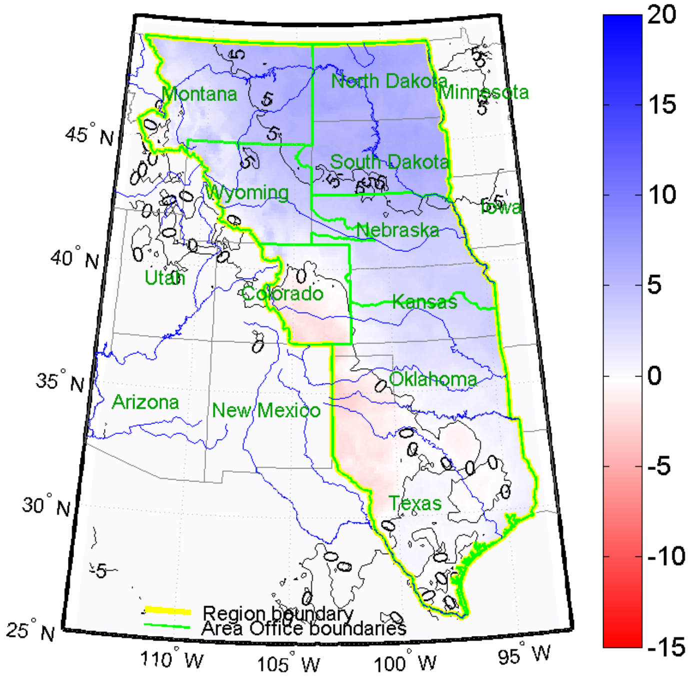



Great Plains Region
Change in Mean Annual Precipitation, Percentage
1980-2009 from 1950-1979

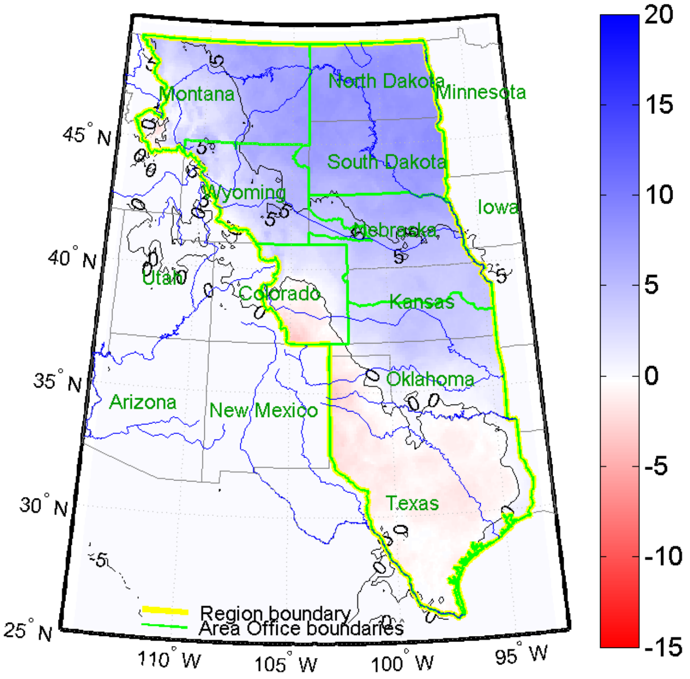

Great Plains Region
Change in Mean Annual Precipitation, Percentage
1990-2019 from 1950-1979



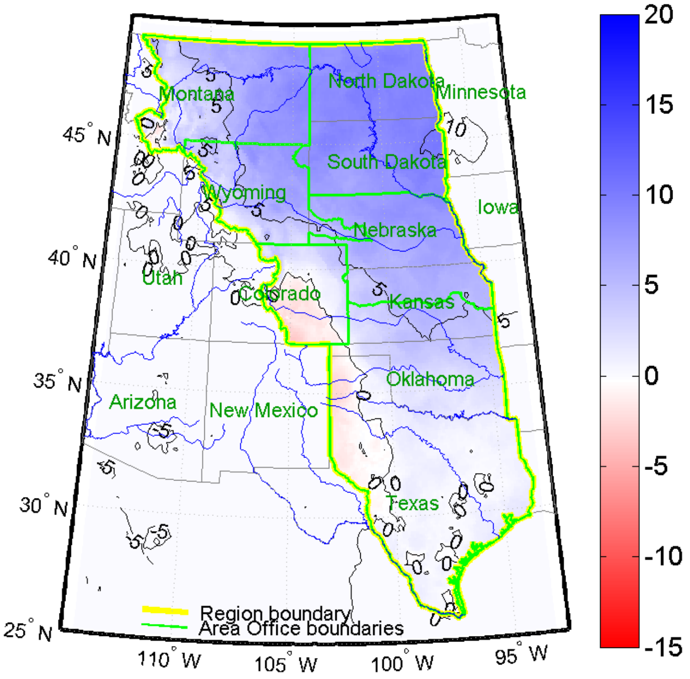
Great Plains Region
Change in Mean Annual Precipitation, Percentage
2000-2029 from 1950-1979



Great Plains Region
Change in Mean Annual Precipitation, Percentage
2010-2039 from 1950-1979

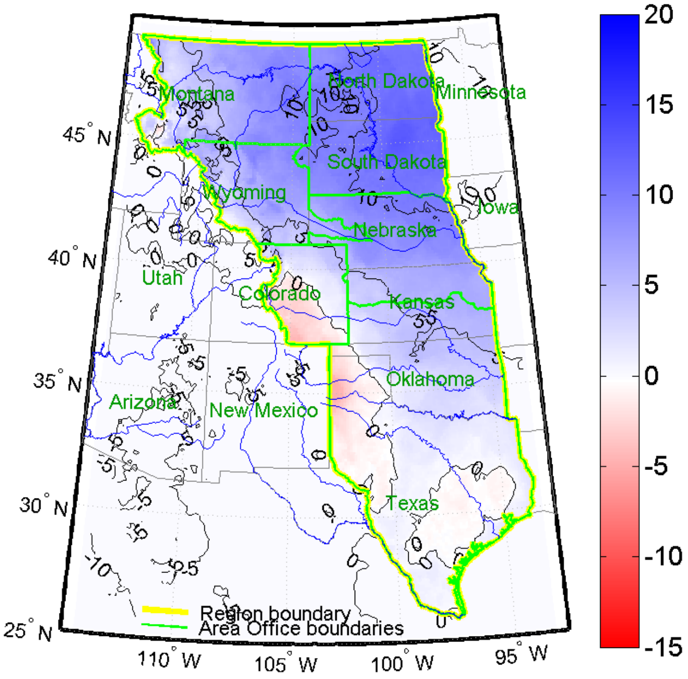


Great Plains Region
Change in Mean Annual Precipitation, Percentage
2020-2049 from 1950-1979

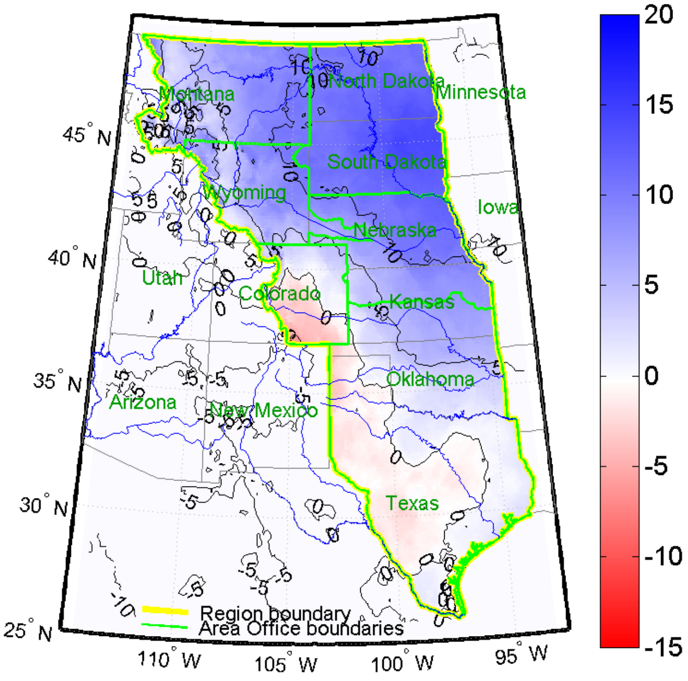


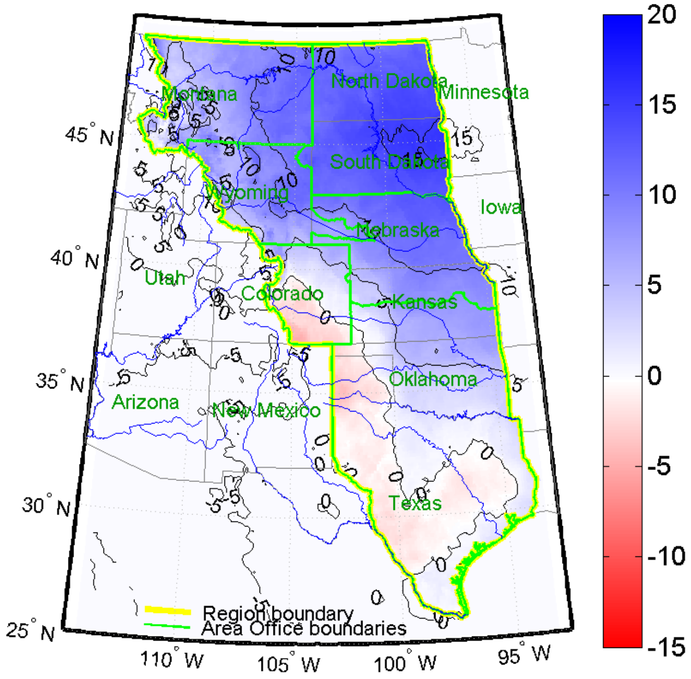
Great Plains Region
Change in Mean Annual Precipitation, Percentage
2030-2059 from 1950-1979

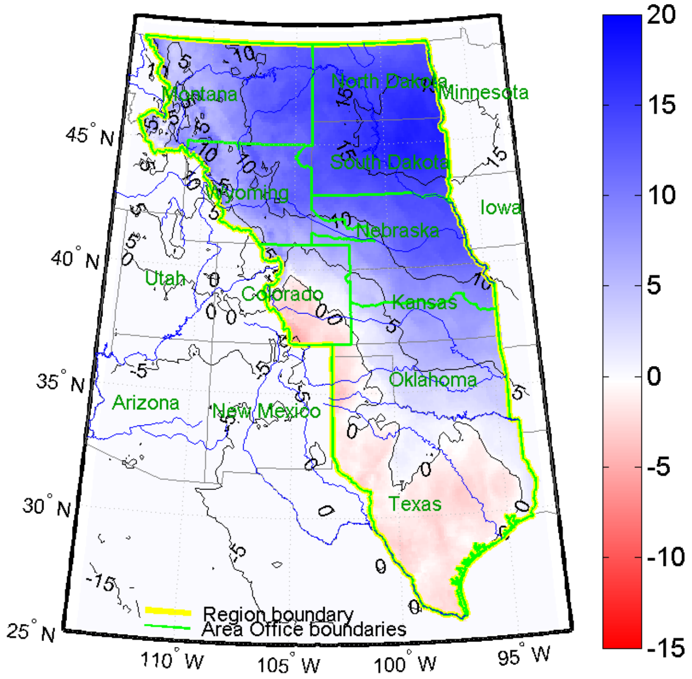
Great Plains Region
Change in Mean Annual Precipitation, Percentage
2040-2069 from 1950-1979



Great Plains Region
Change in Mean Annual Precipitation, Percentage
2050-2079 from 1950-1979

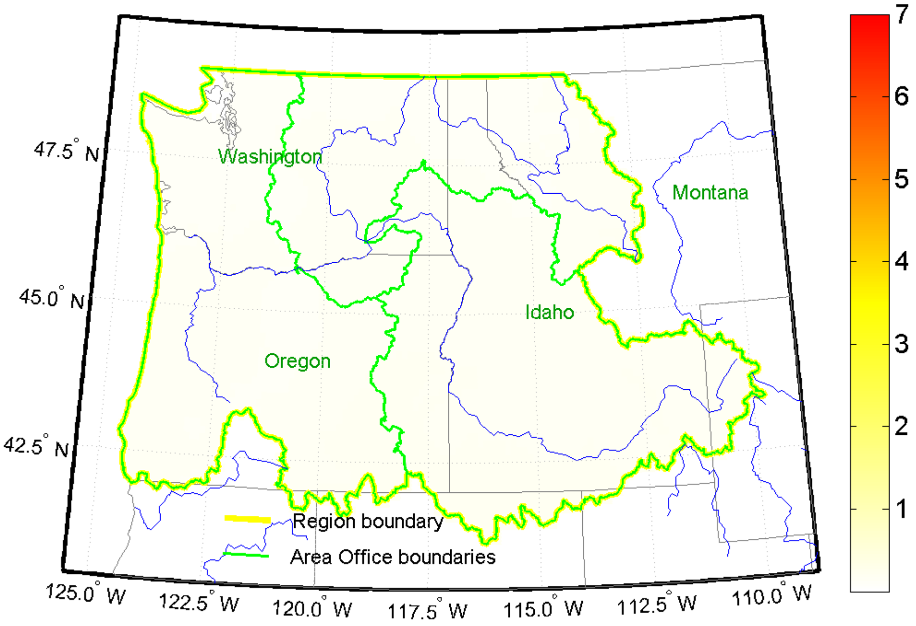



Great Plains Region
Change in Mean Annual Precipitation, Percentage
2060-2089 from 1950-1979

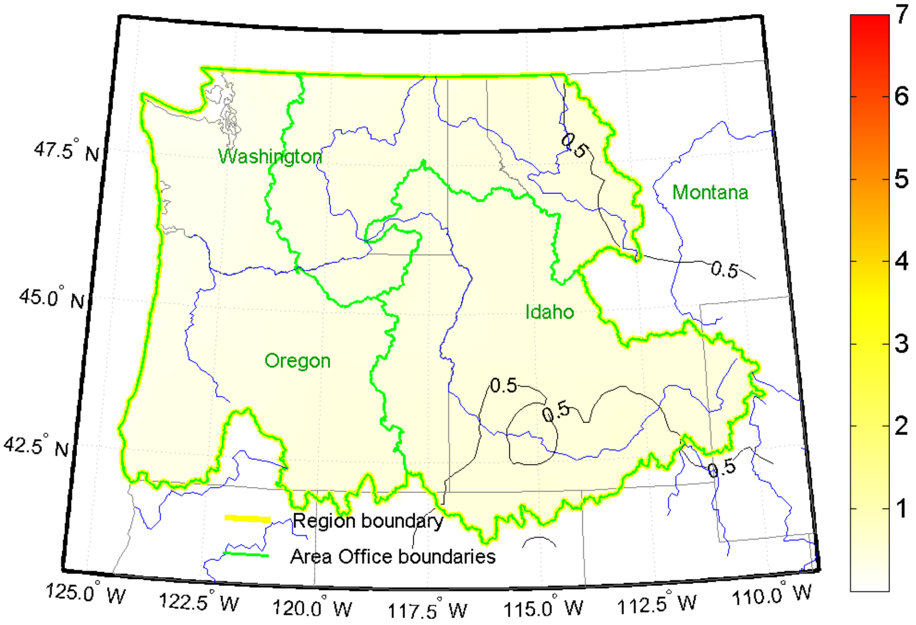

Great Plains Region
Change in Mean Annual Precipitation, Percentage
2070-2099 from 1950-1979

Pacific Northwest Region – Temperature Change

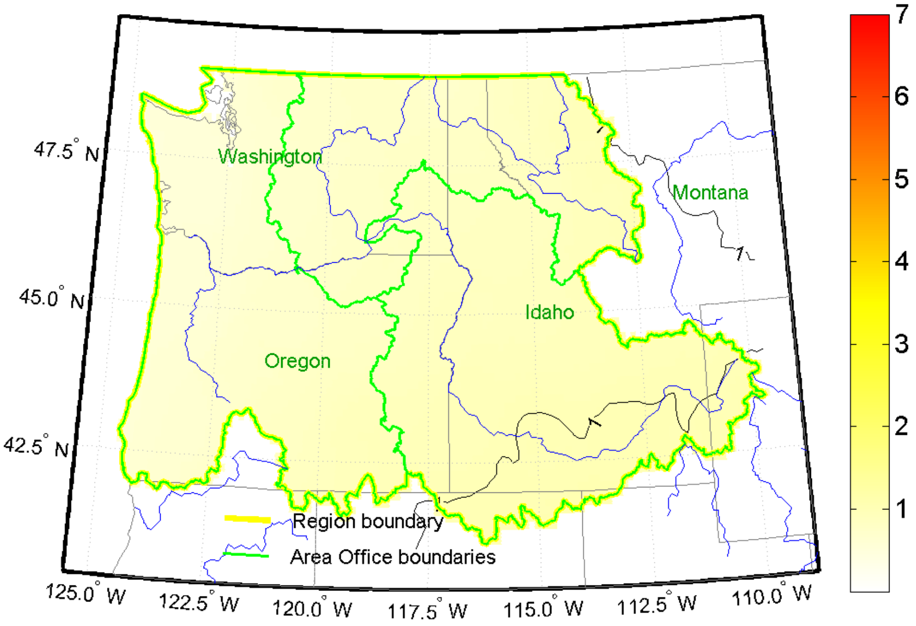
Pacific Northwest Region
Change in Mean Annual Temperature, deg F
1960-1989 from 1950-1979



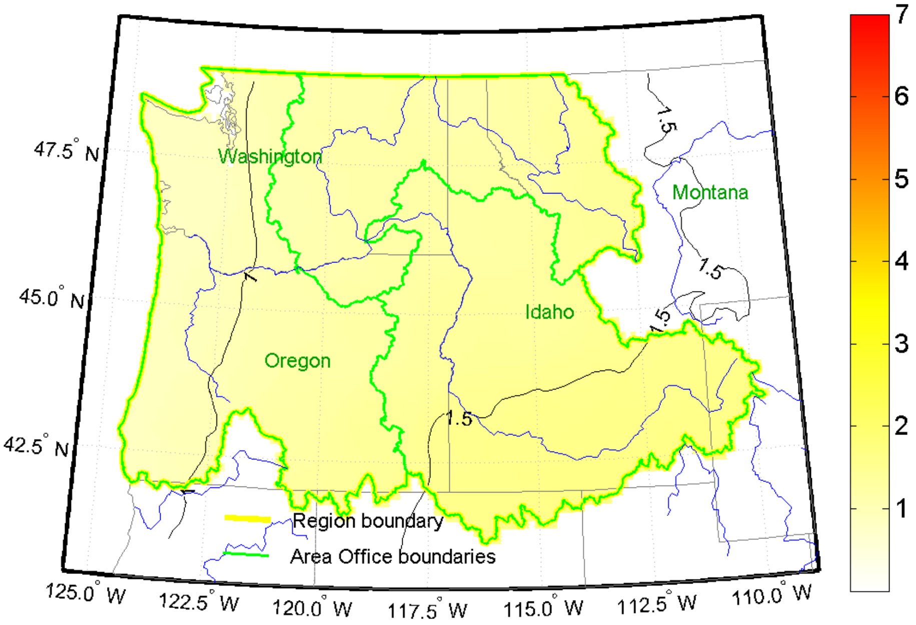
Pacific Northwest Region
Change in Mean Annual Temperature, deg F
1970-1999 from 1950-1979

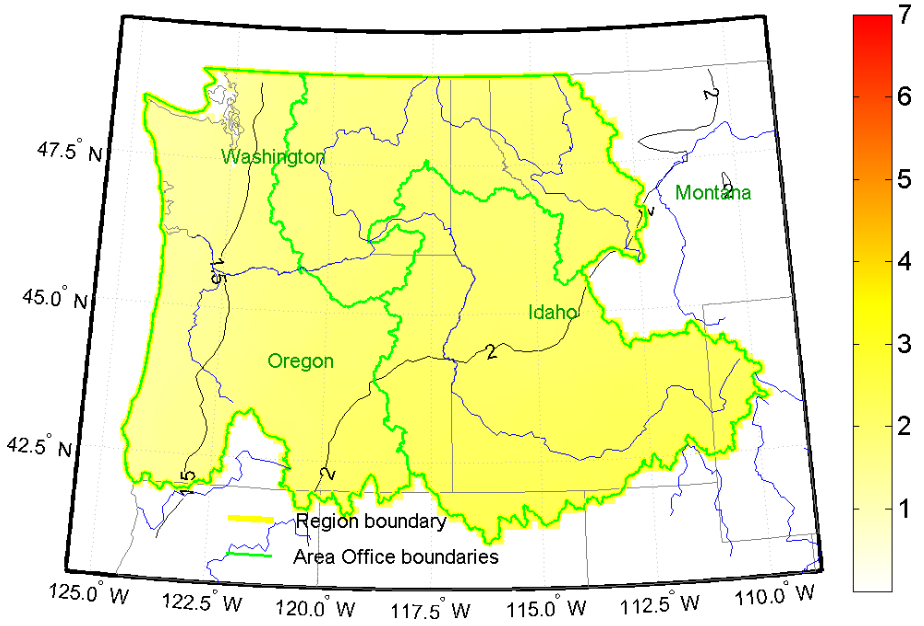


Pacific Northwest Region
Change in Mean Annual Temperature, deg F
1980-2009 from 1950-1979

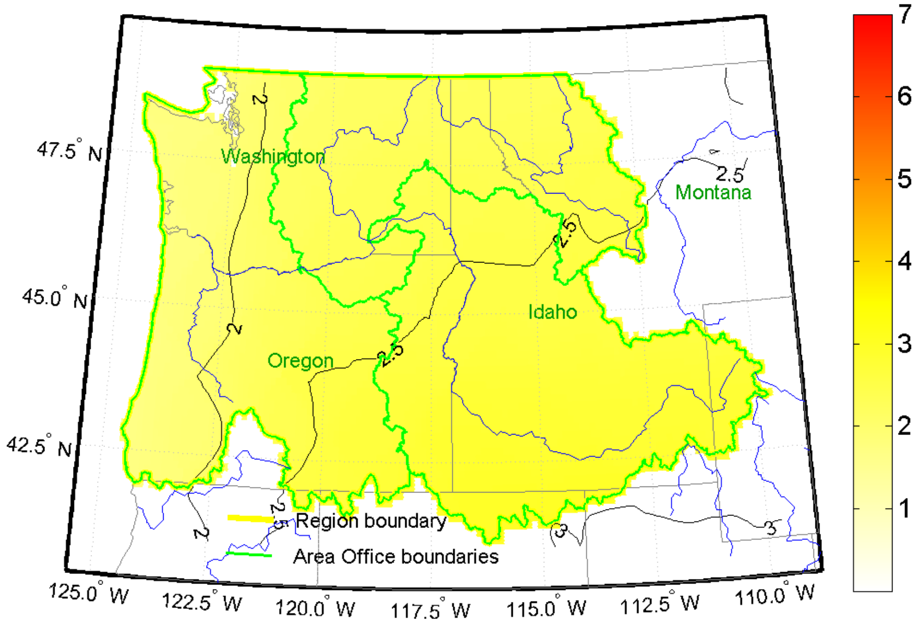


Pacific Northwest Region
Change in Mean Annual Temperature, deg F
1990-2019 from 1950-1979

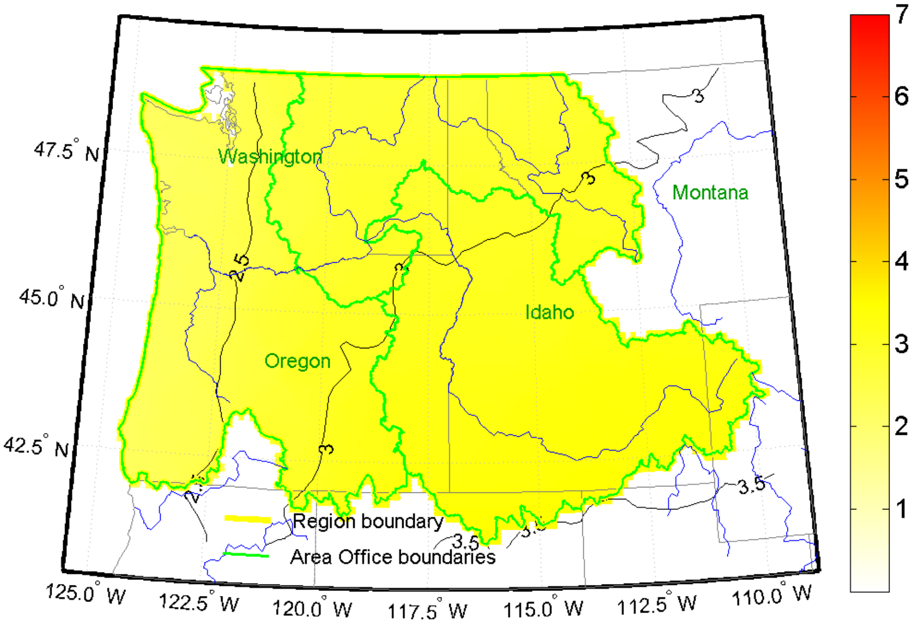




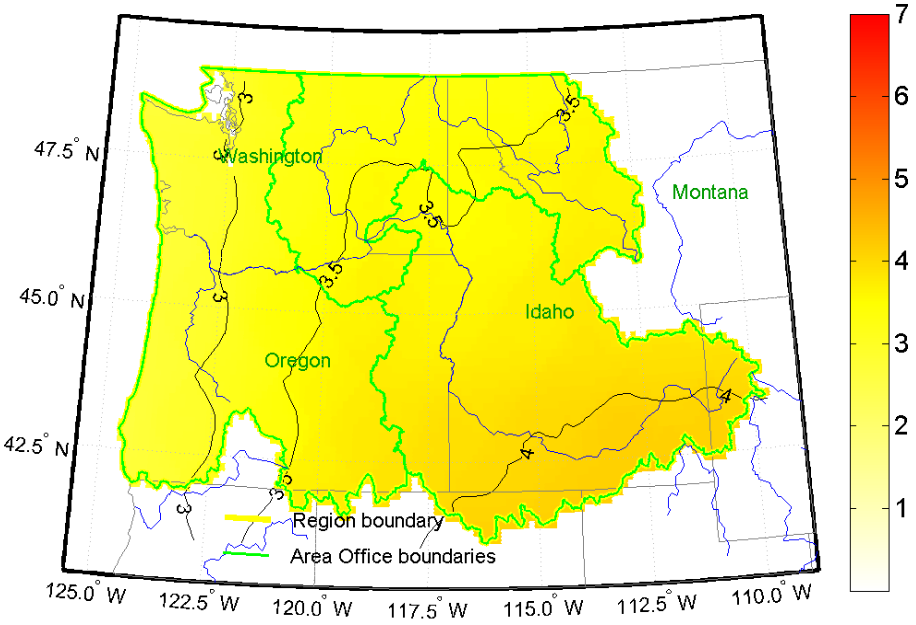
Pacific Northwest Region
Change in Mean Annual Temperature, deg F
2000-2029 from 1950-1979



Pacific Northwest Region
Change in Mean Annual Temperature, deg F
2010-2039 from 1950-1979

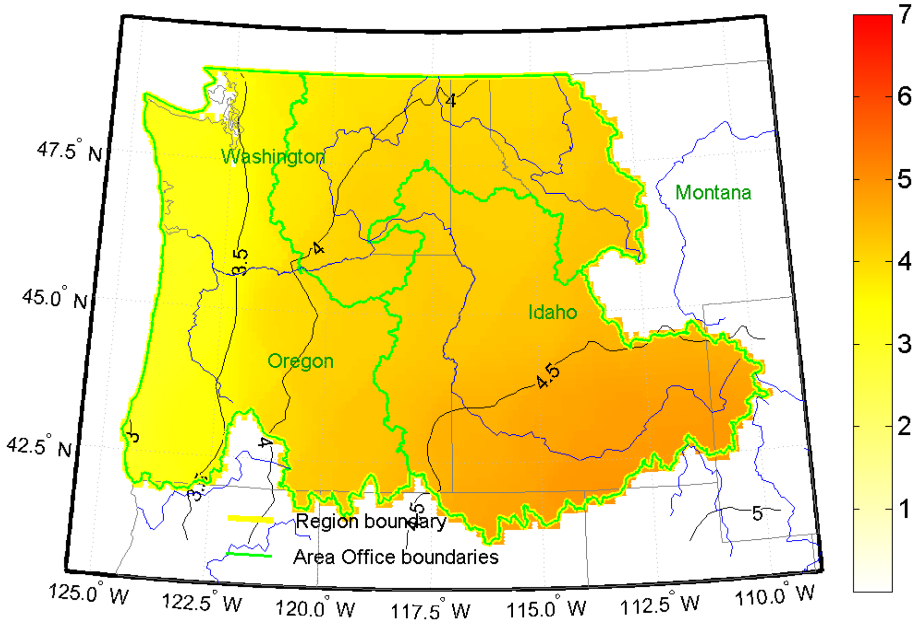


Pacific Northwest Region
Change in Mean Annual Temperature, deg F
2020-2049 from 1950-1979

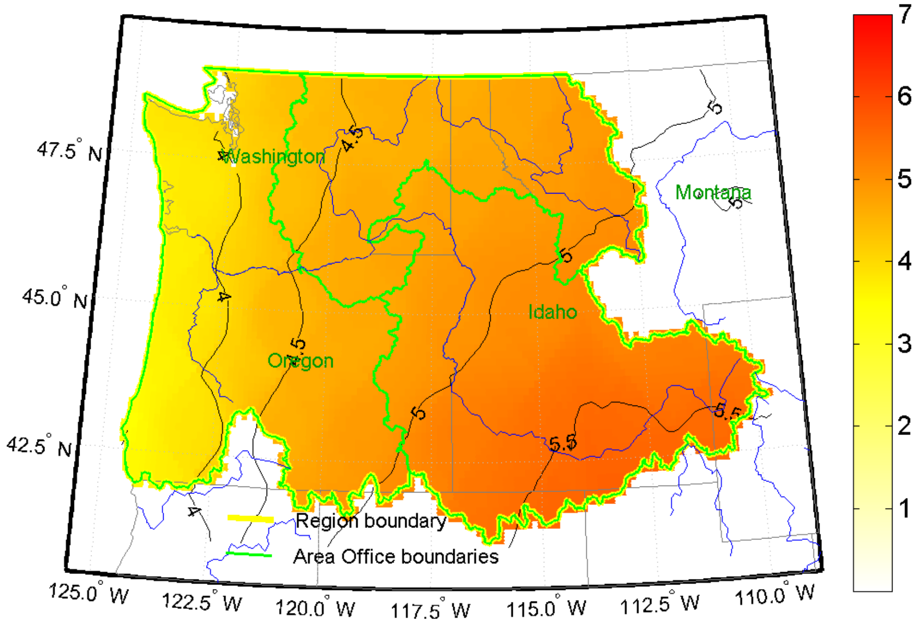


Pacific Northwest Region
Change in Mean Annual Temperature, deg F
2030-2059 from 1950-1979

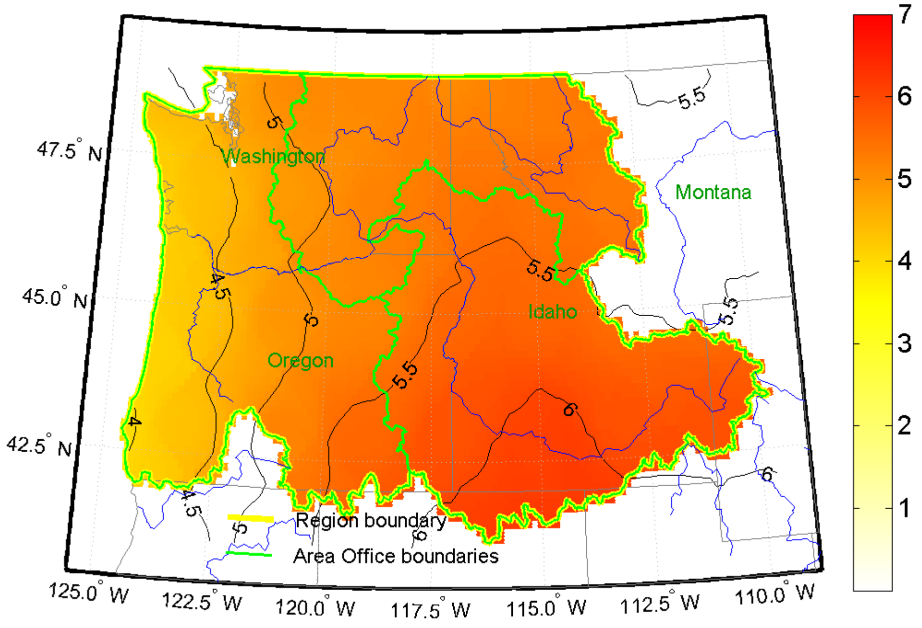
Pacific Northwest Region
Change in Mean Annual Temperature, deg F
2040-2069 from 1950-1979



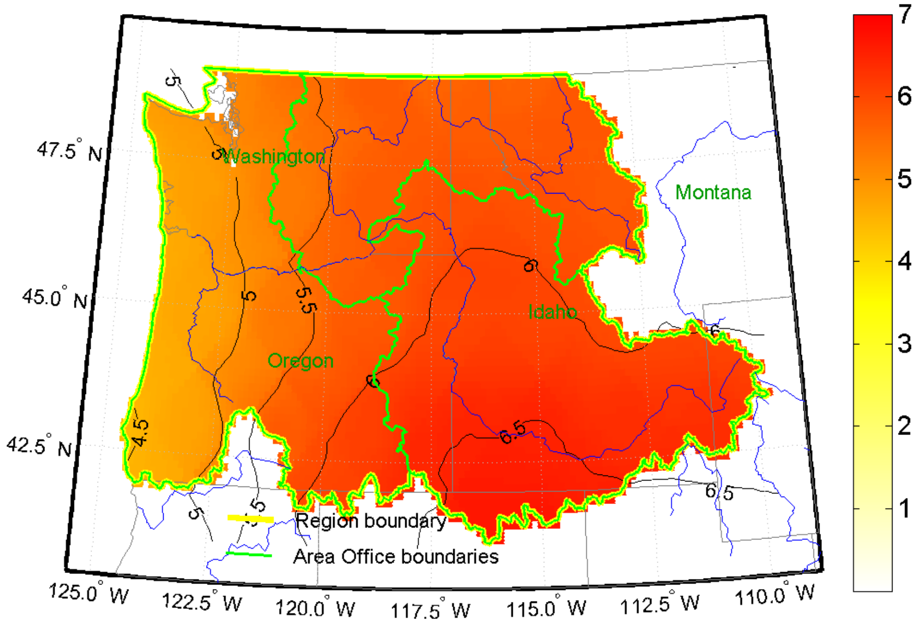
Pacific Northwest Region
Change in Mean Annual Temperature, deg F
2050-2079 from 1950-1979



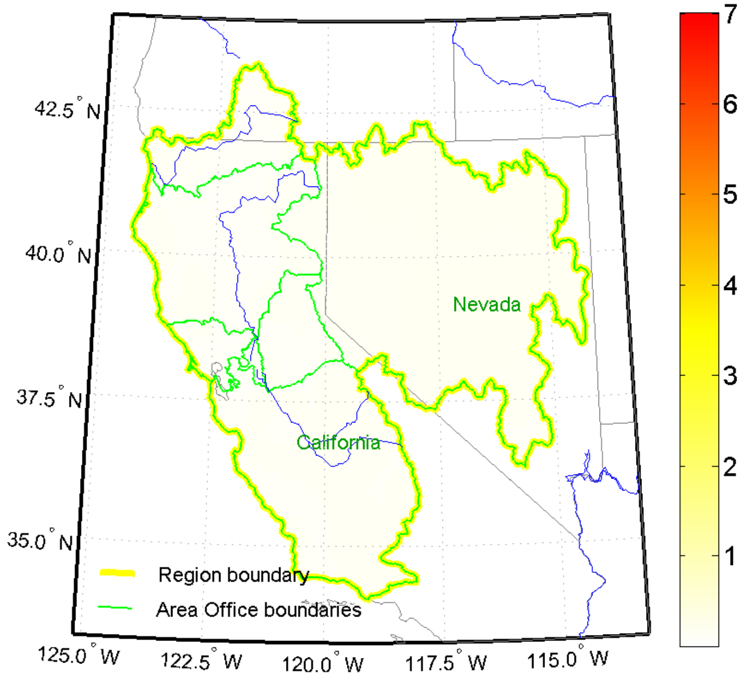
Pacific Northwest Region
Change in Mean Annual Temperature, deg F
2060-2089 from 1950-1979



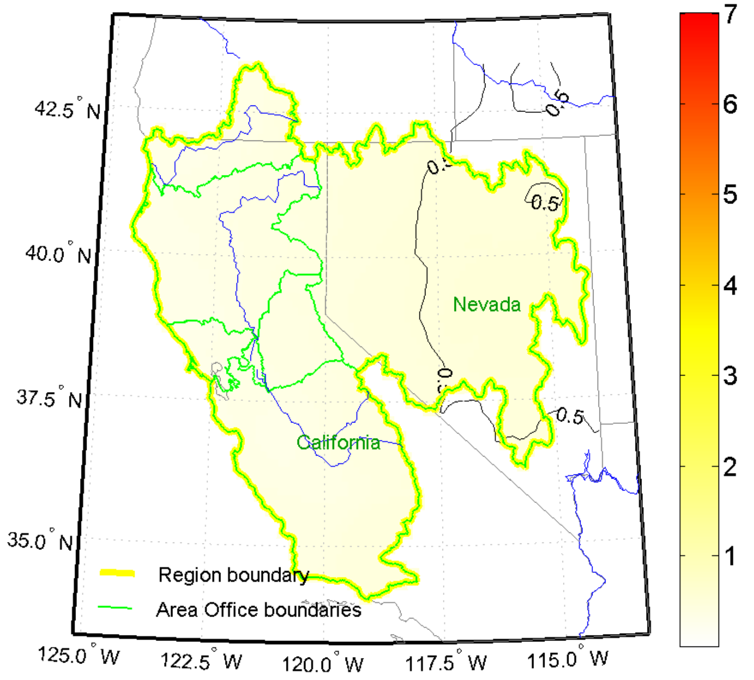
Pacific Northwest Region
Change in Mean Annual Temperature, deg F
2070-2099 from 1950-1979



Mid-Pacific Region – Temperature Change

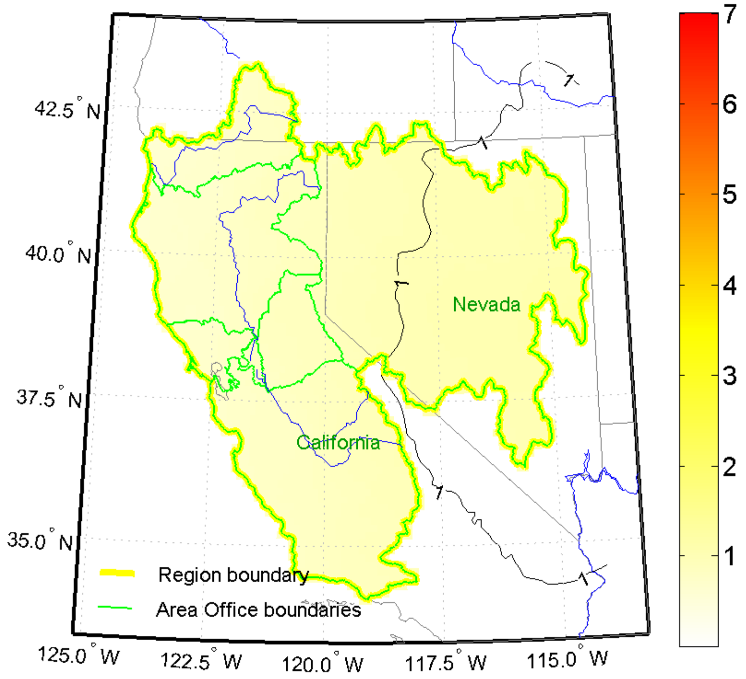


Mid-Pacific Region
Change in Mean Annual Temperature, deg F
1960-1989 from 1950-1979

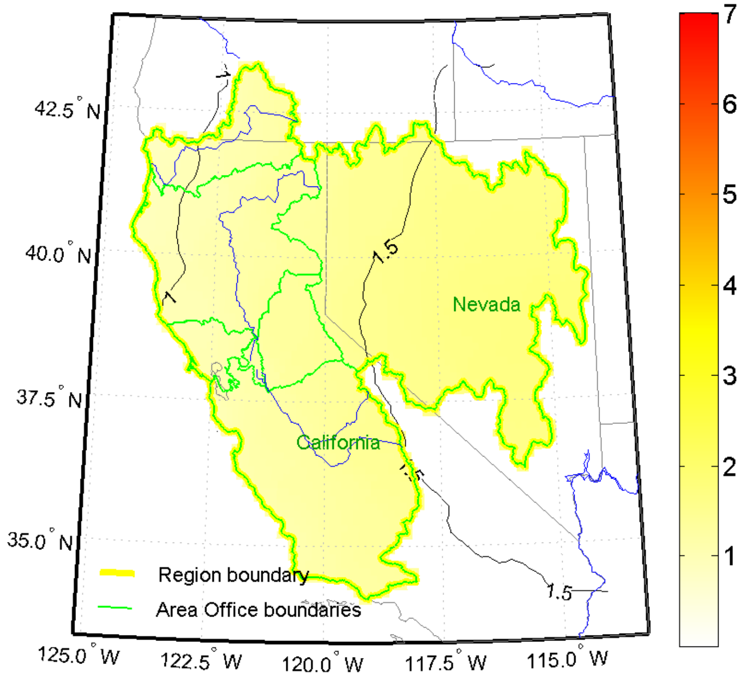


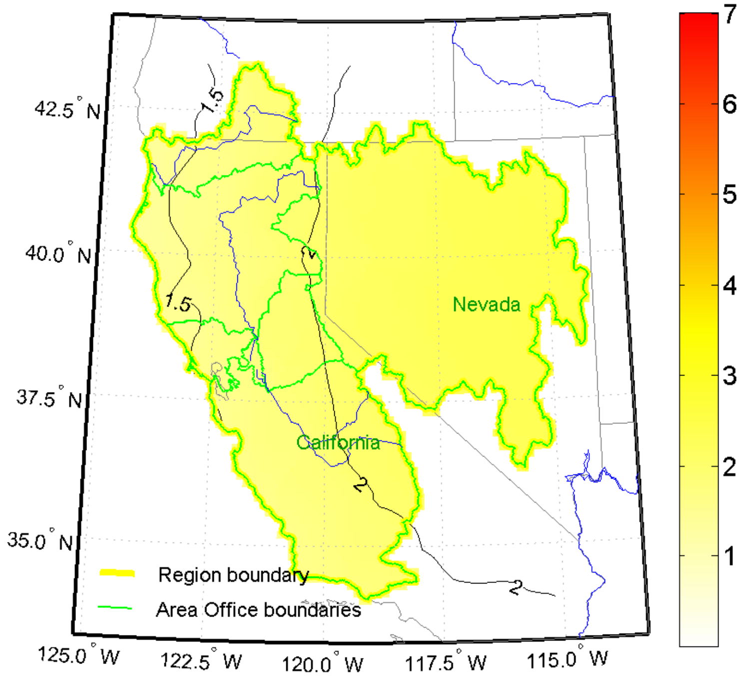
Mid-Pacific Region
Change in Mean Annual Temperature, deg F
1970-1999 from 1950-1979

Mid-Pacific Region
Change in Mean Annual Temperature, deg F
1980-2009 from 1950-1979

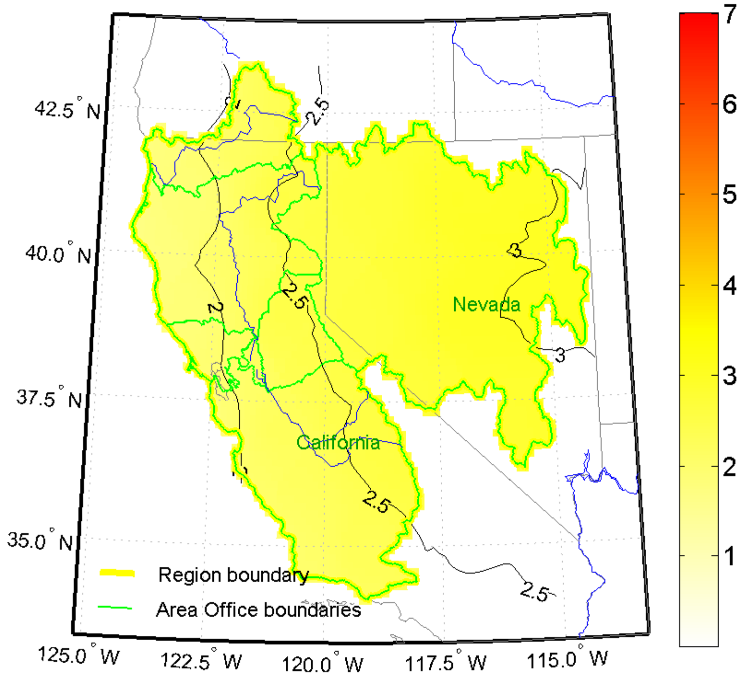


Mid-Pacific Region
Change in Mean Annual Temperature, deg F
1990-2019 from 1950-1979

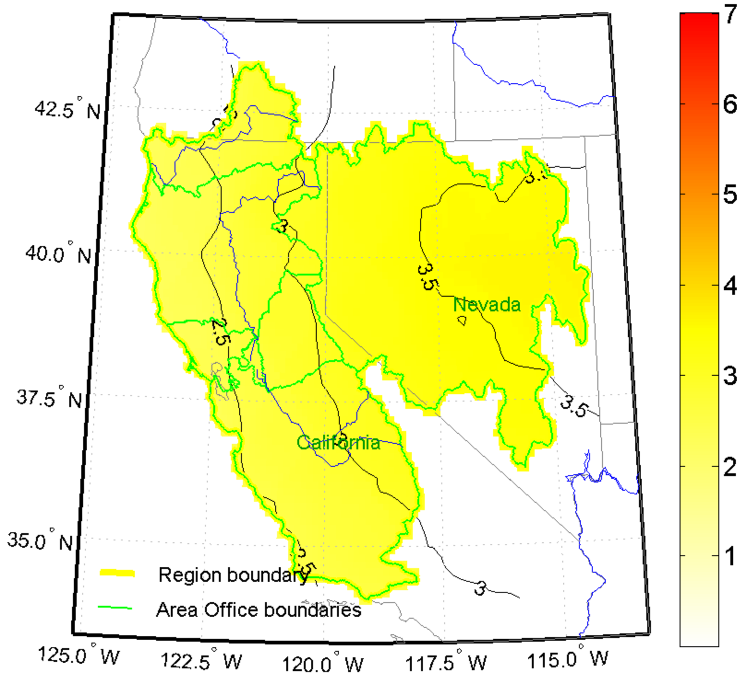




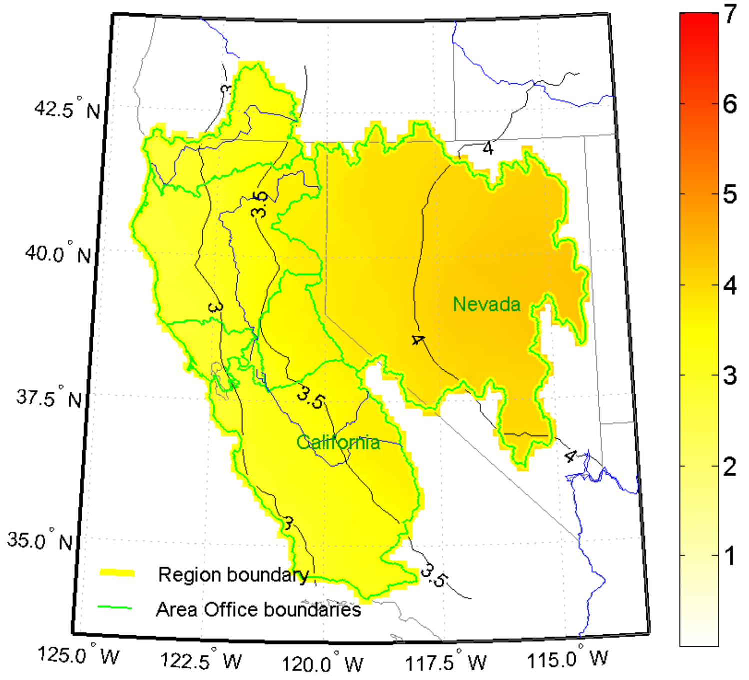
Mid-Pacific Region
Change in Mean Annual Temperature, deg F
2000-2029 from 1950-1979



Mid-Pacific Region
Change in Mean Annual Temperature, deg F
2010-2039 from 1950-1979

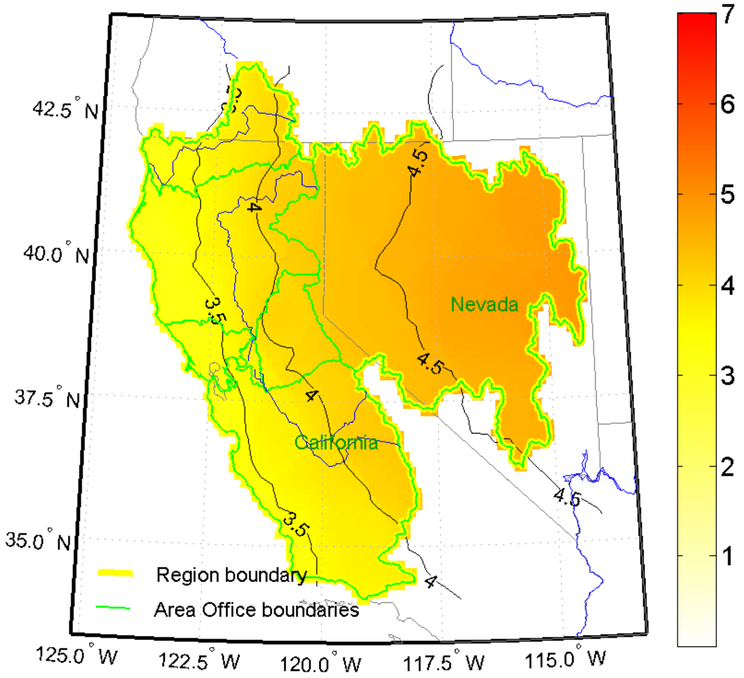


Mid-Pacific Region
Change in Mean Annual Temperature, deg F
2020-2049 from 1950-1979

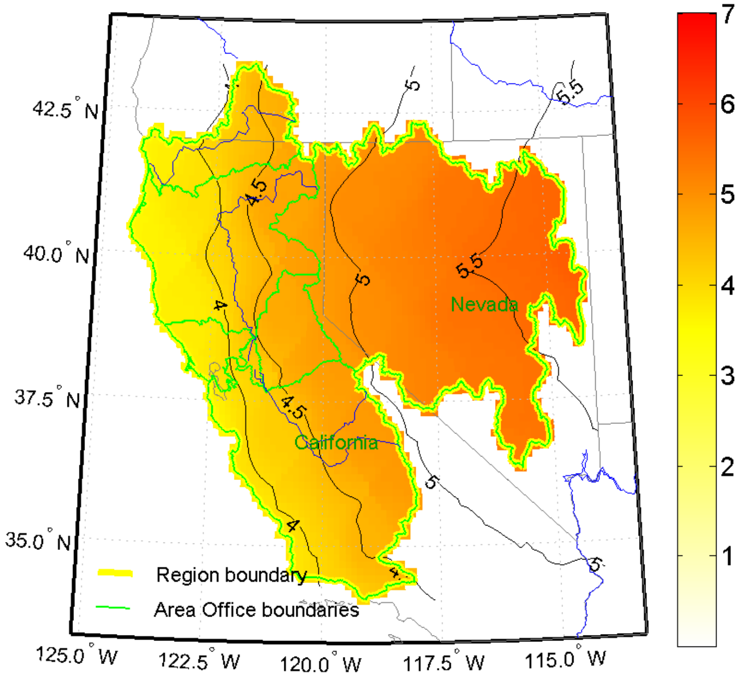


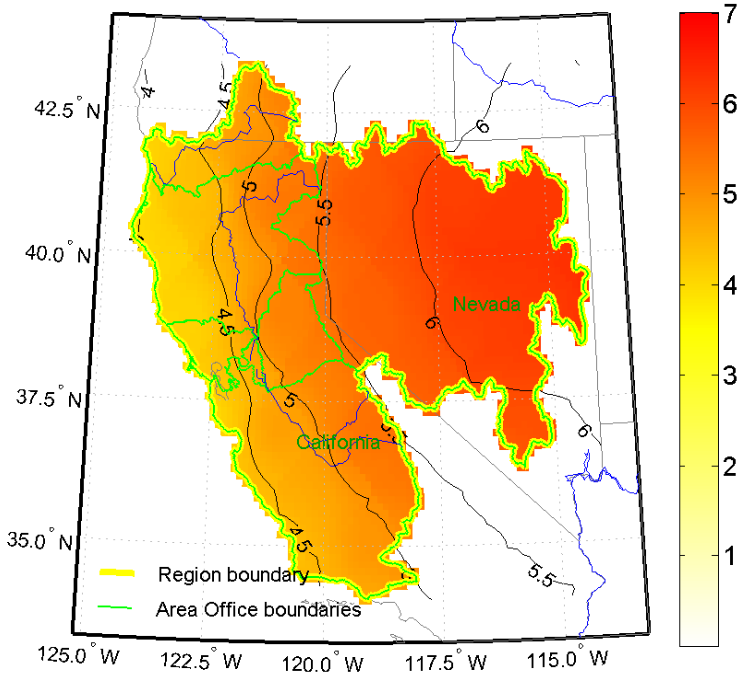
Mid-Pacific Region
Change in Mean Annual Temperature, deg F
2030-2059 from 1950-1979

Mid-Pacific Region
Change in Mean Annual Temperature, deg F
2040-2069 from 1950-1979

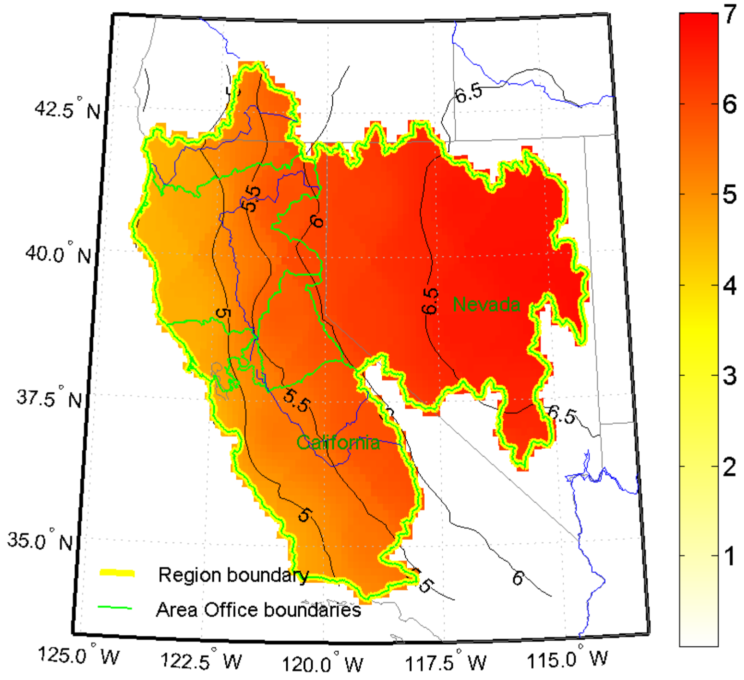


Mid-Pacific Region
Change in Mean Annual Temperature, deg F
2050-2079 from 1950-1979





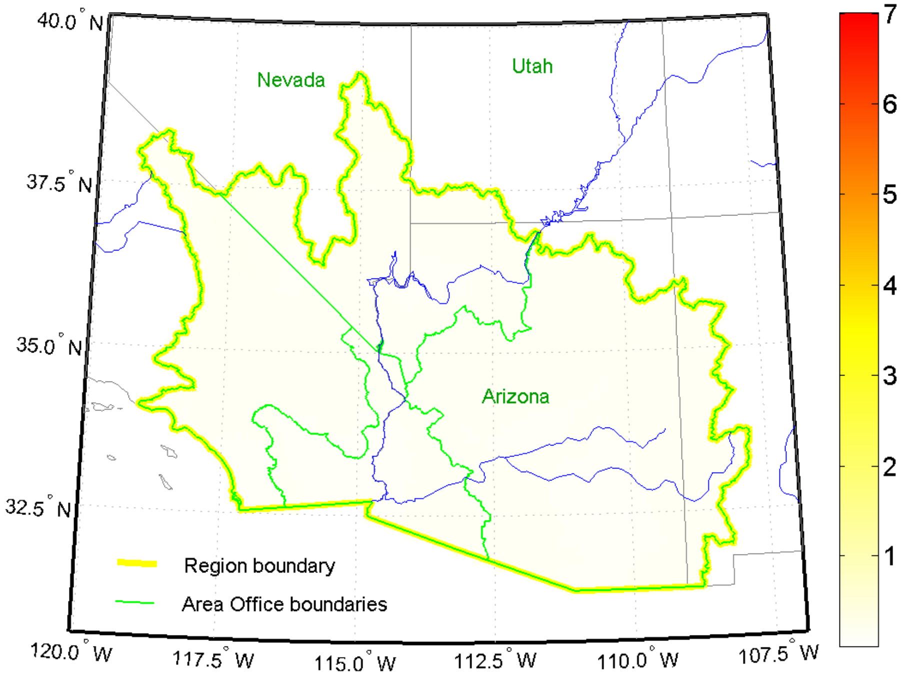
Mid-Pacific Region
Change in Mean Annual Temperature, deg F
2060-2089 from 1950-1979



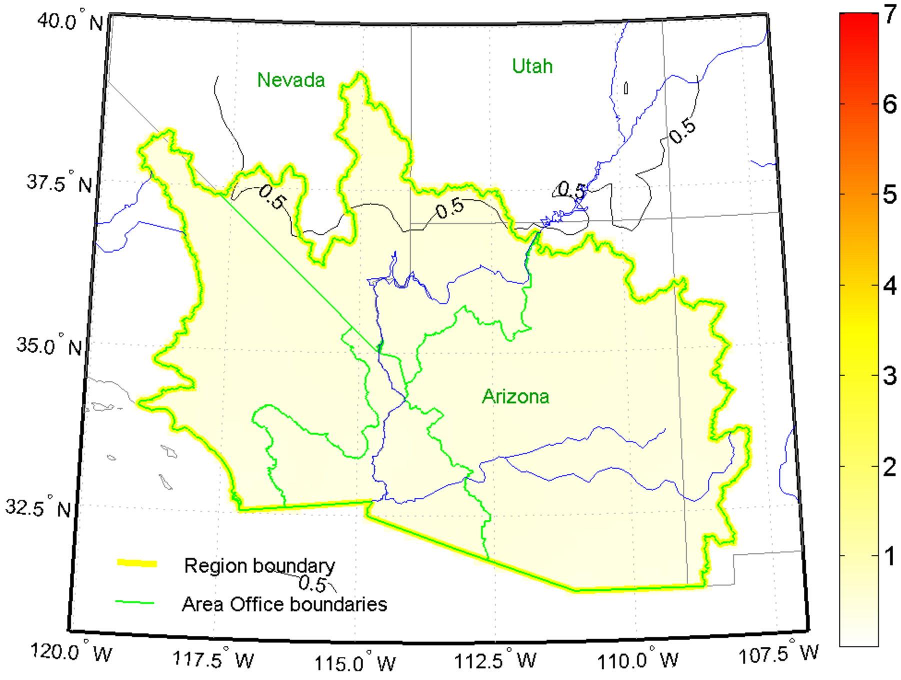
Mid-Pacific Region
Change in Mean Annual Temperature, deg F
2070-2099 from 1950-1979

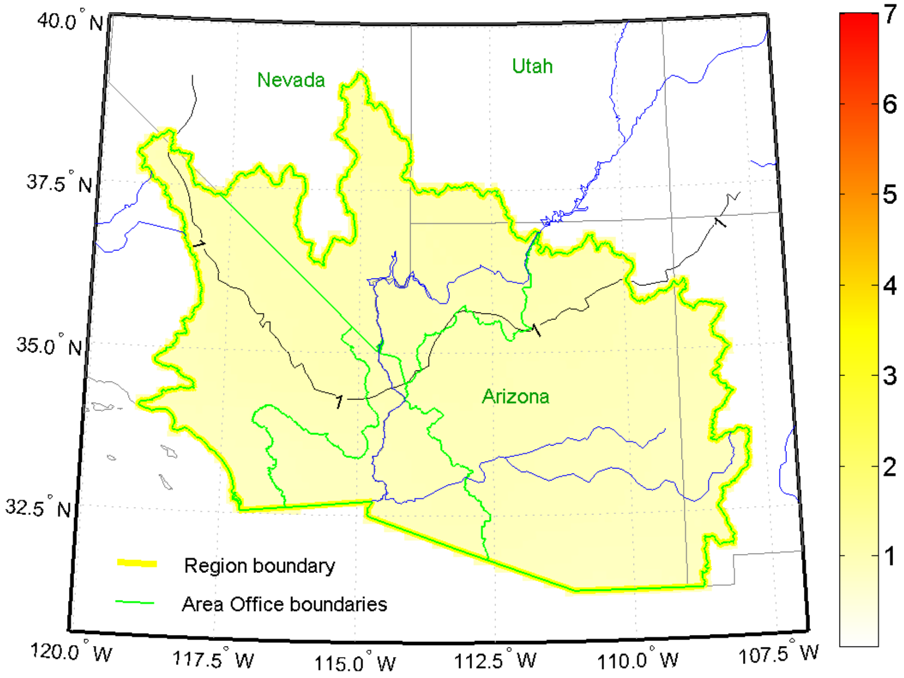
Lower Colorado Region – Temperature Change

Lower Colorado Region
Change in Mean Annual Temperature, deg F
1960-1989 from 1950-1979

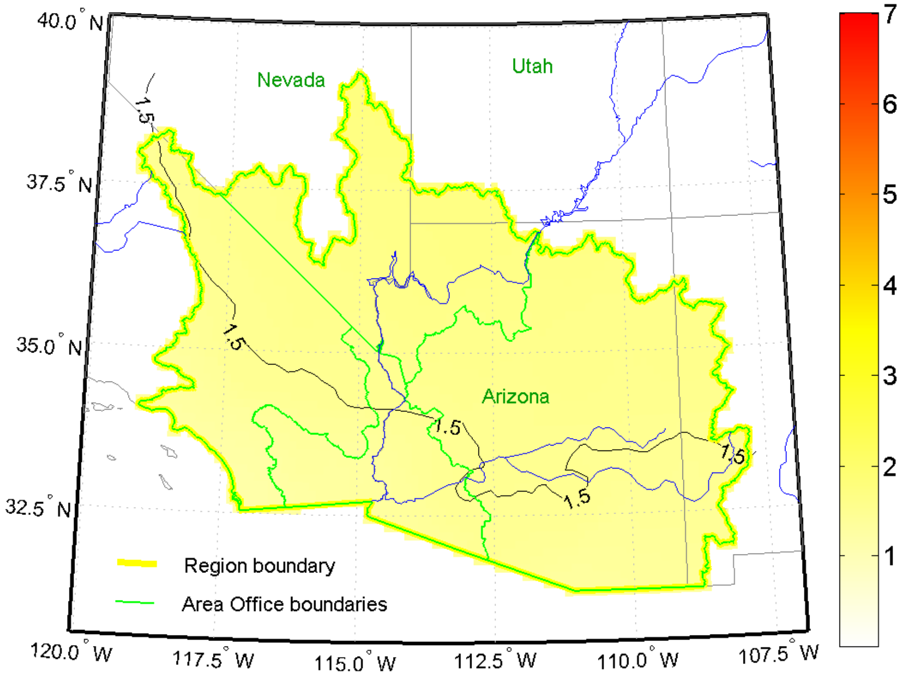


Lower Colorado Region
Change in Mean Annual Temperature, deg F
1970-1999 from 1950-1979



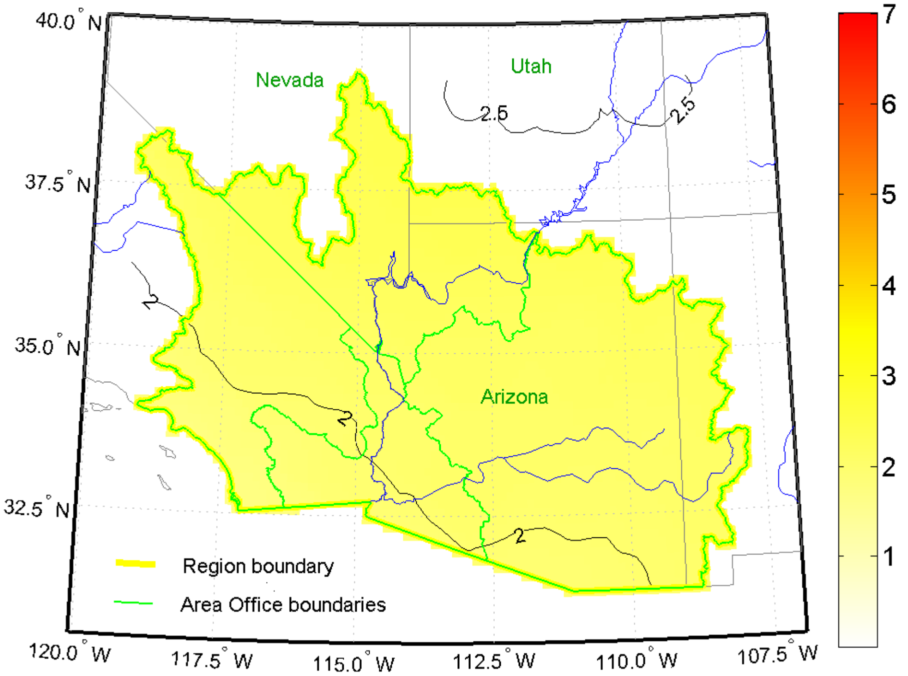


Lower Colorado Region
Change in Mean Annual Temperature, deg F
1980-2009 from 1950-1979

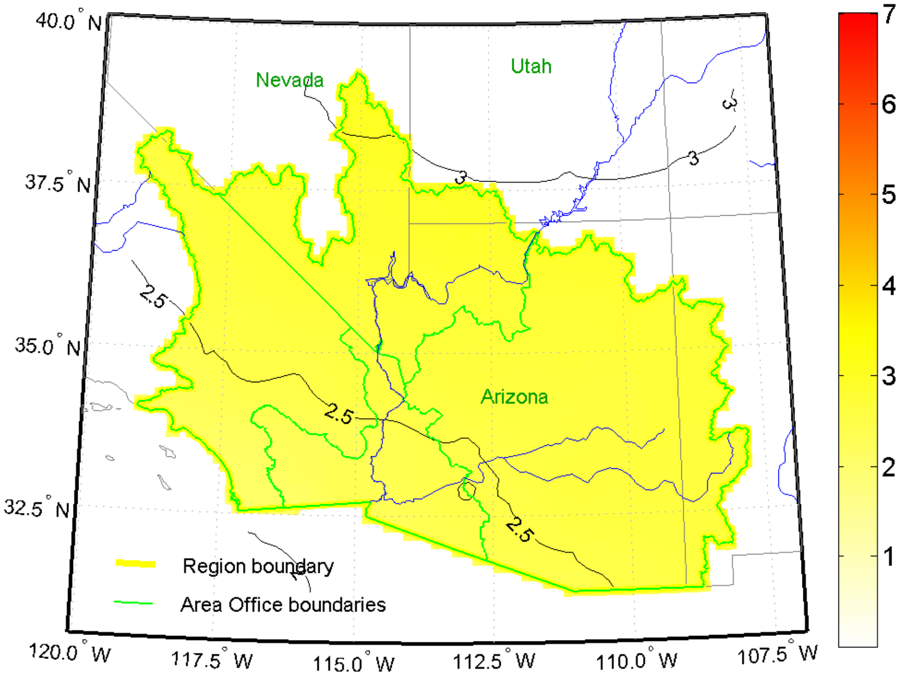


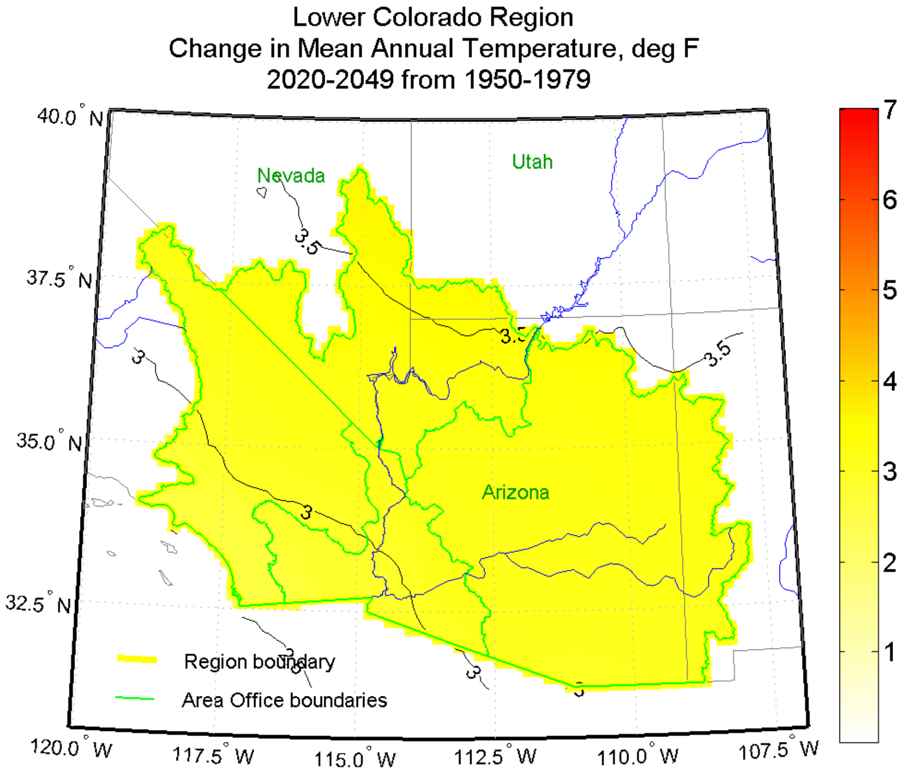
Lower Colorado Region
Change in Mean Annual Temperature, deg F
1990-2019 from 1950-1979

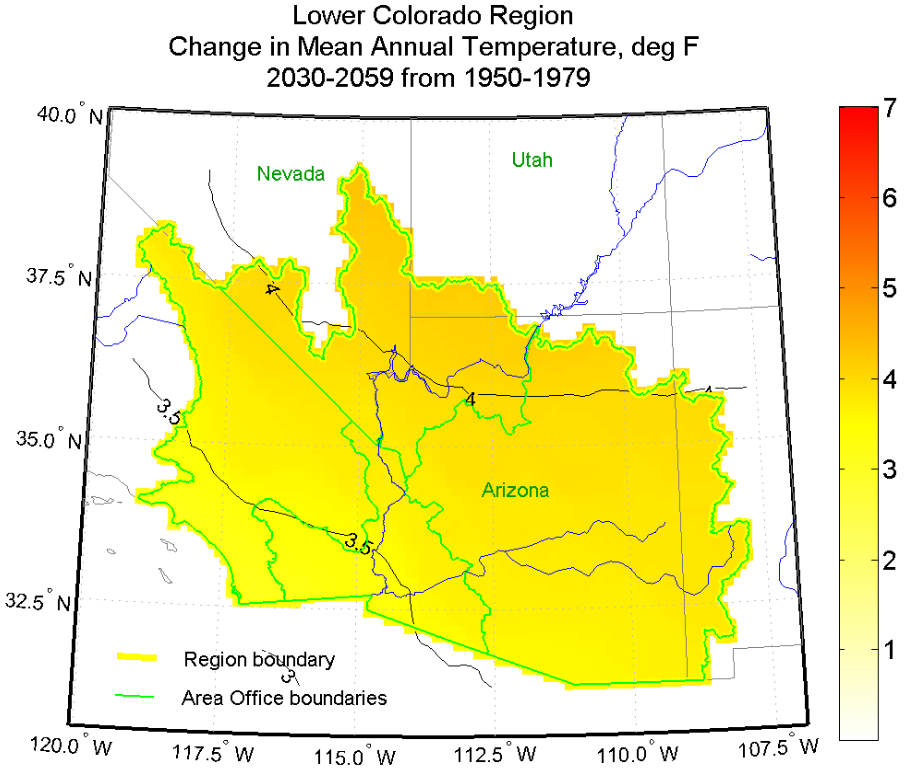
Lower Colorado Region
Change in Mean Annual Temperature, deg F
2000-2029 from 1950-1979



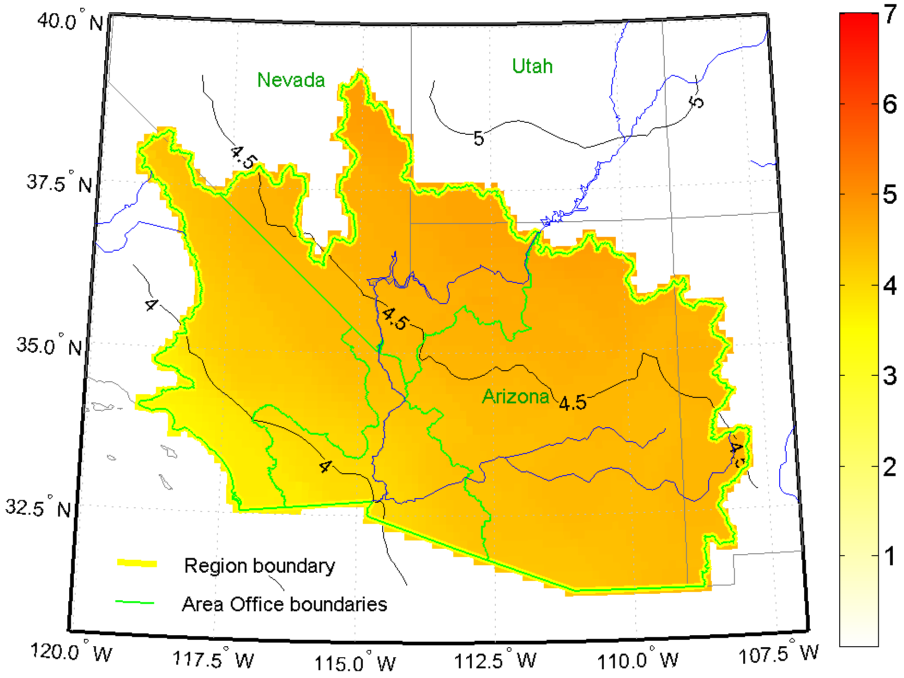
Lower Colorado Region
Change in Mean Annual Temperature, deg F
2010-2039 from 1950-1979



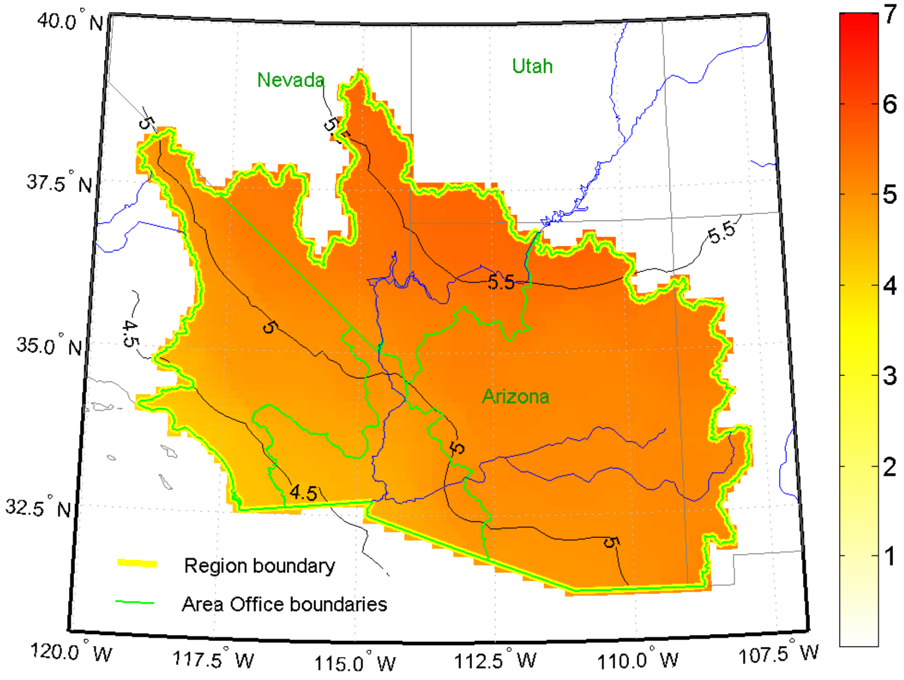

Lower Colorado Region
Change in Mean Annual Temperature, deg F
2020-2049 from 1950-1979
40.0° N
37.5° N
35.0° N
32.5° N
120.0° W
117.5° W
115.0° W
112.5° W
110.0° W
107.5° W
Nevada
Utah
Arizona
3.5
3
Region boundary
Area Office boundaries
7
6
5
4
3
2
1

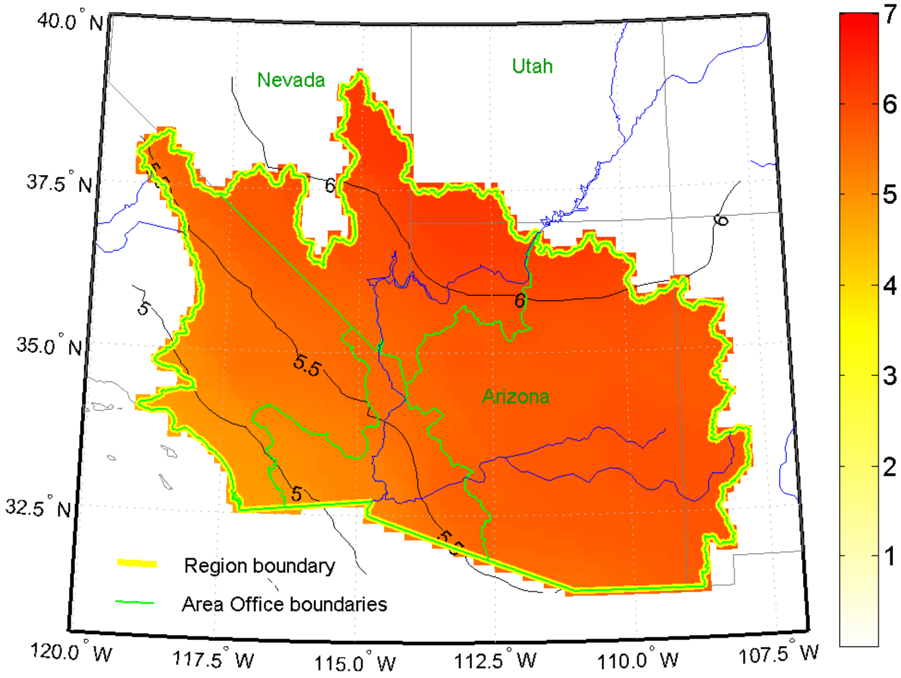

Lower Colorado Region
Change in Mean Annual Temperature, deg F
2030-2059 from 1950-1979
40.0° N
37.5° N
35.0° N
32.5° N
120.0° W
117.5° W
115.0° W
112.5° W
110.0° W
107.5° W
Nevada
Utah
Arizona
4
3.5
3
Region boundary
Area Office boundaries
7
6
5
4
3
2
1

Lower Colorado Region
Change in Mean Annual Temperature, deg F
2040-2069 from 1950-1979

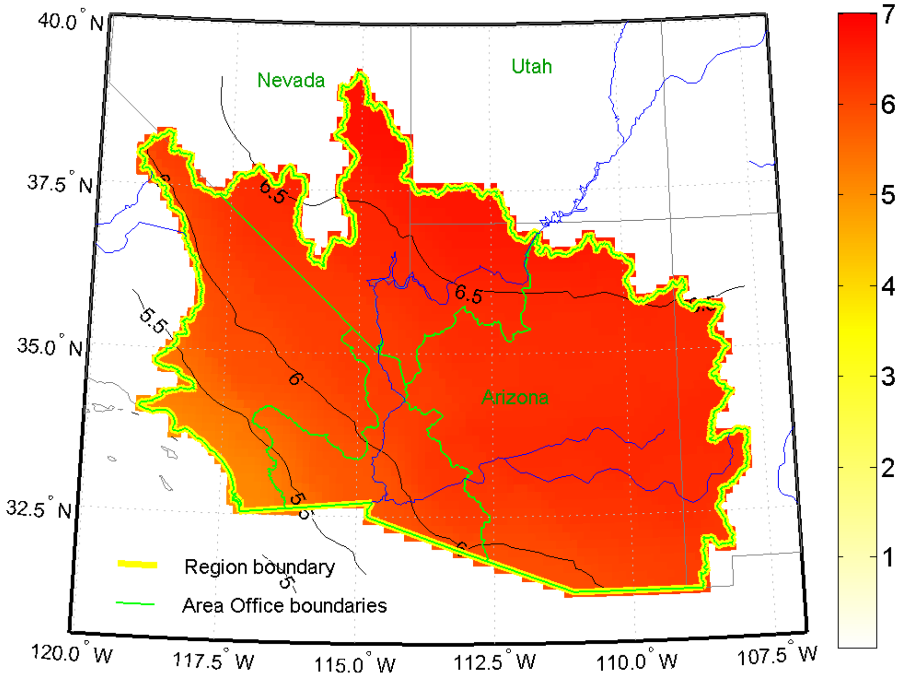


Lower Colorado Region
Change in Mean Annual Temperature, deg F
2050-2079 from 1950-1979





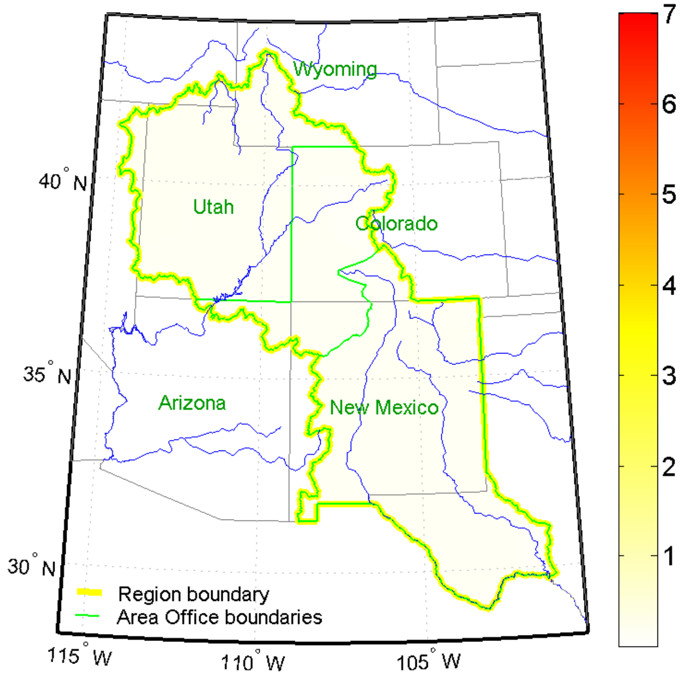
Lower Colorado Region
Change in Mean Annual Temperature, deg F
2060-2089 from 1950-1979



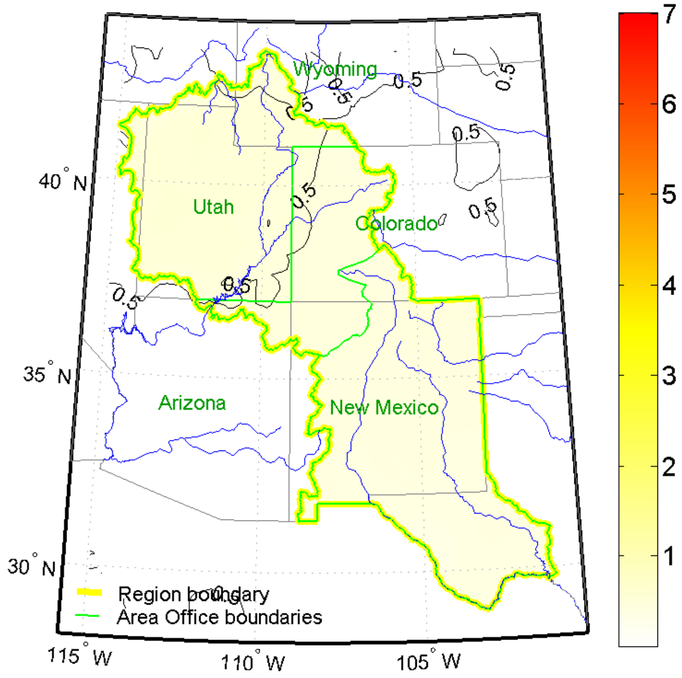
Lower Colorado Region
Change in Mean Annual Temperature, deg F
2070-2099 from 1950-1979

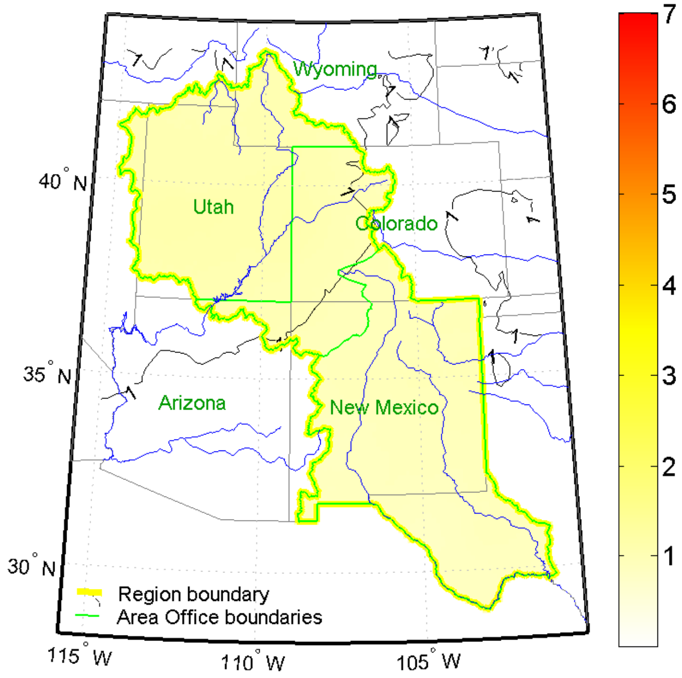
Upper Colorado Region – Temperature Change

Upper Colorado Region
Change in Mean Annual Temperature, deg F
1960-1989 from 1950-1979

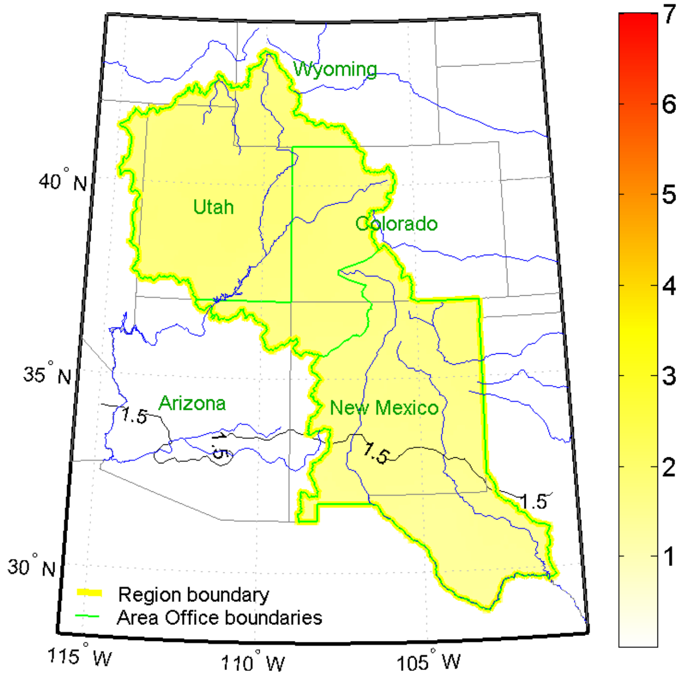


Upper Colorado Region
Change in Mean Annual Temperature, deg F
1970-1999 from 1950-1979

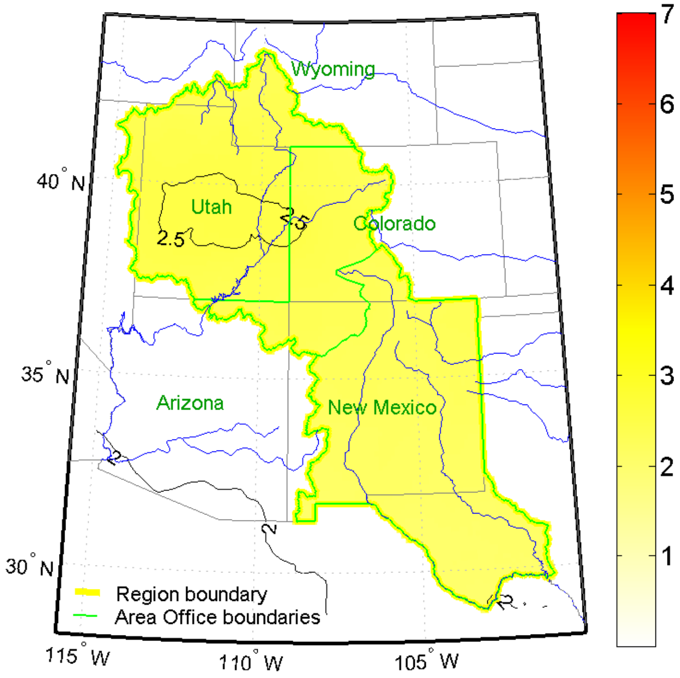




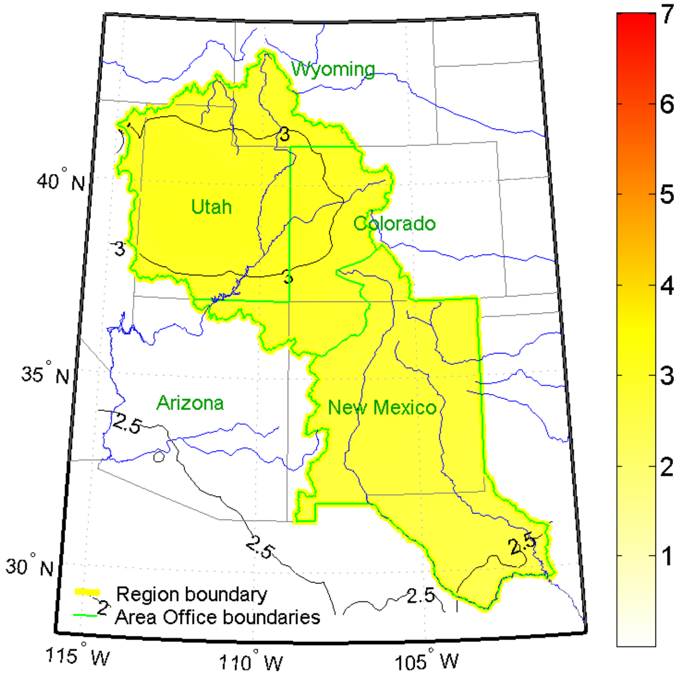
Upper Colorado Region
Change in Mean Annual Temperature, deg F
1980-2009 from 1950-1979



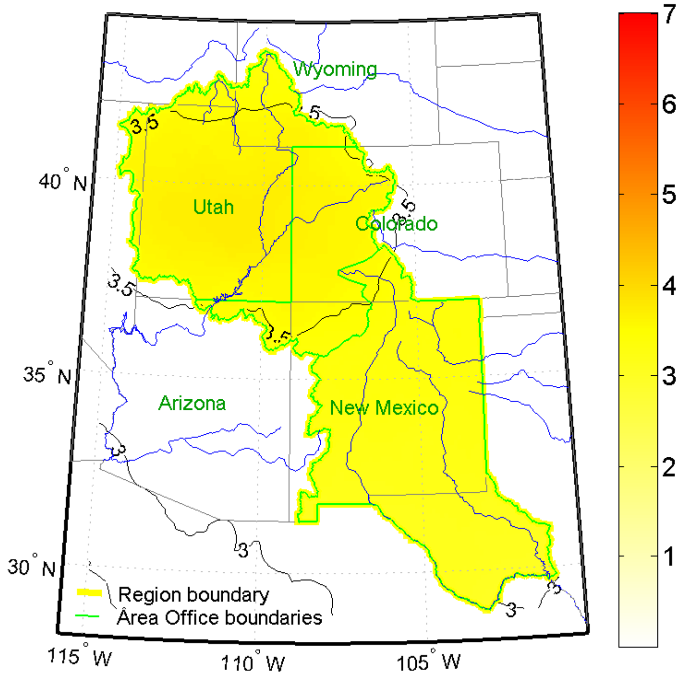
Upper Colorado Region
Change in Mean Annual Temperature, deg F
1990-2019 from 1950-1979



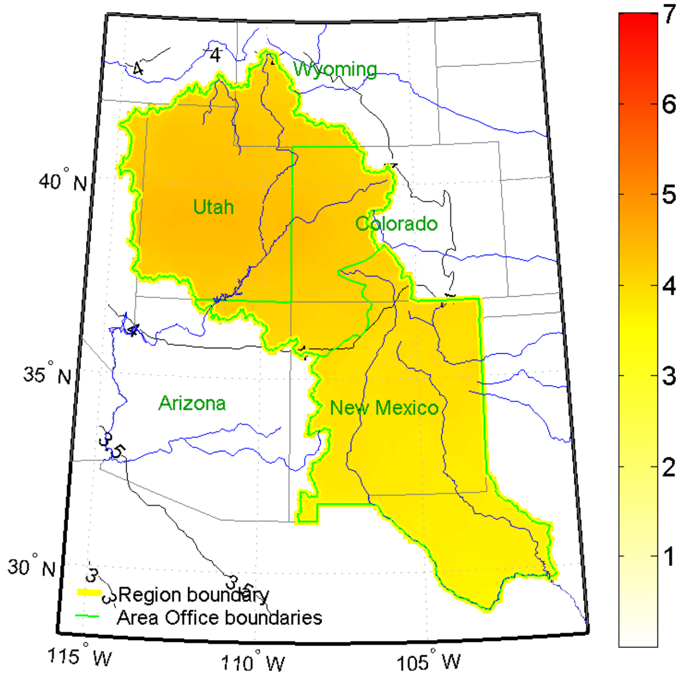
Upper Colorado Region
Change in Mean Annual Temperature, deg F
2000-2029 from 1950-1979



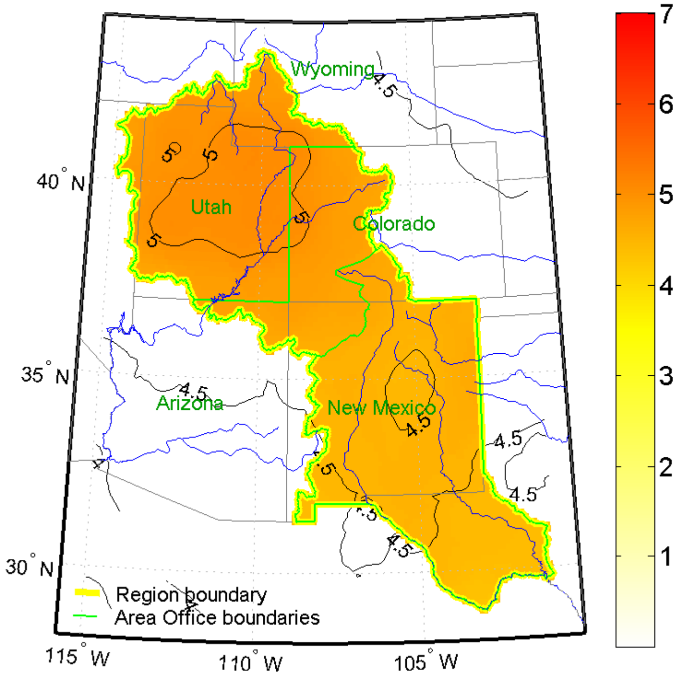
Upper Colorado Region
Change in Mean Annual Temperature, deg F
2010-2039 from 1950-1979



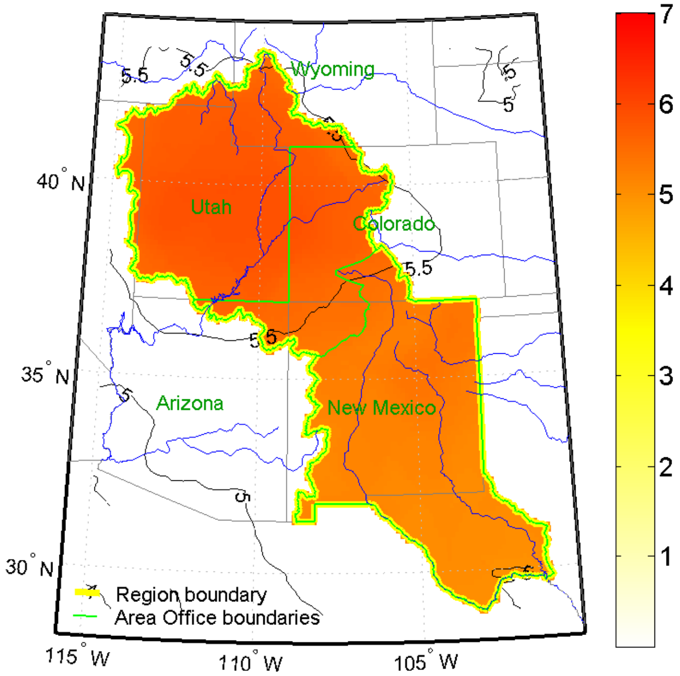
Upper Colorado Region
Change in Mean Annual Temperature, deg F
2020-2049 from 1950-1979



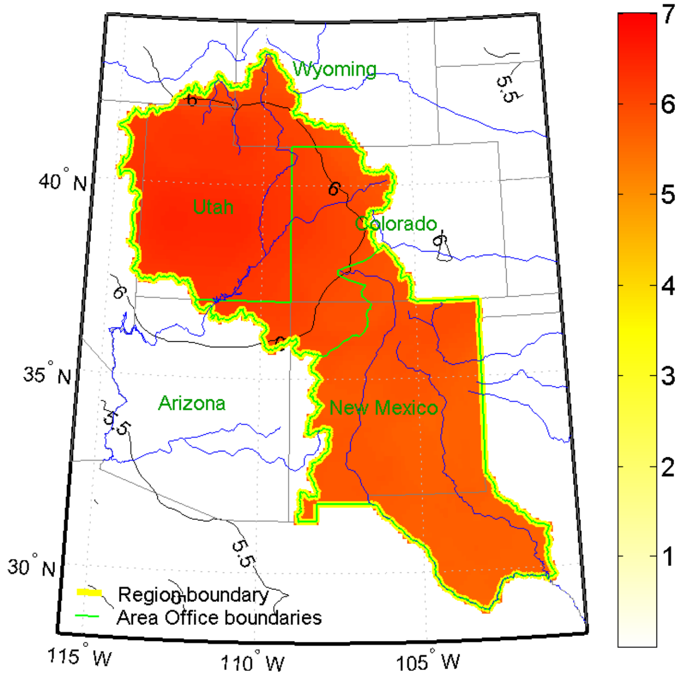
Upper Colorado Region
Change in Mean Annual Temperature, deg F
2030-2059 from 1950-1979



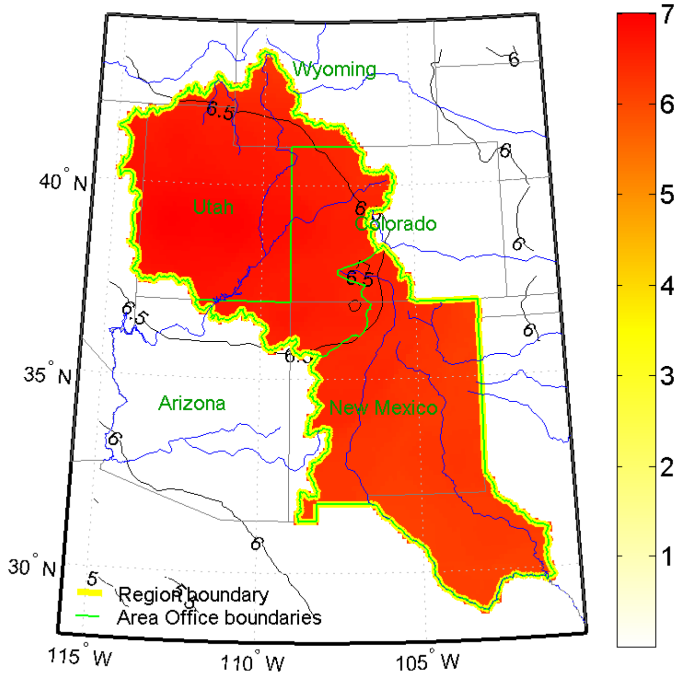
Upper Colorado Region
Change in Mean Annual Temperature, deg F
2040-2069 from 1950-1979



Upper Colorado Region
Change in Mean Annual Temperature, deg F
2050-2079 from 1950-1979



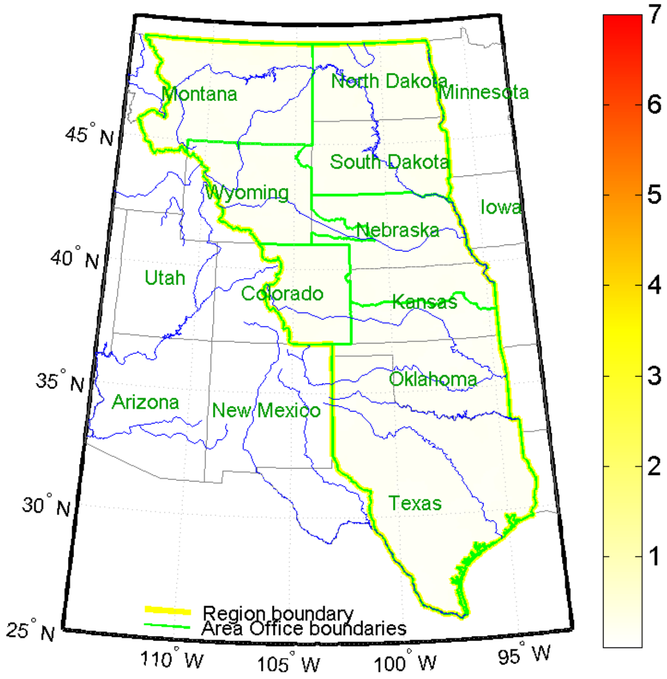
Upper Colorado Region
Change in Mean Annual Temperature, deg F
2060-2089 from 1950-1979



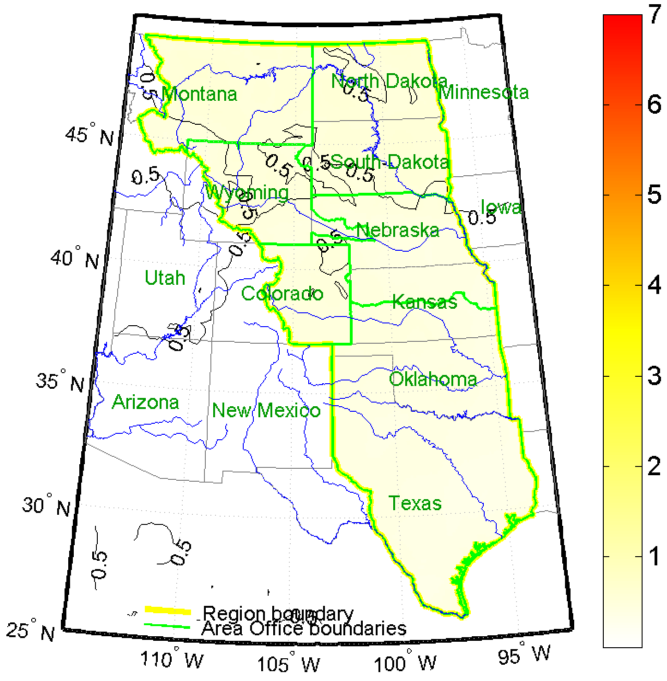
Upper Colorado Region
Change in Mean Annual Temperature, deg F
2070-2099 from 1950-1979

Great Plains Region – Temperature Change

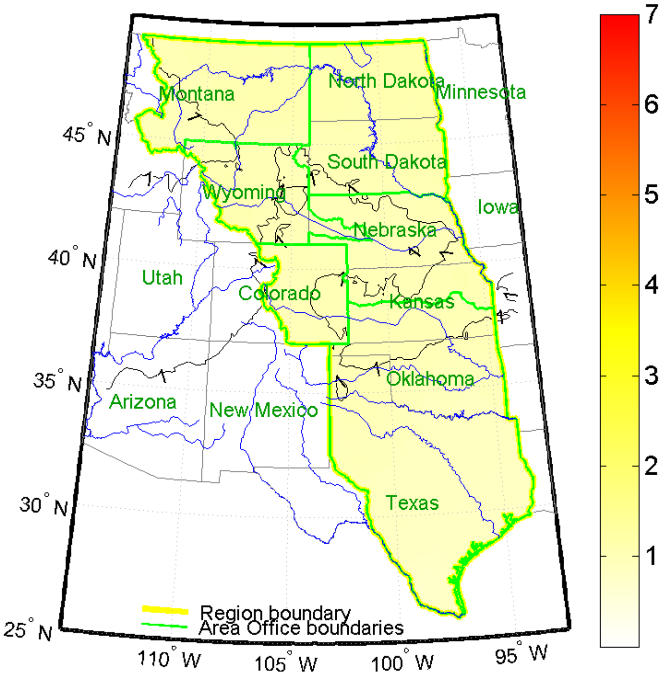
Great Plains Region
Change in Mean Annual Temperature, deg F
1960-1989 from 1950-1979



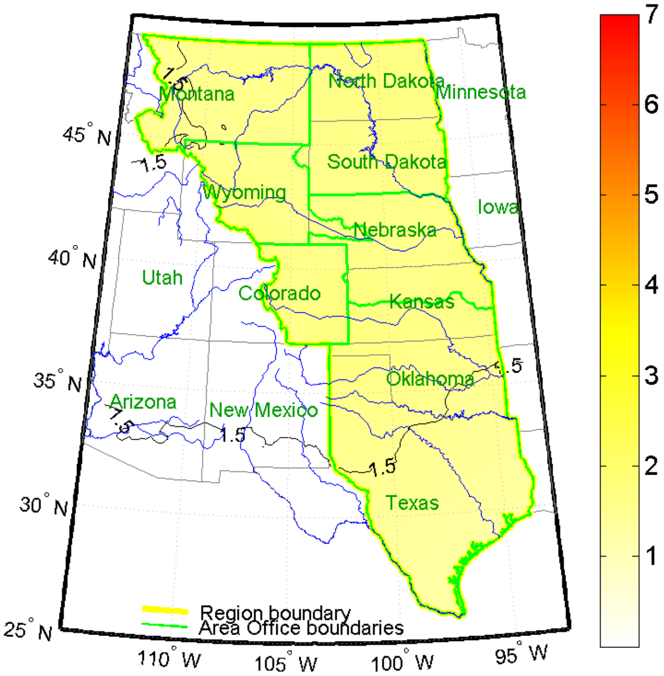
Great Plains Region
Change in Mean Annual Temperature, deg F
1970-1999 from 1950-1979

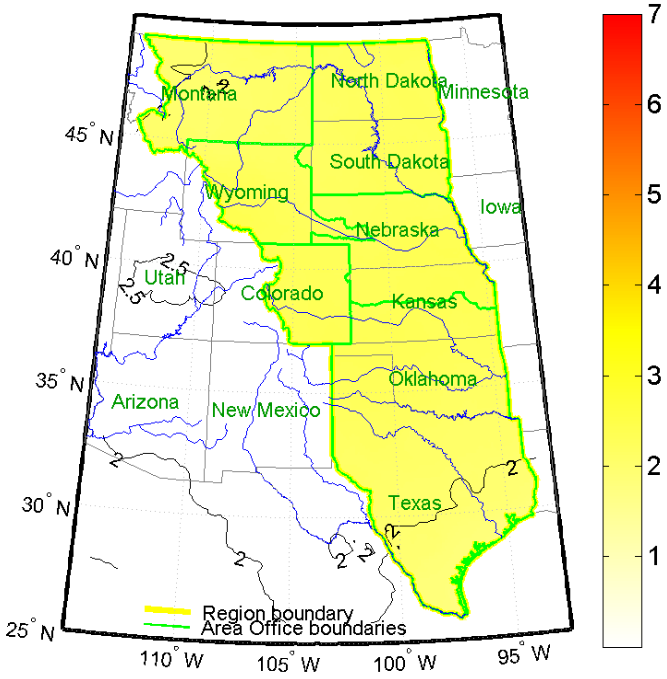


Great Plains Region
Change in Mean Annual Temperature, deg F
1980-2009 from 1950-1979

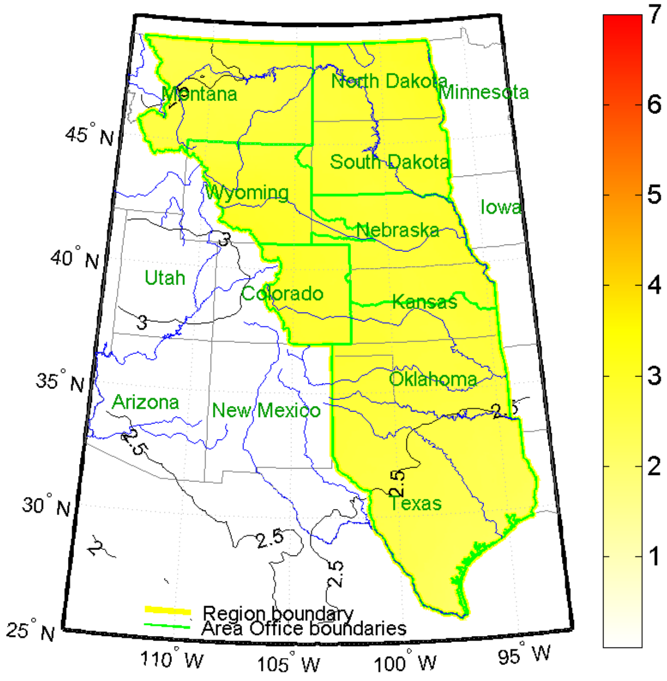


Great Plains Region
Change in Mean Annual Temperature, deg F
1990-2019 from 1950-1979





Great Plains Region
Change in Mean Annual Temperature, deg F
2000-2029 from 1950-1979



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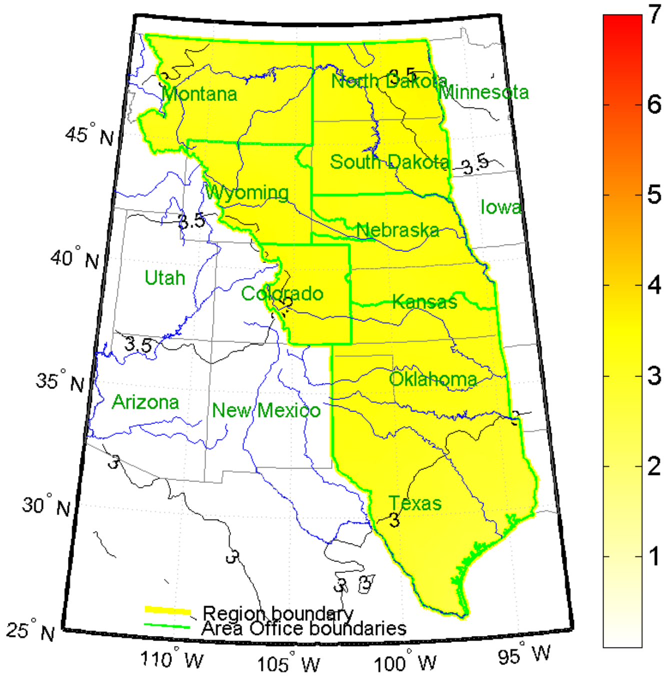
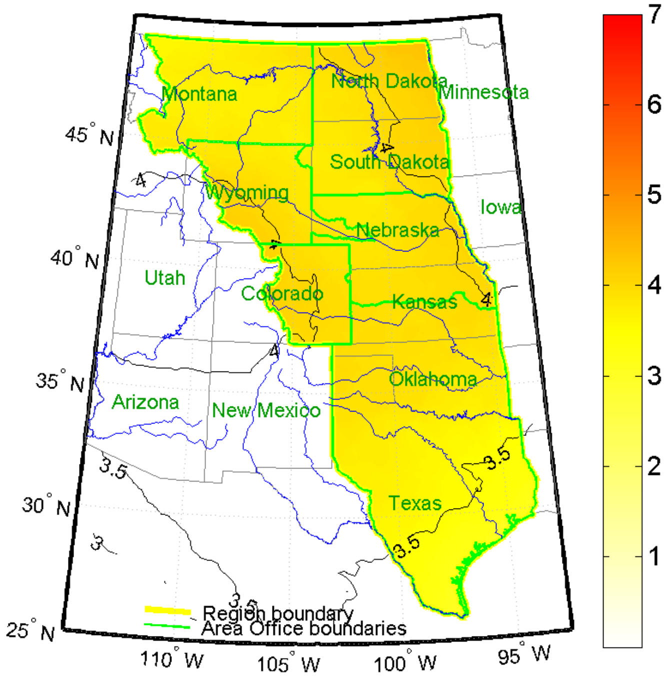
Change in Mean Annual Temperature, deg F
2010-2039 from 1950-1979

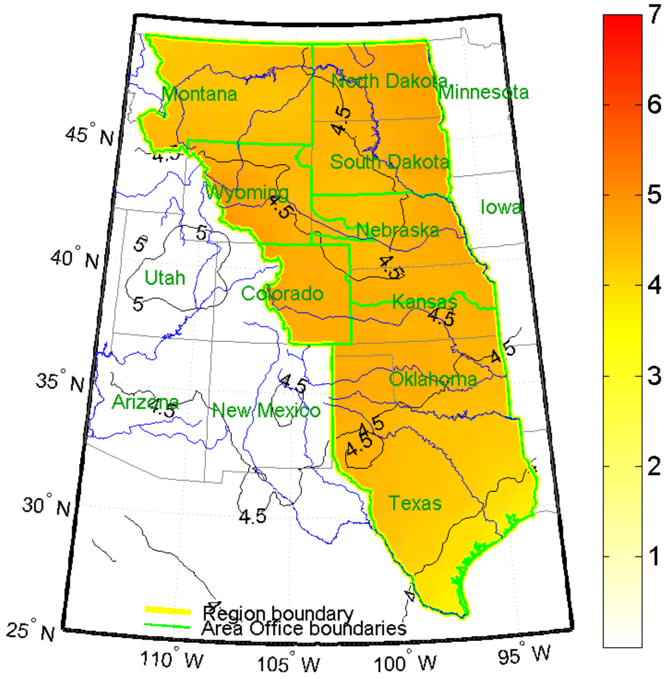


Great Plains Region
Change in Mean Annual Temperature, deg F
2020-2049 from 1950-1979

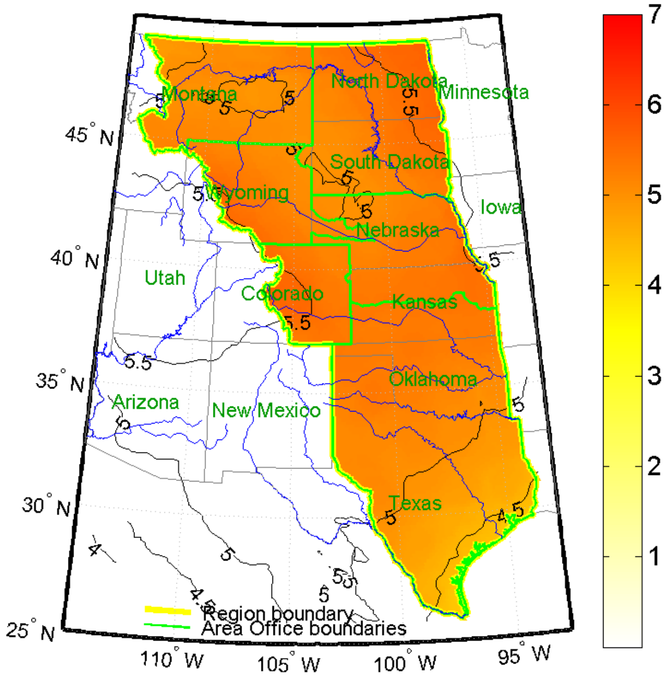


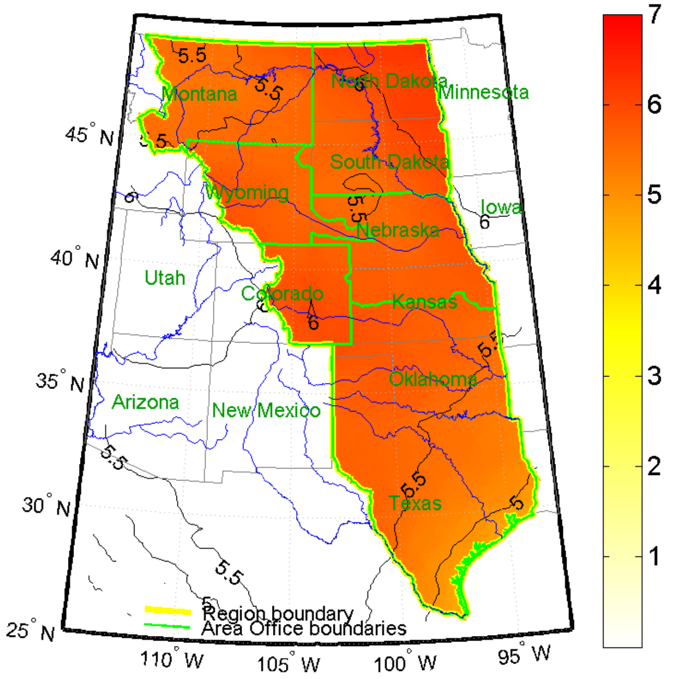
Great Plains Region
Change in Mean Annual Temperature, deg F
2030-2059 from 1950-1979

Great Plains Region
Change in Mean Annual Temperature, deg F
2040-2069 from 1950-1979

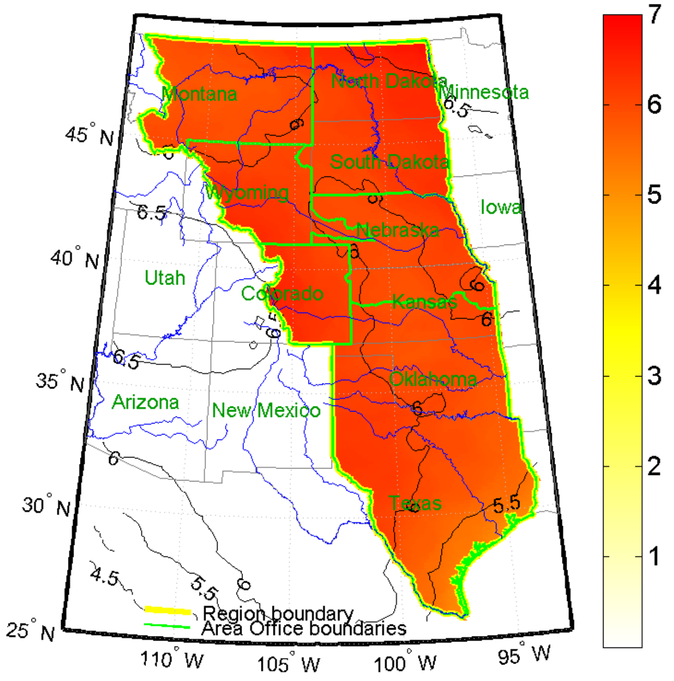


Great Plains Region
Change in Mean Annual Temperature, deg F
2050-2079 from 1950-1979





Great Plains Region
Change in Mean Annual Temperature, deg F
2060-2089 from 1950-1979



Great Plains Region
Change in Mean Annual Temperature, deg F
2070-2099 from 1950-1979

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, 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 that 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 that 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 that 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 then is carefully lifted with the snow inside and weighed on a calibrated scale that gives the SWE directly.

SRES Scenarios (IPCC 2007): SRES scenarios are *GHG emission scenarios* (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:**
>
> 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 Aupply: 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.