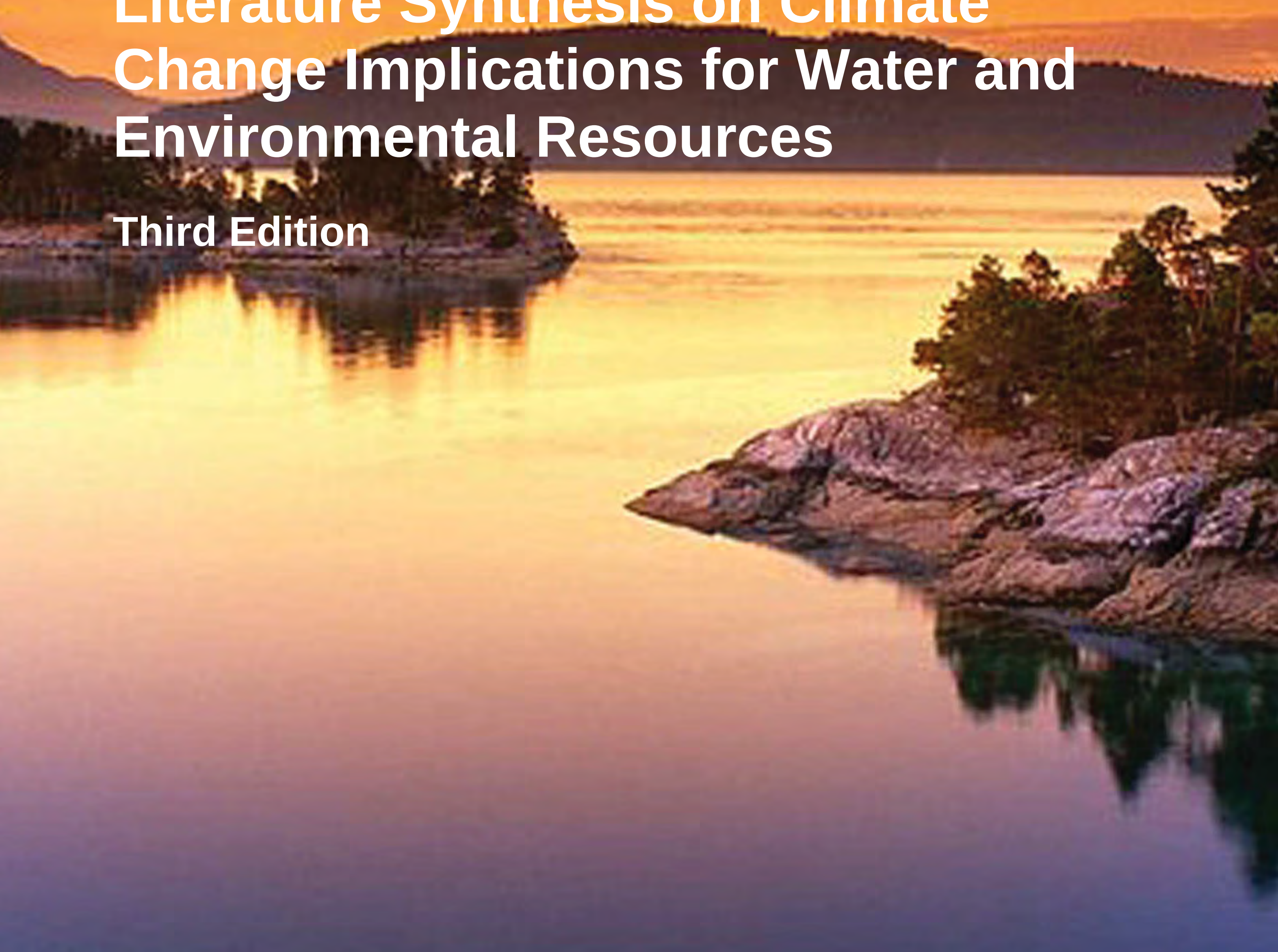
RECLAMATION
Managing Water in the West

Technical Memorandum 86-68210-2013-06

Literature Synthesis on Climate Change Implications for Water and Environmental Resources

Third Edition



U.S. Department of the Interior
Bureau of Reclamation

September 2013

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.

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Literature Synthesis on Climate Change Implications for Water and Environmental Resources

Third Edition

Prepared by:

Technical Service Center
Water Resources Planning and Operations Support Group
Water and Environmental Resources Division
Mark Spears, Alan Harrison, Victoria Sankovich, and Subhrendu Gangopadhyay (peer reviewer)

External Review by Staff From the Following National Oceanic and Atmospheric Administration – Regional Integrated Science and Assessment Centers:

Joe Barsugli – Western Water Assessment
David Pierce – California Applications Program
Gregg Garfin – Climate Assessment for the Southwest
Nathan Mantua – Climate Impacts Group
Gary McManus – Southern Climate Impacts Planning Program

U.S. Department of the Interior
Bureau of Reclamation
Research and Development Office
Denver, Colorado

September 2013

Contents

Appendices

Tables

Abbreviations and Acronyms

~	approximately
%	percent
°C	degrees Celsius
°F	degrees Fahrenheit
AOGCM	Atmosphere-Ocean General Circulation Model (see appendix C, Glossary of Terms)
AR	atmospheric river
AR4	International Panel on Climate Change Fourth Assessment Report (see appendix C, Glossary of Terms)
BCSD	bias correction and spatial disaggregation
CA DWR	California Department of Water Resources
CAT	Climate Action Team
CBRFC	Colorado Basin River Forecasting Center
CBO	Congressional Budget Office
C-CAWWG	Climate Change and Western Water Group
CCSM3	Community Climate System Model
CCSP	Climate Change Science Program
CEQ	Council of Environmental Quality
CERFACS	Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique
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
CSIRO	Commonwealth Scientific and Industrial Research Organization
CT	center timing
ECHAM5	Max Planck Institute for Meteorology climate model, latest version
EIS	Environmental Impact Statement

ENSO	El Niño Southern Oscillation (see appendix C, Glossary of Terms)
ESA	Endangered Species Act
ET	evapotranspiration
GCM	global climate model or general circulation model (see appendix C, Glossary of Terms)
GFDL	Geophysical Fluid Dynamics Laboratory
GFDL CM2.1	Geophysical Fluid Dynamics Laboratory Coupled Model Version 2.1
GHG	greenhouse gas (see appendix C, Glossary of Terms)
GP Region	Bureau of Reclamation's Great Plains Region
HadCM3	Hadley Center for Climate Prediction and Research
IPCC	International Panel on Climate Change (see appendix C, Glossary of Terms)
IPO	Interdecadal Pacific Oscillation
ISB	Independent Science Board
kg/m^2	kilogram per square meter
LC Region	Bureau of Reclamation's Lower Colorado Region
MAF	million acre-feet (see appendix C, Glossary of Terms)
mm/yr	millimeter per year
MP Region	Bureau of Reclamation's Mid-Pacific Region
MPI	Max-Planck Institute
NCA	National Climate Assessment
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NEPA	National Environmental Policy Act (see appendix C, Glossary of Terms)
NPI	North Pacific Index
NOAA	National Oceanic and Atmospheric Administration
O_3	trioxygen or ozone
OCCRI	Oregon Climate Assessment Report
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 Region	Bureau of Reclamation's Pacific Northwest Region
ppm	parts per million (see appendix C, Glossary of Terms)
PRISM	Precipitation Regression on Independent Slopes Method

R&D	research and development
Reclamation	Bureau of Reclamation
RegCM2.5	Regional Climate Model Version 2.5
RegCM3	High-resolution regional climate model
RFS	River Forecasting System
RISA	regional integrated sciences and assessments
Rockies	Rocky Mountains
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
Sierra Nevada	Sierra Nevada Mountains
SRES	Special Report on Emissions Scenarios (see appendix C, Glossary of Terms)
SSM/I	Special Sensor Microwave Image
SST	sea surface temperature
SWE	snow water equivalent (see appendix C, Glossary of Terms)
T and P	temperature and precipitation
Tmin	minimum temperature
UC Region	Bureau of Reclamation's Upper Colorado Region
UKMO	United Kingdom Meteorological Office
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 (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

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 (U.S.).

[1] Originally, C-CAWWG had a Western U.S. focus, stood for Climate Change and Western Water Group, and consisted of three Federal entities: Reclamation, the U.S. Geological Survey (USGS), and the 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 the February 2008 C-CAWWG workshop. Following the workshop, Reclamation's Research and Development Office commissioned the Technical Service Center Water Resources Planning and Operations 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), and the second issue was completed in January 2011 (Reclamation 2011a). This document is the third issue and maintains with the original issue's synthesis framework. Key changes in this update include the representation of new literature published through 2012 and also featuring additional synthesis in under-represented areas or sectors from the 2009 and 2011 issues, 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 U.S. 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 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 that 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.

This report and appendices are organized with respect to each of Reclamation's five regions: Pacific Northwest (PN), Mid-Pacific (MP), Lower Colorado (LC), Upper Colorado (UC), and Great Plains (GP). 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 this report will be used by Reclamation staff as boilerplate narratives, and the authors invite these staff to use the respective 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 third issue report generally is informed by literature surveyed through 2012. As with the first two issues (Reclamation 2009 and Reclamation 2011), this synthesis was subjected to external review provided by staff from each of the five western National Oceanic and Atmospheric Administration Regional Integrated

Sciences and Assessments (RISAs) located in the Western U.S. (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 this 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 that continued to receive sparse treatment in the second issue (e.g., climate change impacts on ecosystems and water demands and climate change impacts for the eastern GP Region).

[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, PN Region; Michael Tansey, MP Region; Carly Jerla, LC Region; Nancy Coulam, Katrina Grantz, and Jim Prairie, UC Region; and Gary Davis, GP 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. The summaries for the PN, MP, LC, and GP Regions 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, the collection of studies focused on historical drought is relatively large for the LC Region (section 2.3.1) and UC Region (section 2.4.1) relative to that of the other regions. Also, there have not been as many studies analyzing climate projections over the GP Region (section 2.5.2) compared to other regions. As this synthesis evolves through future issues, it is intended to create more parallel discussions across the other regions as additional studies become available.

Lastly, as was pointed out in section 1.0, Introduction, of this report these syntheses are meant to tell a representative story covering significant climate change literature from the last couple of decades. They do not provide an exhaustive citation of all recent literature.

2.1 Pacific Northwest Region

Numerous studies have been conducted on the potential consequences of climate change for water resources in Reclamation's PN Region. This section summarizes findings from recent studies 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 U.S. (U.S.) spring temperatures increased 1 to 3 degrees Celsius (ºC) (1.8 to 5.4 degrees Fahrenheit [ºF]) between 1970 and 1998. Regonda et al. (2005) report increased winter precipitation trends during 1950–1999 at many Western U.S. sites, including several in the Pacific Northwest, but a consistent region-wide trend is not apparent over this period.

Coincident with these trends, the Western U.S. and PN Region also experienced a general decline in spring snowpack, reduced snowfall to winter precipitation ratios, and earlier snowmelt runoff between the mid- and late-20th century. Reduced snowpack and snowfall ratios are indicated by analyses of 1948–2001 snow water equivalent (SWE) measurements at 173 Western U.S. stations (Knowles et al. 2007). Pierce et al. (2008) analyzed data from 548 snow courses in the Western U.S. over the period 1950–1999, and found a general decrease in the fraction of winter precipitation that is retained in the spring snowpack, including significant declines in the Washington and Oregon Cascades. Pederson et al. (2011) also found reduced snowpack across the entire North American cordillera between the 1980s and 1990s/early 2000s based on tree-ring reconstructions. Brown and Mote (2009) performed a Northern Hemisphere snowpack sensitivity study and compared the results to observed conditions (1966–2007 National Oceanic and Atmospheric Administration [NOAA] satellite dataset) and snow cover simulations from the Coupled Model Intercomparison Project Phase 3 (CMIP3). Annual snow cover duration was the most sensitive variable and especially so in maritime climates with high snowfall, such as the Western U.S. coastal mountain areas. Both observed conditions and CMIP3 simulations support this finding with the largest decreases in historical annual snow cover duration occurring in the midlatitudinal coastal areas where seasonal mean air temperatures range from -5 to +5 °C. The least sensitive areas were found to be in the interior regions with relatively cold and dry winters where precipitation plays a larger role in snow cover variability. Observations show that spring snow cover extent in North America has set record lows in 3 of the past 5 years (Derksen and Brown, 2012). Kapnick and Hall (2012) found that the sensitivity of the snowpack to temperature increases varies over the snow season, peaking in March through May, but is quite small in February.

Kapnick and Hall (2010) looked at the interannual variability in snowpack in an attempt to interpret the causes of recent snowpack trends in western North America. Of particular interest in this analysis is the impact of temperatures in the mid to late portion of the snow season (March through May). There is little impact in the early part of the snow season (February) when temperatures rarely rise above freezing. That is also the key part of the season when stations that exhibit an increase in April 1 SWE receive an increase in accumulation. Their final conclusion is that recent snowpack changes across western North America are due to regional-scale warming. This has implications for future warming regimes, and indicates a possible loss of late season snowpack and an earlier melt season.

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 percent (%) 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 time series. Casola et al. (2009) estimated the temperature sensitivity of the Cascades snowpack as an approximate 20% decrease in 1 April SWE per degree Celsius temperature rise in the absence of any increase in precipitation; this value was reduced to 16% when an increase in specific humidity and associated precipitation was assumed in response to such 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 to 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.

Switching from snowpack to runoff, Regonda et al. (2005) evaluated 1950–1999 data from 89 stream gauges in the Western U.S. and reports trends of earlier peak runoff at most stations during the period; additionally, significant trends toward earlier runoff were found in the Pacific Northwest. Stewart et al. (2005) examined the timing of runoff in a network of 302 western gauges and found that the center of mass of streamflow has shifted earlier by 1 to 4 weeks in many of the records. Luce and Holden (2009) report on distribution of streamflow reductions observed during 1948–2006, showing significant trends in annual streamflow reductions during dry years. Lundquist et al. (2009) find that in recent decades, the fraction of annual streamflow from late spring to summer runoff has declined 10 to 25%, and that snowmelt-driven runoff arrives 1 to 3 weeks earlier over the majority of the mountainous Western U.S. With regard to long-term historical drought trends in the PN, Nelson et al. (2011) report on their findings from lake sediment analyses describing drought conditions during the past 6,000 years. Their results suggest that 25% of droughts and 19% of wet periods lasted longer than 30 years, and also that the drought cycles appear to be driven by the evolution of the El Niño Southern Oscillation (ENSO) and its teleconnections with the PN Region. The authors discuss that, although anthropogenic changes in ENSO cannot yet be predicted with confidence (e.g., Stevenson, 2012), their data confirm that teleconnections with the PN are a robust feature of the ENSO system and, therefore, any change in ENSO is likely to have a profound impact on water availability. Clement et al. (2011) evaluated a variety of climate models to demonstrate the existence of a low-frequency component of the Southern Oscillation (SO) that is intrinsic to climate models. They noted that if the spectrum of natural variability in the real-world SO is “red” up to multiple decades or longer (meaning it has increasing variance at decadal to multidecadal or longer periods) the way it is in climate models, the detection of anthropogenic trends in the real-world SO (and presumably real-world variables teleconnected to the SO) is likely to be exceedingly difficult.

Villarini et al. (2009) analyzed annual peak discharge records from 50 stations in the U.S. with 100 years of record and attempted to document reduced stationarity. However, their results were not 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 (Climate Change Science Program [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 U.S. 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.

Some researchers have tried to draw connections between changes in precipitation extremes and atmospheric moisture holding capacity. The latter is a significant factor when considering climate change impacts to the overall hydrologic cycle because warmer air has greater capacity to hold moisture. Santer et al. (2007) report data from the satellite-based Special Sensor Microwave Imager (SSM/I) show that the total atmospheric moisture content over oceans has increased by 0.41 kilogram per square meter (kg/m^2) per decade since 1988. The authors performed a detection and attribution analysis comparing output from 22 global climate models (GCMs) under multiple forcing scenarios to the observed SSM/I data. They report a statistically significant correlation between the observed pattern of increasing water vapor and that expected to be found from anthropogenic forcing of the climate. It is suggested these findings together with related work on continental-scale river runoff, zonal mean rainfall, and surface specific humidity, indicate there is an emerging anthropogenic signal in both the moisture content of earth’s atmosphere and in the cycling of moisture between atmosphere, land, and ocean. An anthropogenic signal consistent with an intensified hydrological cycle can already be identified in the ocean salinity field (Terray et al. 2012; Durack et al. 2012; Pierce et al. 2012a), supporting this view. In a followup study, Santer et al. (2009) performed a detection and attribution analysis to determine if the anthropogenic water vapor fingerprint is insensitive to current GCM uncertainties. The authors report that the fingerprint is robust to current model uncertainties, dissimilar to the dominant noise patterns. They also report that the ability to identify an anthropogenic influence on observed multidecadal changes in water vapor is not affected by ‘‘model screening’’ based on model quality, a result also found for climate simulations focusing specifically on the Western U.S. (Pierce et al. 2009). However, Seager et al. (2012a) note that the global average tendency towards an intensified hydrological cycle may not be evident in all locations, depending on the particular changes in precipitation and evaporation in a region and how they might be affected by a teleconnected ENSO response.

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 20^{th} century. This has led Deser et al. (2010 and 2012) to urge climate scientists to make clear the important role of natural climate variability in future trends over North America when communicating the results of climate change projections with stakeholders and other decision makers. Among the implications of this work is that future scenarios developed from climate models are likely to reflect some mix of forced and internal variability, with the internal variability larger for precipitation than surface air temperature, over mid-latitude regions like western North America. Another implication is that natural variability is likely to remain important for future precipitation trends and variations for mid-latitude regions, like North America, for at least the next half century. There is some evidence, however, that the CMIP5 global climate models may underestimate decadal to multi-decadal precipitation variability in western North America, complicating projections of future precipitation changes and drought in this region (Ault et al. 2012).

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 U.S. 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 20^{th} century trends in hydrologically important variables in the Western U.S., aimed directly at

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

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 35 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 U.S.; 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 U.S. and weak or absent at the scale of regional scale drainages with the exception of the Columbia River Basin (Hidalgo et al. 2009). Pierce and Cayan (2012) systematically explored the effect of using ever-larger averaging areas on the statistical significance of trends in snow measures across the Western U.S., and confirmed that there is a tradeoff between how early a trend can be detected and how large the area to be averaged over is.

Fritze et al., 2011 investigated changes in western North American streamflow timing over the 1948–2008 period. Their results indicate that streamflow has continued to shift to earlier in the water year, most notably for those basins with the largest snowmelt runoff component. But an acceleration of these streamflow timing changes for the recent warm decades is not clearly indicated. Most coastal rain-dominated and some interior basins have experienced later timing.

While the trends in Western U.S. riverflow, winter air temperature, and snowpack might be partially explained by anthropogenic influences on climate, annually averaged precipitation trends arising from anthropogenic forcing are not necessarily well separated from zero in this region (e.g., Dettinger 2005). Worldwide, both observed mean (Zhang et al., 2007) and extreme (Min et al., 2011) precipitation trends show signs of the influence of human forcing of the climate, but climate models produce a notably weaker signal than is seen in the observations. 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 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. A recent caution on the use of the PDSI in such studies is that Sheffield et al. (2012) and Hoerling et al. (2012) find that the PDSI may be an inappropriate measure of drought that arises from climate change, due to an overly-simplistic dependence of potential evaporation on temperature. Looking to the future, even when substantial regional averaging is used, a significant signal of precipitation change does not emerge over the U.S. as a whole by 2100 (Mahlstein et al. 2012).

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 [Yin 2005; Salathé 2006; Seager et al. 2007]), atmospheric circulation over North America, and precipitation and temperature responses in the Western U.S. 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 U.S. (Cayan et al. 2001).

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 (e.g., Mote et al. 2005; Barnett et al. 2005). 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

In 2011, as part of its responsibilities under section 9503 of the SECURE Water Act (Reclamation 2011c),[5] Reclamation reported on climate change implications for water supplies and related water resources within eight major Western U.S. river basins, including PN Region's Columbia-Snake River Basin. The report (Reclamation 2011) includes an original assessment of natural hydrology impacts under projected climate conditions, informed by the same downscaled climate projection summarized in appendix B.

Focusing on the broader Western U.S. region, Reclamation (2011b) reports that projections of future precipitation indicate that the northwestern and north-central portions of the U.S. may gradually become wetter while the southwestern and south-central portions gradually become drier, albeit with substantial fluctuations

[5] The Omnibus Public Lands Act (Public Law 111-11) Subtitle F – SECURE Water.

on interannual to decadal timescales due to natural variability (Deser et al. 2010 and 2012). It is noted that these summary statements reflect regionally averaged changes and that projected changes have geographic variation; they vary through time; and the progression of change through time varies among climate projection ensemble members. What this means is that, going forward in time, different regions are likely to continue to experience the kind of interannual to interdecadal variations in precipitation that they have experienced in the past. For the next few decades, these variations are likely to be superimposed upon background trends that in most cases are likely to be subtle compared with the variations.

These projected changes in climate have implications for hydrology. Warming trends contribute to a shift in cool season precipitation towards more rain and less snow (Knowles et al. 2007), which causes increased rainfall-runoff volume during the cool season accompanied by less snowpack accumulation. The shift of precipitation from snow to rain, which falls more quickly and so is carried a shorter distance by winds, could also exaggerate rain shadows in the mountainous west (Pavelsky et al., 2012). Projections of future hydrology (Reclamation 2011) suggest that warming and associated loss of snowpack will occur over much of the Western U.S. However, not all locations are projected to experience similar changes. Analyses suggest that losses to snowpack will be greatest where the baseline climate is closer to freezing thresholds (e.g., lower lying valley areas and lower altitude mountain ranges) (Bales et al. 2006). Analyses also suggest that, in high-altitude and high-latitude areas, cool-season snowpack actually could increase during the 21st century (e.g., Columbia headwaters in Canada, Colorado headwaters in Wyoming).

Pierce and Cayan (2012) used 13 downscaled global climate models to quantify the influence of mechanisms that contribute to changes in end-of-century peak snowpack: increased precipitation, increased melting, and the conversion of precipitation from snow to rain. The authors systematically explored climate-model projected changes by 2100 in six different snow-related variables over the Western U.S., and found that statistically significant linear trends are seen earliest in the fraction of winter precipitation that falls as snow, followed by SWE/P, and 5 to 20 years later by SWE. Least sensitive of all snow measures examined was total seasonal snowfall, which is strongly linked to precipitation. Different regions have different balances of mechanisms, although in the Western U.S. as a whole the conversion of precipitation from snow to rain dominates.

Projected changes in surface water runoff are more complex than projections of snowpack. Hydrologic projections introduced in Reclamation (2011b and 2011c) suggest that geographic trends may emerge. The Southwestern U.S. to the southern Rocky Mountains (Rockies) may experience gradual annual runoff declines during the 21st century and the northwest to north-central U.S. may experience little change through the mid-21st century with increases projected for the late-21st century. With respect to seasonal runoff, warming is projected to affect snowpack conditions both in terms of cool season accumulation and warm season melt. Without changes to overall precipitation quantity, these changes in snowpack dynamics would lead to increases in cool season rainfall-runoff and decreases in warm season snowmelt-runoff, leading to a season-varying sensitivity of runoff to warming (Das et al., 2011). The hydrologic projections indicate that the degree to which this expectation may occur varies by location in the Western U.S. For example, cool season runoff is projected to increase over the west coast's historically snowfed basins from California to Washington and over the north-central U.S., but with little change to slight decreases over the Southwestern U.S. to southern Rockies. Warm season runoff is projected to experience substantial decreases over a region spanning southern Oregon, the Southwestern U.S., and southern Rockies. In summary, the hydrologic projections featured in Reclamation (2011b) suggest that projected precipitation increases in the northern tier of the Western U.S. could counteract warming-related decreases in warm season runoff, whereas projected decreases in precipitation in the southern tier of the Western U.S. could amplify warming-related decreases in warm season runoff. Lutz et al. (2012) put the anticipated changes in PN hydrology into the context of longer period natural variability using a 366-year record of regional cold-season precipitation reconstructed from tree rings.

Focusing on Reclamation (2011b) results representative of PN Region conditions, **table 1** summarizes the projection median change from an ensemble of downscaled CMIP3 models run through VIC for various hydroclimate conditions in three Columbia-Snake River subbasins. Generally speaking, the ensemble-median changes of **table 1** suggest that these basins will experience increasing mean-annual temperature and precipitation during the 21st century, accompanied by decreasing trend in spring SWE, decreasing trend in April–July runoff volume, and increasing trends in December–March and annual runoff volumes.

While **table 1** summarizes the model ensemble's median change values, it is noted the models typically project a wide range of possible trends in precipitation for many midlatitude regions. The significance of this fact is that the uncertainty (or spread among ensemble members) is very large for precipitation projections for many parts of the U.S. over the next 10 to 60 years, at least (Deser et al. 2010 and 2012).

Table 1.—Summary of simulated changes in decade-mean hydroclimate for several subbasins in the Columbia River Basin from an ensemble of downscaled CMIP3 models run through VIC

Hydroclimate Metric (Change from 1990s)	2020s	2050s	2070s
Columbia River at The Dalles			
Mean Annual Temperature (°F)	1.4	3.2	4.6
Mean Annual Precipitation (%)	3.4	6.2	8.5
Mean April 1 SWE (%)[1]	-1.0	-3.1	-6.7
Mean Annual Runoff (%)	2.3	3.7	7.5
Mean December–March Runoff (%)	9.8	18.5	27.3
Mean April–July Runoff (%)	2.2	4.1	2.4
Mean Annual Maximum Week Runoff (%)	3.5	4.0	5.5
Mean Annual Minimum Week Runoff (%)	-1.5	-5.9	-8.5
Snake River at Brownlee Dam			
Mean Annual Temperature (°F)	1.6	3.6	5.0
Mean Annual Precipitation (%)	2.3	3.9	6.6
Mean April 1 SWE (%)[1]	-5.0	-12.0	-16.0
Mean Annual Runoff (%)	-0.1	1.2	3.4
Mean December–March Runoff (%)	5.6	13.7	21.0
Mean April–July Runoff (%)	-1.3	-2.0	-0.9
Mean Annual Maximum Week Runoff (%)	2.4	3.5	5.8
Mean Annual Minimum Week Runoff (%)	-3.0	-4.3	-5.9
Yakima River at Parker			
Mean Annual Temperature (°F)	1.3	2.9	4.2
Mean Annual Precipitation (%)	3.7	5.7	7.7
Mean April 1 SWE (%)[1]	-10.3	-19.6	-28.7
Mean Annual Runoff (%)	3.8	3.7	5.6
Mean December–March Runoff (%)	19.6	39.9	56.9
Mean April–July Runoff (%)	-2.0	-9.5	-17.0
Mean Annual Maximum Week Runoff (%)	2.7	4.2	6.7
Mean Annual Minimum Week Runoff (%)	-4.0	-10.6	-14.2

[1] The reported percentage changes in mean April 1 SWE have been updated to correct a reporting error in Reclamation (2011b). The error stemmed from reporting this change as the mean change in cell-specific changes from all 1/8-degree grid-cells within the given basin. Such a change metric does not equal the change in total basin SWE integrated across all grid-cells within the basin, which was the intended reporting metric and is now indicated by the updated percentage changes.

The projected climate change implications for water resources reported in Reclamation (2011b) are similar to those reported in prior assessments. A paper by the Congressional Budget Office (CBO) (CBO 2009) presents an overview of the current understanding of the impacts of climate change in the U.S., including that warming will tend to be greater at high latitudes and in the interiors of the U.S. Global average warming values therefore tend to underestimate the warming the interior U.S. will experience (IPCC, 2007). 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. This change in precipitation intensity, in and of itself, can affect the snowpack (Kumar et al., 2012). A similar overview is included in the Interagency Climate Change Adaptation Task Force National Action Plan (Council on Environmental Quality [CEQ] 2011), with emphasis on freshwater resources impacts and discussions of strategies to address these impacts. 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, although recent work shows that model agreement on precipitation changes is not always evaluated correctly (Power et al., 2012).[6] Appreciable natural variability means that over most of the world, regional-scale changes in precipitation will not be detectible before the Earth warms by 1.4 C (Mahlstein et al., 2012).

The CBO findings are qualitatively consistent with findings in the Washington Climate Change Impacts Assessment (WACCIA) (Littell et al. 2009a) and Oregon Climate Assessment Report (OCCRI) (OCCRI 2010). The WACCIA and OCCRI both report 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 to 3.3 °F by the 2020s (2010–2039), 1.5 to 5.2 °F by the 2040s (2030–2059), and 2.8 to 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 changes 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 (GHG) emissions scenarios, the WACCIA reported that 2080s annual average precipitation change relative to

[6] 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.

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[7] 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.

Temperature effects alone could cause significant impacts to hydrologic systems. Diffenbaugh and Ashfaq (2010) report on near-term GCM projections of future extreme temperature events in the U.S. and correlation to reduced soil moisture levels. Although the authors identified robust correlations between changes in temperature, precipitation, and soil moisture, the specific relationship between surface drying and intensified hot extremes is confounding since the predicted decreases in soil moisture could be a product of decreases in precipitation and/or increases in net surface radiation.

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 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, an effect that is already observed (Min et al., 2011). Allan (2011) and Pall et al. (2011) both concur that there will be an increase in the frequency of intense rainfall events with warming. Dominguez et al. (2012) found that an ensemble of global climate models downscaled by regional models predict more extreme winter precipitation events, with daily events at the 20- and 50-year return periods increasing by 12 to 14%. 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. Watterson and Dix (2003) report a predicted worldwide average 14% increase in 30-year extreme daily precipitation for 2071–2100 compared to 1961–1990 based on simulations by the Commonwealth Scientific and Industrial Research Organization (CSIRO) Mark 2 GCM under A2 (high) and B2 (moderate) emissions scenarios. From a separate stochastic model study of the same GCM output, Watterson (2005) reports the interannual standard deviation of mean monthly precipitation increases with warming temperature. The 1961–1990 to 2071–2100 increases found were 9.0% for January and 11.5% for July. Min et al. (2011) proposed that some GCM simulations may actually underestimate the trend toward increased extreme

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

precipitation events in the Northern Hemisphere, which suggests that extreme precipitation events may be stronger than projected. Chou and Lan (2012) note that the increase in precipitation extremes means that the annual range of precipitation will increase over much of the world. However, Dulière et al. (2011) caution the use of GCM simulations for local extreme precipitation projections because the resolution of these models is very coarse. For localized extreme precipitation events, it appears as though regional models retain the large-scale forcings and may preserve the mesoscale forcings and topographic interactions necessary to produce events at this finer scale. Using regional climate models for Washington State, Salathé et al. (2009) predict positive or very small statewide trends and considerable increases in future extreme precipitation events relative to 20th century conditions. Extreme runoff due to changes in the statistics of extreme events will present flood control challenges to varying degrees at many locations (e.g., Das et al., 2011). A variety of factors are likely to affect future precipitation extremes, including changes in temperature, precipitation efficiency, and vertical velocity (O'Gorman and Schneider, 2009; Muller et al., 2011), and the ability of warmer atmospheric conditions to sustain a higher equilibrium pressure of water vapor.

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 temperature 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 U.S. 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.

It is important to recognize that these assessments of hydrologic impacts under climate change are sensitive to numerous uncertainties. Much attention has been given to the uncertainties introduced by climate projection selection, bias correction, and spatial downscaling. For example, Ashfaq et al. (2010) report on an evaluation of climate model bias effects and hydrologic impacts using a high-resolution regional climate model (RegCM3) to drive a hydrological model (Variable Infiltration Capacity [VIC]) for the full contiguous U.S. In addition to showing the significance of climate model bias in predicting hydrologic responses, their results highlight the importance of daily temperature and precipitation extremes in predicting future hydrological effects of climate change. Pierce et al. (2013) compared the results from downscaling 16 global climate models using 3 dynamical methods and 2 statistical methods, and found that future (2060’s) projected changes in winter precipitation were more sensitive to the global model used, while summer changes were more sensitive to the downscaling method used. The selection of downscaling method can therefore affect the overall hydrological results of a simulation. Recently, the uncertainties associated with the hydrologic analysis also have been garnering attention. Vano et al. (2012) applied multiple land-surface hydrologic models in the Colorado River Basin under multiple, common climate change scenarios. Their results showed that runoff response to these scenarios varied by model and stemmed from how the models feature a collective of plausible hydrologic process portrayals, where a certain combination of process portrayal choices led to a model’s simulated runoff being more or less sensitive to climate change. Although these results are most applicable to the Colorado River Basin, it is still expected that application of the models in Vano et al. (2012) to other Western U.S. basins likewise would show model-dependent runoff sensitivity to climate change. Improving our understanding of these data and model uncertainties will help refine future estimates of climate change implications for hydrology.

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 U.S. (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 percentiles. For the fourth basin (Gunnison), greater flow rates were projected for roughly the upper tercile. 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 U.S. 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). Vano et al. 2010 includes assessment of reservoir operations in the Yakima River Basin under a multimodel average climate change scenario 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 to 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 control rule curves are updated.

2.1.3 Climate Change Impacts on Environmental Resources

This section is organized under the following subheadings: Multiple Species/Resources and Ecosystems; Fisheries and Aquatic Ecosystems; Individual Species/Resources; Agriculture; and Forest Fires. The literature covered includes both historical and projected future conditions.

2.1.3.1 Multiple Species/Resources and Ecosystems

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.[8] 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.

Parmesan (2006) provides a synthesis of recent studies pertaining to observed responses of wild biological species and systems to recent climate change. This author's literature search revealed 866 peer-reviewed papers that documented changes in species or systems that could be attributed at least in part to climate change. The synthesis focuses on advancing of spring events, variations in phenological responses between interacting species, species range shifts, range restricted species, pests and parasites, extinction, and evolutionary responses and genetic shifts.

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[8] 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.

Using meta-analysis, Chen, et. al. (2011) documented a change of elevation and latitude of terrestrial organisms as a result of climate variability. Using available studies of Europe, North America, Chile, Malaysia, and the Marion Islands, range shifts were documented for 764 individual species' responses for latitude adjustment and 1,367 species' responses for elevation variability. The results of this analysis indicate that species have moved away from the equator at a median rate of 16.9 kilometers per decade. Additionally, species have moved to higher elevations at a median rate of 11.0 meters per decade.

Research by Ault and others (2011) shows that the average timing of plant phenology events, such as bud formation and flowering, is occurring 1.5 days earlier per decade across western North America. They note that the major modes of atmospheric circulation only account for about one-third of the trend.

The Vegetation/Ecosystem Modeling and Analysis Project (VEMAP)[9] and other similar projects have increased our understanding of ecosystem dynamics under climate change; however, our understanding of the interactions between stresses on individual species at the ecosystem level is still relatively limited. Specific examples include the interaction between atmospheric carbon dioxide (CO_2) and soil water and nutrient limitations on plant productivity, carbon sequestration , and species composition ; the interactions between CO_2 and tropospheric oxygen (trioxygen [O_3] or ozone) on plant water-use efficiency; and the future rates of plant species migration and ecosystem establishment under climate change (Aber et al. 2001). In general, vegetation models indicate that a moderate increase in future temperatures produces an increase in vegetation density and carbon sequestration across most of the U.S. with small changes in vegetation types and large increases in future temperatures cause losses of carbon with large shifts in vegetation types (Bachelet et al. 2001).

Climate change 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 U.S., 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 one-two punch of temperature driven moisture stress on trees and the enhanced life cycles and ranges of insect

[9] Available online at: http://www.cgd.ucar.edu/vemap/.

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.

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). Bentz et al. (2010) report that "models suggest a movement of temperature suitability to higher latitudes and elevations and identify regions with a high potential for bark beetle outbreaks and associated tree mortality in the coming century."

Robinson et al. (2008) describe and compare several ecological models that estimate vegetation development (productivity or vegetation type) under climate change conditions.

2.1.3.2 Fisheries and Aquatic Ecosystems

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 typically are 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 U.S., including Western U.S. 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 U.S. Wenger et al. (2011) projected that suitable habitat for four trout species of the interior Western U.S. would decline 47% on average compared to 1978–1997 under a multi-model average climate change scenario using A1B emissions.

Chapter 6 of WACCIA (Mantua et al. 2010) reports that rising stream temperatures likely will reduce the quality and extent of freshwater salmon habitat in Washington State. Warming in the PN Region is likely to have a greater effect on stream temperatures in streams dominated by snowmelt rather than those dominated by rain (Wu et al. 2012). 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. Additionally, Arismendi et al. (2012) find little evidence for warming stream temperatures in the Pacific continental U.S., and point out the need for both understanding the mechanisms that link stream temperature to human effects and better sensor networks.

The following is from the January 2013 Federal Advisory Committee Draft Climate Assessment Report (chapter 21, page 725):

> “Some Northwest streams (Isaak et al. 2011) and lakes have already warmed, on average, over the past three decades, contributing to changes such as earlier Columbia River sockeye salmon migration (Crozier et al. 2011) and earlier blooms of algae in Lake Washington (Winder and Schindler 2004). As species respond to climate change in diverse ways, there is a potential for ecological mismatches to occur – such as in the timing of the emergence of predators and their prey (Winder and Schindler 2004).”

Crozier (2011) presents a literature synthesis that identifies and summarizes literature published in 2010 that is most relevant to predicting impacts of climate change on Columbia River salmon listed under the Endangered Species Act. It represents the review of over 800 papers, of which 223 are included in the summary.

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). Marcarelli et al. (2010) estimated past and future hydrographs and patterns of ecosystem metabolism for a Western U.S. river and analyzed the impacts of climate change and water use. The reported combined hydrologic related impacts, measured in terms of gross primary production and ecosystem respiration, are indicative of the potentially important role hydrologic regime plays in controlling ecosystem function.

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.

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.

2.1.3.3 Individual Species/Resources

Chapter 7 of the WACCIA (Littell et al. 2010) 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.

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.

McCarty (2001) reports the abundance of Sooty shearwaters (a seabird) declined by 90% between 1987–1994 associated with rapid warming of the California current.

Cayan et al. (2001) document earlier blooming of lilacs and honeysuckles correlated to increasing spring temperatures.

2.1.3.4 Agriculture

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 IPCC Technical Paper on Climate Change and Water includes similar discussions (Bates et al. 2008) on the above issues and notes that only a few studies have attempted to predict climate change impacts on irrigation demands.

Lobell et al. (2011) present the findings of a global analysis of crop production impacts due to past climate change. The authors developed statistical models comparing 1980 to 2008 actual production levels for the four largest commodity crops (corn, wheat, soybeans, and rice) to theoretical levels without climate change. Their results indicate respective 3.8 and 5.5% decreases in worldwide corn and wheat production and approximately no net change for soybeans and rice. Significant changes in U.S. production levels were not found, and this is attributed to relatively low increases in temperatures in our agricultural regions. The authors attribute the modeled impacts to changes in temperature rather than precipitation, and they acknowledge that their analysis does not account for adaptations by growers or the effect of elevated CO_2 on crop yields.

Nardone et al., 2010 discusses the effects of climate change on livestock following the "theory of global warming." Topics include impaired production due to increased temperatures, desertification of rangelands, impacts to grain availability, and adaptability of animal genotypes.

2.1.3.5 Forest Fires and Wildfires

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 U.S., 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 in Westerling et al. (2006), which documents large increases in fire season duration and fire frequency, especially at mid-elevations in the Western U.S. Coincident with trends toward warmer and drier climate in the Western U.S. over the past two decades (1990–2009), forest fires were 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. 2009a), 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). Westerling et al. (2011a) find that the projected increase in wildfires could substantially change the flora and fauna of the greater Yellowstone region by mid-century. These findings are consistent with earlier studies. Brown et al. (2004) evaluated future (2006–2099) Western U.S. 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 U.S. 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. Root (2012) cautions that increased wildfires can lead to unexpected results on some fire-adapted species, for example if fires become so frequent that juvenile plants do not have time to produce seeds. 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.

Moritz et al. (2012) used projections from 16 different GCMs to formulate a comprehensive look at global fire patterns. Those projections focused on two timeframes: 2010–2039 and 2070–2099. The results indicated climate change will results in an increase in the frequency of wildfires in the Western U.S. in the next 30 years, and across the entire U.S. at the end of the century.

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

On the matter of global sea level rise under climate change, the IPCC Fourth Assessment Report (AR4) from Working Group I (chapter 10, “Sea Level Change in the 21st Century” [IPCC 2007]) provides projections of global average sea level rise that primarily represent thermal expansion associated with global air temperature projections from current 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 due to thermal expansion alone 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 CMIP3 models’ simulation of ocean response to atmospheric warming under a collection of 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. National Research Council (2012) provides a comprehensive review of global sea level rise and how it will affect the west coast of the U.S. Ice loss processes ignored in IPCC 2007 are included in the NRC report, leading to approximately a doubling of the projected sea level rise (50 to 140 cm by 2100).

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 study conducted by Yin et al. (2011) suggests that the acceleration of outlet glacier melting in Greenland and Antarctica is closely linked to subsurface ocean layer temperatures. Additionally, using 19 GCMs, they were able to project ocean temperatures through 2200. These models showed the potential for maximum ocean temperature increases around Greenland to be 1.7 to 2.0 °C by the end of the 21st century. The same modeling around Antarctica showed maximum ocean temperature increases of 0.5 to 0.6 °C by the year 2100. Both of these results represent ocean temperature increases greater than what was previously thought, indicating the potential for even greater sea level rises in the future. Because ocean temperatures require centuries to come into equilibrium with warmer surface forcing, sea level rise can continue long after land temperatures stop rising (Wigley, 2005).

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). 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, sea levels are predicted to be 1 to 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.

Bromirski et al. (2011) specifically studied the Pacific coast in regard to sea level rise. The study notes that, from approximately 1930–1980, sea levels along the Pacific coast of North America rose at a rate equivalent to the global rate of change (2 millimeters per year). Between 1980 and 2009, however, sea levels remained relatively constant according to tide gauge and satellite altimetry measurements. Contributing factors to this regional variance include a shift from cold to warm phase of the Pacific Decadal Oscillation (PDO) that occurred in the mid-1970s, which was followed by a shift in wind stress patterns. The shift in wind stress patterns likely has suppressed the previously observed rising trend (Bromirski et al. 2011).

Konikow (2011) discusses the relationship between sea level rise and ground water depletion and suggest a better understanding of this relationship is needed to better predict future rates of sea level rise. According to the author, the 1900–2008 global ground water depletion was approximately 4,500 cubic kilometers (3.6 million acre-feet) which would be equivalent to a 12.6 millimeter rise in sea level.

2.2 Mid-Pacific Region

Numerous studies have been conducted on the potential consequences of climate change for water resources in Reclamation's MP Region, which covers the northern two-thirds of California, most of western Nevada, and part of southern Oregon. This section summarizes findings from recent studies (1994–2012) 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.[10] A recent summary of historical and projected climate changes that includes the MP Region is given in the Southwest Climate Change Assessment (Overpeck et al. 2012), part of the U.S. National Climate Assessment.

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 U.S. spring temperatures increased 1 to 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 U.S. sites, including several in California's Sierra Nevada Mountains (Sierra Nevada); but a consistent region-wide trend over this period is not apparent. Christy (2012) finds no

[10] 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.

significant trend in snowfall over the Sierra Nevada over the past century or more, while Pierce and Cayan (2012) find that snowfall is the snow-related variable that is least sensitive to a warming climate.

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 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 U.S. were related to larger-scale atmospheric conditions across North America and the North Pacific, but concluded at the time that whether these anomalies are due to natural variability or are a symptom of global warming was 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 nighttime rather than daytime temperature extremes. The authors discuss the relative contributions of the factors identified and possible relations to climate change.

Dettinger et al. (2011) discuss the significance of unusually large variations in annual precipitation and streamflow totals in California relative to the rest of the U.S. These variations mostly reflect the unusually small average number of wet days per year needed to accumulate most of the State's annual precipitation totals (ranging from 5 to 15). Whether or not a few large storms arrive can make the difference between a wet year and a drought. California receives some of the largest 3-day storm totals in the country, and its largest storms are generally fueled by landfalling atmospheric rivers (ARs) (also known as the pineapple express). The fractions of precipitation and streamflow totals at stations across California contribute 20 to 50% of the State's precipitation and streamflow. The authors discuss the prospects for long-lead forecasts of these fractions and the significance of improving this forecasting. The large year-to-year variability in precipitation in the region is one reason why any modest precipitation trends in the region would be hard to detect.

Coincident with these trends, the Western U.S. 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. Observations show that spring snow cover extent in North America has set record lows in 3 of the past 5 years (Derksen and Brown, 2012). Reduced snowpack and snowfall ratios are indicated by analyses of 1948–2001 SWE measurements at 173 Western U.S. stations (Knowles et al. 2007). Pierce et al. (2008) showed that the fraction of winter precipitation retained in the snowpack on April 1st has been declining over the region. Kapnick and Hall (2012) found that the sensitivity of the snowpack to temperature increases varies over the snow season, peaking in March through May, but is quite small in February. Pederson et al. (2011) also found reduced snowpack across the entire North American cordillera between the

1980s and early 2000s using tree-ring reconstructions. Brown and Mote (2009) performed a Northern Hemisphere snowpack sensitivity study and compared the results to observed conditions (1966–2007 NOAA satellite dataset) and snow cover simulations from the CMIP3. Annual snow cover duration was found to be the most sensitive variable and especially so in maritime climates with high snowfall, such as the Western U.S. coastal mountain areas. Both observed conditions and CMIP3 simulations support this finding with the largest decreases in historical annual snow cover duration occurring in the midlatitudinal coastal areas where seasonal mean air temperatures range from -5° to +5 °C, in agreement with Bales et al. (2006). The least sensitive areas were found to be in the interior regions with relatively cold and dry winters where precipitation plays a larger role in snow cover variability. Pierce and Cayan (2012) systematically explored the sensitivity of different snow variables to climate warming, and found a wide range of values, with the fraction of winter precipitation that falls as snow being the most sensitive variable and the actual amount of snowfall being the least.

Kapnick and Hall (2010) looked at the interannual variability in snowpack in an attempt to interpret the causes of recent snowpack trends in western North America. Of particular interest in this analysis is the impact of temperatures in the mid to late portion of the snow season (March through May). There is little impact in the early part of the snow season (February) when temperatures rarely rise above freezing. That is also the key part of the season when stations that exhibit an increase in April 1 SWE receive an increase in accumulation. Their final conclusion is that recent snowpack changes across western North America are due to regional-scale warming. This has implications for future warming regimes, and indicates a possible loss of late season snowpack and an earlier melt season.

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 U.S. sites evaluated for 1970–1998. Lundquist et al. (2009) find that in recent decades, the fraction of annual streamflow from late spring to summer runoff has declined 10 to 25%, and that snowmelt-driven runoff arrives 1 to 3 weeks earlier over the majority of the mountainous Western U.S. Stewart et al. (2005) found trends towards an earlier spring runoff pulse and earlier center of timing of streamflow across much of the region. Peterson et al. (2008) also found earlier runoff trends in an analysis of 18 Sierra Nevada River basins with various periods beginning between 1947–1961 and ending between 1988–2002. 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 U.S. with 100 years of record and attempted to document reduced stationarity. However, their results were not 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.” A similar conclusion was reached by Maurer et al. (2007), who examined changes in timing of streamflow in the Sierra Nevada.

Focusing on changes in precipitation extremes, the former CCSP 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 U.S., 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.

A variety of factors are likely to affect future precipitation extremes, including changes in temperature, precipitation efficiency, and vertical velocity (O’Gorman and Schneider, 2009; Muller et al., 2011), and the ability of warmer atmospheric conditions to sustain a higher equilibrium pressure of water vapor. Some researchers have tried to draw connections between changes in precipitation extremes and atmospheric moisture holding capacity. The latter is a significant factor when considering climate change impacts to the overall hydrologic cycle because warmer air has greater capacity to hold moisture. Santer et al. (2007) report data from the satellite-based SSM/I show that the total atmospheric moisture content over oceans increased by 0.41 kg/m^2 per decade between 1988 and 2006. The authors performed a detection and attribution analysis comparing output from 22 GCMs under multiple forcing scenarios to the observed SSM/I data. They report a statistically significant correlation between the observed pattern of increasing water vapor and that expected to be found from anthropogenic forcing of the climate. It is suggested that these findings, together with related work on continental-scale river runoff, zonal mean rainfall, and surface specific humidity, indicate there is an emerging anthropogenic signal in both the moisture content of earth’s atmosphere and in the cycling of moisture between atmosphere, land, and ocean. An anthropogenic signal consistent with an intensified hydrological cycle can already be identified in the ocean salinity field (Terray et al. 2012; Durack et al. 2012; Pierce et al. 2012a), supporting this view. In a followup study, Santer et al. (2009) performed a detection and attribution analysis to determine if the anthropogenic water vapor fingerprint is insensitive to current GCM uncertainties. The authors report the fingerprint is robust to current model uncertainties, dissimilar to the dominant noise patterns. They also report that the ability to identify an anthropogenic influence on observed multidecadal changes in water vapor is not affected by ‘‘model screening’’ based on model quality, a result also found for climate simulations focusing specifically on the Western U.S. (Pierce et al. 2009). However, Seager et al. (2012a) note that the global average tendency towards an intensified hydrological cycle may not be evident in all locations, depending on the particular changes in precipitation and evaporation in a region and how they might be affected by a teleconnected ENSO response.

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. This has led Deser et al. (2010 and 2012) to urge climate scientists to make clear the important role of natural climate variability in future trends over North America when communicating the results of climate change projections with stakeholders and other decision makers. Among the implications of this work is that future scenarios developed from climate models are likely to reflect some mix of forced and internal variability, with the internal variability larger for precipitation than surface air temperature, over mid-latitude regions like western North America. Another implication is that natural variability is likely to remain important for future precipitation trends and variations for mid-latitude regions, like North America, for at least the next half century. Unfortunately, there is some evidence that the CMIP5 global climate models may underestimate decadal to multi-decadal precipitation variability in western North America, complicating projections of future precipitation changes and drought in this region (Ault et al. 2012).

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 U.S. 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 U.S., 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 35 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 U.S., 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 U.S. and weak or absent at the scale of regional scale drainages with the exception of the Columbia River Basin (Hidalgo et al. 2009). Pierce and Cayan (2012) systematically explored the effect of using ever-larger averaging areas on the statistical significance of trends in snow measures across the Western U.S., and confirmed that there is a tradeoff between how early a trend can be detected and how large the area to be averaged over is.

Fritze et al., 2011 investigated changes in western North American streamflow timing over the 1948–2008 period. Their results indicate that streamflow has continued to shift to earlier in the water year, most notably for those basins with the largest snowmelt runoff component. But an acceleration of these streamflow timing changes for the recent warm decades is not clearly indicated. Most coastal rain-dominated and some interior basins have experienced later timing.

While the trends in Western U.S. riverflow, winter air temperature, and snowpack might be partially explained by anthropogenic influences on climate, annually averaged precipitation trends arising from anthropogenic forcing are not necessarily well separated from zero in this region (e.g., Dettinger 2005). Worldwide, both observed mean (Zhang et al. 2007) and extreme (Min et al. 2011) precipitation trends show signs of the influence of human forcing of the climate, but climate models produce a notably weaker signal than is seen in the observations. 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 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. A recent caution on the use of the PDSI in such studies is that Sheffield et al. (2012) find that the PDSI may be an inappropriate measure of drought that arises from climate change, due to an overly-simplistic dependence of potential evaporation on temperature. Looking to the future, even when substantial regional averaging is used, a significant signal of precipitation change does not emerge over the U.S. as a whole by 2100 (Mahlstein et al., 2012).

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 [Yin 2005; Salathé 2006; Seager et al. 2007]), atmospheric circulation over North America, and precipitation and temperature responses in the Western U.S. 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 U.S. (Cayan et al., 2001).

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 (e.g., Mote et al. 2005; Barnett et al. 2005). 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

In 2011, as part of its responsibilities under section 9503 of the SECURE Water Act,[11] Reclamation reported on climate change implications for water supplies and related water resources within eight major Western U.S. river basins, including MP Region's Sacramento River, San Joaquin River, Truckee River, and Klamath River Basins. The report (Reclamation 2011) includes an original assessment of natural hydrology impacts under projected climate conditions, informed by the same downscaled climate projection summarized in appendix B.

Focusing on the broader Western U.S. region, Reclamation (2011b) reports that projections of future precipitation indicate that the northwestern and north-central portions of the U.S. may gradually become wetter while the southwestern and south-central portions gradually become drier, albeit with substantial fluctuations on interannual to decadal timescales due to natural variability (Deser et al. 2010 and 2012). It is noted that these summary statements reflect regionally averaged changes and that projected changes have geographic variation; they vary through time; and the progression of change through time varies among climate projection ensemble members. What this means is that, going forward in time, different regions are likely to continue to experience the kind of interannual to interdecadal variations in precipitation that they have experienced in the past. For the next few decades, these variations are likely to be superimposed upon background trends that in most cases are likely to be subtle compared with the variations.

[11] The Omnibus Public Lands Act (Public Law 111-11) Subtitle F–SECURE Water.

Examining California in particular, Pierce et al. (2012b) find that 16 global climate models project slight annual drying in the southern part of the state by the 2060s, but little change in the northern part of the state and Sierra Nevada. However, there are changes in the seasonal cycle of precipitation, with increases in the winter and decreases in the spring and summer.

These projected changes in climate have implications for hydrology. Warming trends contribute to a shift in cool season precipitation towards more rain and less snow (Knowles et al. 2007), which causes increased rainfall-runoff volume during the cool season accompanied by less snowpack accumulation. The shift of precipitation from snow to rain, which falls more quickly and so is carried a shorter distance by winds, could also exaggerate rain shadows in the mountainous west (Pavelsky et al., 2012). Projections of future hydrology (Reclamation 2011) suggest that warming and associated loss of snowpack will occur over much of the Western U.S. However, not all locations are projected to experience similar changes. Analyses suggest that losses to snowpack will be greatest where the baseline climate is closer to freezing thresholds (e.g., lower lying valley areas and lower altitude mountain ranges) (Bales et al. 2006). Analyses also suggest that, in high-altitude and high-latitude areas, cool-season snowpack actually could increase during the 21st century (e.g., Columbia headwaters in Canada, Colorado headwaters in Wyoming). Pierce and Cayan (2012) use 13 downscaled global climate models to quantify the influence of mechanisms that contribute to changes in end-of-century peak snowpack: increased precipitation, increased melting, and the conversion of precipitation from snow to rain. Different regions have different balances of mechanisms, although in the Western U.S. as a whole the conversion of precipitation from snow to rain dominates.

Projected changes in surface water runoff are more complex than projections of snowpack. Hydrologic projections introduced in Reclamation (2011b and 2011c) suggest that geographic trends may emerge. The Southwestern U.S. to the southern Rockies may experience gradual annual runoff declines during the 21st century, and the northwest to north-central U.S. may experience little change through mid-21st century with increases projected for the late-21st century. With respect to seasonal runoff, warming is projected to affect snowpack conditions both in terms of cool season accumulation and warm season melt. Without changes to overall precipitation quantity, these changes in snowpack dynamics would lead to increases in cool season rainfall-runoff and decreases in warm season snowmelt-runoff, leading to a season-varying sensitivity of runoff to warming (Das et al., 2011). The hydrologic projections indicate that the degree to which this expectation may occur varies by location in the Western U.S. For example, cool season runoff is projected to increase over the west coast basins from California to Washington and over the north-central U.S., but with little change to slight decreases over the Southwestern U.S. to southern Rockies. Warm season runoff is projected to experience substantial decreases over a region spanning southern Oregon, the Southwestern U.S., and southern Rockies. In summary, the hydrologic projections featured in Reclamation (2011b) suggest that projected precipitation increases in the northern tier of the Western U.S. could counteract warming-related decreases in warm season runoff, whereas projected decreases in precipitation in the southern tier of the Western U.S. could amplify warming-related decreases in warm season runoff.

Focusing on Reclamation (2011b) results representative of the MP Region conditions, **tables 2 through 4** summarize the projection median change from an ensemble of downscaled CMIP3 models run through VIC for various hydroclimate conditions in Sacramento-San Joaquin, Truckee, and Klamath subbasins, respectively. Generally speaking, the ensemble median changes of **tables 2 through 4** suggest that these basins will experience increasing mean-annual temperature and with precipitation change during the 21st century that varies from slight increase in more northerly subbasins to slight decrease in more southerly subbasins.

While **tables 2 through 4** summarize the model ensemble's median change values, it is noted the models typically project a wide range of possible trends in precipitation for many midlatitude regions. The significance of this fact is that the uncertainty (or spread among ensemble members) is very large for precipitation projections for many parts of the U.S. over the next 10 to 60 years, at least (Deser et al. 2010 and 2012).

These changes are projected to be accompanied by decreasing trend in spring SWE, decreasing trend in April–July runoff volume, and increasing trends in December–March and annual runoff volumes.

Table 2.—Summary of simulated changes in decade-mean hydroclimate for several subbasins in the Sacramento and San Joaquin River Basins from an ensemble of downscaled CMIP3 models run through VIC

Hydroclimate Metric (change from 1990s)	2020s	2050s	2070s
Sacramento River at Bend Bridge			
Mean Annual Temperature (°F)	1.3	3.0	4.2
Mean Annual Precipitation (%)	-0.3	0.6	-2.7
Mean April 1 SWE (%)[1]	-22.6	-42.8	-52.9
Mean Annual Runoff (%)	3.5	2.5	-3.6
Mean December–March Runoff (%)	9.0	13.6	11.0
Mean April–July Runoff (%)	-11.1	-23.0	-36.1
Mean Annual Maximum Week Runoff (%)	12.9	18.4	18.3
Mean Annual Minimum Week Runoff (%)	-0.3	-0.5	-0.6
Sacramento River at Freeport			
Mean Annual Temperature (°F)	1.3	3.0	4.2
Mean Annual Precipitation (%)	-0.3	0.6	-2.7
Mean April 1 SWE (%)[1]	-22.4	-43.4	-54.1
Mean Annual Runoff (%)	3.5	2.5	-3.6
Mean December–March Runoff (%)	9.0	13.6	11.0
Mean April–July Runoff (%)	-11.1	-23.0	-36.1
Mean Annual Maximum Week Runoff (%)	12.9	18.4	18.3
Mean Annual Minimum Week Runoff (%)	-0.3	-0.5	-0.6
San Joaquin River at Friant Dam			
Mean Annual Temperature (°F)	1.4	3.3	4.5
Mean Annual Precipitation (%)	-1.3	-5.3	-8.6
Mean April 1 SWE (%)[1]	-7.7	-15.9	-20.3
Mean Annual Runoff (%)	0.7	-8.7	-10.7
Mean December–March Runoff (%)	13.9	15.8	31.0
Mean April–July Runoff (%)	-6.1	-20.2	-25.0
Mean Annual Maximum Week Runoff (%)	-2.3	-6.6	-16.0
Mean Annual Minimum Week Runoff (%)	-4.0	-6.4	-7.6
San Joaquin River at Vernalis			
Mean Annual Temperature (°F)	1.3	3.1	4.3
Mean Annual Precipitation (%)	-1.0	-4.2	-7.7
Mean April 1 SWE (%)[1]	-8.4	-16.6	-21.5
Mean Annual Runoff (%)	0.8	-5.9	-8.4
Mean December–March Runoff (%)	10.1	10.7	17.2
Mean April–July Runoff (%)	-4.8	-20.6	-25.8
Mean Annual Maximum Week Runoff (%)	1.6	-1.8	-4.9
Mean Annual Minimum Week Runoff (%)	-1.2	-1.9	-2.3

[1] The reported percentage changes in mean April 1st SWE have been updated to correct a reporting error in Reclamation (2011b). The error stemmed from reporting this change as the mean change in cell-specific changes from all 1/8-degree grid-cells within the given basin. Such a change metric does not equal the change in total basin SWE integrated across all grid-cells within the basin, which was the intended reporting metric and is now indicated by the updated percentage changes.

Table 3.—Summary of simulated changes in decade-mean hydroclimate for several subbasins in the Truckee and Carson River subbasins from an ensemble of downscaled CMIP3 models run through VIC

Hydroclimate Metric (change from 1990s)	2020s	2050s	2070s
Truckee River at Farad			
Mean Annual Temperature (°F)	1.5	3.3	4.5
Mean Annual Precipitation (%)	0.8	-0.3	-3.0
Mean April 1 SWE (%)[1]	-18.5	-37.0	-46.8
Mean Annual Runoff (%)	3.8	-2.8	-3.1
Mean December–March Runoff (%)	46.7	82.4	106.4
Mean April–July Runoff (%)	-10.0	-27.2	-40.5
Mean Annual Maximum Week Runoff (%)	2.6	0.8	2.4
Mean Annual Minimum Week Runoff (%)	-0.9	-1.2	-1.4
Truckee River at Nixon			
Mean Annual Temperature (°F)	1.5	3.3	4.5
Mean Annual Precipitation (%)	0.6	-0.7	-3.1
Mean April 1 SWE (%)[1]	-17.3	-34.1	-43.4
Mean Annual Runoff (%)	4.3	-2.5	-2.5
Mean December–March Runoff (%)	38.8	72.9	90.8
Mean April–July Runoff (%)	-8.5	-25.9	-37.6
Mean Annual Maximum Week Runoff (%)	3.3	1.3	2.7
Mean Annual Minimum Week Runoff (%)	-0.6	-1.0	-1.3
Carson River at Fort Churchill			
Mean Annual Temperature (°F)	1.5	3.4	4.6
Mean Annual Precipitation (%)	0.1	-1.6	-4.7
Mean April 1 SWE (%)[1]	-13.0	-26.3	-35.6
Mean Annual Runoff (%)	4.1	-4.5	-6.1
Mean December–March Runoff (%)	30.1	41.7	57.5
Mean April–July Runoff (%)	-7.9	-23.9	-32.4
Mean Annual Maximum Week Runoff (%)	-0.4	-0.9	-3.3
Mean Annual Minimum Week Runoff (%)	-1.1	-1.8	-2.7

[1] The reported percentage changes in mean April 1st SWE have been updated to correct a reporting error in Reclamation (2011b). The error stemmed from reporting this change as the mean change in cell-specific changes from all 1/8-degree grid-cells within the given basin. Such a change metric does not equal the change in total basin SWE integrated across all grid-cells within the basin, which was the intended reporting metric and is now indicated by the updated percentage changes.

Table 4.—Summary of simulated changes in decade-mean hydroclimate for several subbasins in the Klamath River Basin from an ensemble of downscaled CMIP3 models run through VIC

Hydroclimate Metric (change from 1990s)	2020s	2050s	2070s
Williamson River below Sprague River			
Mean Annual Temperature (°F)	1.3	3.0	4.3
Mean Annual Precipitation (%)	2.4	2.7	2.2
Mean April 1 SWE (%)[1]	-19.0	-36.5	-46.7
Mean Annual Runoff (%)	7.1	9.6	4.4
Mean December–March Runoff (%)	22.3	29.7	36.7
Mean April–July Runoff (%)	-2.0	-8.3	-20.5
Mean Annual Maximum Week Runoff (%)	8.8	10.6	10.9
Mean Annual Minimum Week Runoff (%)	-0.4	-0.8	-1.6
Klamath River near Seiad Valley			
Mean Annual Temperature (°F)	1.2	2.8	4.1
Mean Annual Precipitation (%)	1.3	2.6	1.1
Mean April 1 SWE (%)[1]	-15.8	-31.1	-40.4
Mean Annual Runoff (%)	3.7	2.9	3.5
Mean December–March Runoff (%)	16.9	31.2	35.1
Mean April-July Runoff (%)	-6.5	-17.6	-32.6
Mean Annual Maximum Week Runoff (%)	11.8	24.0	30.1
Mean Annual Minimum Week Runoff (%)	-0.7	-1.2	-1.6
Klamath River near Klamath			
Mean Annual Temperature (°F)	1.2	2.7	4.0
Mean Annual Precipitation (%)	0.1	2.2	-0.2
Mean April 1 SWE (%)[1]	-17.8	-34.1	-43.2
Mean Annual Runoff (%)	2.6	4.0	-1.0
Mean December–March Runoff (%)	8.7	15.5	17.8
Mean April–July Runoff (%)	-7.5	-19.5	-34.2
Mean Annual Maximum Week Runoff (%)	7.9	18.5	24.9
Mean Annual Minimum Week Runoff (%)	-0.5	-0.9	-1.3

[1] The reported percentage changes in mean April 1st SWE have been updated to correct a reporting error in Reclamation (2011b). The error stemmed from reporting this change as the mean change in cell-specific changes from all 1/8-degree grid-cells within the given basin. Such a change metric does not equal the change in total basin SWE integrated across all grid-cells within the basin, which was the intended reporting metric and is now indicated by the updated percentage changes.

The projected climate change implications for water resources reported in Reclamation (2011b) are similar to those reported in prior assessments. In general, there is greater agreement reported between model projections and, thus, higher confidence in future temperature change relative to precipitation change, although recent work shows that model agreement on precipitation changes is not always evaluated correctly (Power et al., 2012).[12] Appreciable natural variability means that over most of the world, regional-scale changes in precipitation will not be detectible before the Earth warms by 1.4 C (Mahlstein et al., 2012). A paper by the CBO (CBO 2009) presents an overview of the current understanding of the impacts of climate change in the U.S., including that warming will tend to be greater at high latitudes and in the interiors of the U.S. 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. A similar overview is included in the Interagency Climate Change Adaptation Task Force National Action Plan (CEQ 2011), with emphasis on freshwater resources impacts and discussions of strategies to address these impacts. Lundquist et al. (2009) report similar hydrologic impact findings. Focusing on climate change over California, Moser et al. (2009) report specifically on future climate possibilities over California[13] and suggest that warmer temperatures are expected throughout the State during the 21st century, with an end-of-century increase of 3 to 5.5 °F under a lower emissions scenario (B1), 8 to 10.5 °F under a higher emissions scenario (A1FI), and intermediate temperature increase under the A2 emissions scenario. The increase in temperature is expected to be greater in nighttime minimum temperatures than in daytime maximums, potentially putting additional stresses on public health and energy resources (Gershunov and Guirguis, 2012).

Pierce et al. (2012b) report probabilistic projections of temperature (T) and precipitation (P) change over California by the 2060s relative to a historical period (1985–1994) based on bias corrected and downscaled output from 16 GCMs under a single GHG emissions scenario (Special Report on Emissions Scenarios [SRES] A2) with focus on changes in daily distributions of T and P. Similar to previous studies, the T climate change signal is more consistent geographically and across models than the P signal. The distribution of warmest days in July tends to increase uniformly, except along the north coast of the State. In the monthly average, July temperatures shift enough that that the hottest July found in any simulation over the historical period becomes a modestly cool July

[12] 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.

[13] 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.

in the future period. The distribution of warmest days in January is little changed at the median or below but becomes notably warmer on the few warmest days of the year. As a result, Januarys as cold as any found in the historical period are still found in the 2060s, but the median and maximum monthly average temperatures increase notably. Although the annual P changes are small compared to interannual or intermodal variability, the annual change is composed of seasonally varying changes in storm intensity and number of stormy days that are themselves much larger but tend to cancel in the annual mean. Winters show modest wetter conditions in the northern part of the State, while spring and autumn show drying. Switching focus to Oregon and the upper Klamath River Basin, the Oregon Climate Assessment Report (OCCRI, 2010) reports on future climate change possibilities and associated impacts to hydrology, water resources, ecosystems, and other sectors. This report draws on a large body of work on climate change impacts in the Western U.S. from the Climate Impacts Group at the University of Washington and the California Climate Action Team. It discusses the general consensus for a continued warming trend in Oregon and lack of consensus for precipitation change trends by these researchers.

Temperature effects alone could cause significant impacts to hydrologic systems. Diffenbaugh and Ashfaq (2010) report on near-term GCM projections of future extreme temperature events in the U.S. and correlation to reduced soil moisture levels. Although the authors identified robust correlations between changes in temperature, precipitation, and soil moisture, the specific relationship between surface drying and intensified hot extremes is confounding since the predicted decreases in soil moisture could be a product of decreases in precipitation and/or increases in net surface radiation.

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, an effect already that is already observed (Min et al., 2011). Allan (2011) and Pall et al. (2011) both concur that there will be an increase in the frequency of intense rainfalls with warming. Dominguez et al. (2012) found that an ensemble of global climate models downscaled by regional models predict more extreme winter precipitation events, with daily events at the 20- and 50-year return periods increasing by 12 to 14%. 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. Watterson and Dix (2003) report a predicted worldwide average 14% increase in 30-year extreme daily precipitation for 2071–2100 compared to 1961–1990 based on simulations by the CSIRO Mark 2 GCM under A2 (high) and B2 (moderate) emissions scenarios. From a separate stochastic model study of the same GCM output, Watterson (2005) reports the interannual standard deviation of mean monthly precipitation increases with warming temperature. The 1961–1990 to 2071–2100 increases found were 9.0% for January and 11.5% for July. Min et al.

(2011) proposed that some GCM simulations may actually underestimate the trend towards increased extreme precipitation events in the Northern Hemisphere, which suggests that extreme precipitation events may be stronger than projected. Chou and Lan (2012) note that the increase in precipitation extremes means that the annual range of precipitation will increase over much of the world. However, Dulière et al. (2011) caution the use of GCM simulations for local, extreme precipitation projections because the resolution of these models is very coarse. For localized extreme precipitation events, it appears as though regional models retain the large-scale forcings and may preserve the mesoscale forcings and topographic interactions necessary to produce events at this finer scale. Extreme runoff due to changes in the statistics of extreme events will present flood control challenges to varying degrees at many locations (e.g., Das et al., 2011).

A variety of factors are likely to affect future precipitation extremes, including changes in temperature, precipitation efficiency, and vertical velocity (O'Gorman and Schneider, 2009; Muller et al., 2011), and the ability of warmer atmospheric conditions to sustain a higher equilibrium pressure of water vapor.

Primarily all of the historical floods in California may be attributed to precipitation from AR events. ARs are near-surface concentrated 'rivers' of moist air (Zhu and Newell, 1998); in the MP Region they originate mainly from the North Pacific Ocean, and normally occur in the winter season. Dettinger (2011) used a 7-model ensemble to simulate historical and projected AR events. The results suggest that AR events are generally projected to increase in frequency under an A2 climate change emissions scenario. The season in which ARs are typically seen also may lengthen. Further, the temperatures associated with AR events may increase, thus producing conditions where snowlines may rise higher in elevation. If snowlines were to rise, then areas that typically received snow would receive rain. This could potentially result in decreased snowpacks and increased flooding (Dettinger, 2011). Pierce et al. (2013) find that much of the model disagreement on future changes in precipitation over California may be explainable by differences in how the models simulate changes in ARs. In particular, climate models trend to agree that precipitation in this region will become less frequent but heavier. Inter-model differences in the sign of the annual precipitation change are dominated by different projections in the incidence of rare, heavy precipitation events of > 60 mm/day.

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 U.S. 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 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; 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.

It is important to recognize that these assessments of hydrologic impacts under climate change are sensitive to numerous uncertainties. Much attention has been given to the uncertainties introduced by climate projection selection, bias correction and spatial downscaling. For example, Ashfaq et al. (2010) report on an evaluation of climate model bias effects and hydrologic impacts using a RegCM3 to drive a hydrological model (VIC) for the full contiguous U.S. In addition to showing the significance of climate model bias in predicting hydrologic responses, their results highlight the importance of daily temperature and precipitation extremes in predicting future hydrological effects of climate change. Pierce et al. (2012b) compared the results from downscaling 16 global climate models using 3 dynamical methods and 2 statistical methods, and found that future (2060's) projected changes in winter precipitation were more sensitive to the global model used, while summer changes were more sensitive to the downscaling method used. The selection of downscaling method can therefore affect the overall hydrological results of a simulation. Recently, the uncertainties associated with the hydrologic analysis also have been garnering attention. Vano et al. (2012) applied multiple land-surface hydrologic models in the Colorado River Basin under multiple, common climate change scenarios. Their results showed that runoff response to these scenarios varied by model and stemmed from how the models feature a collective of plausible hydrologic process portrayals, where a certain combination of process portrayal choices led to a model's simulated runoff being more or less sensitive to climate change. Although these results are most applicable to the Colorado River Basin, it is still expected that application of the models in Vano et al. (2012) to other Western U.S. basins likewise would show model-dependent runoff sensitivity to climate change. Improving our understanding of these data and model uncertainties will help refine future estimates of climate change implications for hydrology.

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 U.S. (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 percentiles. For the fourth basin (Gunnison), greater flow rates were projected for roughly the upper tercile. 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).

An analysis of GCM-based future flooding events in the drainages of the western Sierra Nevada is presented in Das et al. (2011). The downscaled output from three daily time-step GCMs was used to run VIC hydrologic simulations comparing the periods 2001–2049 and 2051–2099 to 1951–1999. Results include a general increase in the magnitude of 3-day flood events, which is statistically significant for 2051–2099 (110 to 150% of historical). The frequency of flood events increased for predictions from two of the three GCMs, and the authors discuss that the primary factors for this are increases in the sizes of the largest storms, increased storm frequencies, and days with more precipitation falling as rain and less as snow. Antecedent winter soil moisture also appears to be a factor, especially so in the southern portion of the range.

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 U.S. 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. Brekke et al. (2004), in an early study using only two global climate models, found that they disagreed in their projected changes in water resources of the San Joaquin river, and suggested that water managers develop contingency strategies in response to such climate model uncertainty. 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 (Painter et al. 2007).

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 were 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. Wang et al. (2011) shows potential climate change impacts to the operation of the State Water Project and Central Valley Project at the mid-century and late-century points. The study incorporated the current planning model, CALSIM II, and used six GCMs and two emission scenarios to bracket potential impacts in conjunction with a three-step perturbation method to isolate the impacts of changes in annual inflow, pattern shifts, and sea level rise. The results show that, for mid-century (2030–2059), annual inflow changes contribute most to climate change impacts to the system: an approximate south of Delta export reduction of 9% and an approximate 20% north of Delta Reservoir carryover storage volume. By the late-century (2070–2099), an estimated sea level rise of 61 cm plays an important role in system climate change impacts: south of Delta export reduction of about 21% and a north of Delta carryover storage volume reduction of approximately 36%.

Sea level rise in and of itself can pose problems for the Sacramento-San Joaquin Delta water infrastructure. Aging levees form an important part of the water control system, yet the region is experiencing subsidence trends of 3 to 20 mm/year. If no mitigating action is taken, much of the levee system could fall below its design threshold in coming decades as sea level continues to rise (Brooks et al. 2012). A summary of other impacts of climate change on the Sacramento-San Joaquin Delta water system, including risks to local water supplies, coastal lands, and native species, is given in Cloern et al. (2011).

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

This section is organized under the following subheadings: Multiple Species/Resources and Ecosystems; Fisheries and Aquatic Ecosystems; Individual Species/Resources; Agriculture; and Forest Fires. The literature covered includes both historical and projected future conditions.

2.2.3.1 Multiple Species/Resources and Ecosystems

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.[14] 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.

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[14] 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.

Parmesan (2006) provides a synthesis of recent studies pertaining to observed responses of wild biological species and systems to recent climate change. This author's literature search revealed 866 peer-reviewed papers that documented changes in species or systems that could be attributed at least in part to climate change. The synthesis focuses on advancing of spring events, variations in phenological responses between interacting species, species range shifts, range restricted species, pests and parasites, extinction, and evolutionary responses and genetic shifts.

Using meta-analysis, Chen, et.al. (2011) documented a change of elevation and latitude of terrestrial organisms as a result of climate variability. Using available studies of Europe, North America, Chile, Malasia, and the Marion Islands, range shifts were documented for 764 individual species responses for latitude adjustment and 1,367 species responses for elevation variability. The results of this analysis indicate that species have moved away from the equator at a median rate of 16.9 kilometers per decade. Additionally, species have moved to higher elevations at a median rate of 11.0 meters per decade.

Research by Ault and others (2011) shows that the average timing of plant phenology events, such as bud formation and flowering, is occurring 1.5 days earlier per decade across western North America. They note that the major modes of atmospheric circulation only account for about one-third of the trend.

The VEMAP[15] and other similar projects have increased our understanding of ecosystem dynamics under climate change; however, our understanding of the interactions between stresses on individual species at the ecosystem level is still relatively limited. Specific examples include the interaction between atmospheric CO_2 and soil water and nutrient limitations on plant productivity, carbon sequestration , and species composition; the interactions between CO_2 and tropospheric O_3 on plant water-use efficiency; and the rates of future plant species migration and ecosystem establishment under climate change (Aber et al. 2001). In general, vegetation models indicate that a moderate increase in future temperatures produce an increase in vegetation density and carbon sequestration across most of the U.S. with small changes in vegetation types and large increases in future temperatures that cause losses of carbon with large shifts in vegetation types (Bachelet et al. 2001).

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

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[15] Available online at: http://www.cgd.ucar.edu/vemap/.

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 U.S., and increased temperature and drought likely influenced these outbreaks. 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.

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). Bentz et al. (2010) report that “models suggest a movement of temperature suitability to higher latitudes and elevations and identify regions with a high potential for bark beetle outbreaks and associated tree mortality in the coming century.”

Shaw et al. (2009) provides an assessment of the potential impacts of climate change on selected ecosystem services and their associated economic value in California. The GCM based assessment focuses on the social cost and the market value of carbon sequestration, the profits associated with the production of natural forage, and the consumer surplus of skiing and salmon fishing. Other ecosystem services which currently lack quantitative models and the impact of climate change on California’s biodiversity are also discussed. The authors report climate change will likely affect the abundance, production, distribution, and quality of ecosystem services throughout California. Specific impacts includes the delivery of water to support human consumption and wildlife, climate stabilization through carbon sequestration, and the supply of fish for commercial and recreational sport fishing.

Robinson et al. (2008) describe and compare several ecological models that estimate vegetation development (productivity or vegetation type) under climate change.

2.2.3.2 Fisheries and Aquatic Ecosystems

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 U.S., including Western U.S. 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 (2009) predicts 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 U.S.

Wagner et al. (2010) present statistical model results predicting changes in Sacramento-San Joaquin Delta water temperatures and associated fishery impacts under future climate change. The models are driven by downscaled output from two GCMs under two emissions scenarios for the period 1950–2100. Significant impacts to the Delta smelt are predicted under all four scenarios, including increased mortality and shifts in the spawning period.

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). Marcarelli et al. (2010) estimated past and future hydrographs and patterns of ecosystem metabolism for a Western U.S. river and analyzed the impacts of climate change and water use. The reported combined hydrologic-related impacts, measured in terms of gross primary production and ecosystem respiration, are indicative of the potentially important role hydrologic regime plays in controlling ecosystem function.

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.

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.

2.2.3.3 Individual Species/Resources

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 and 2011) report study findings associated with potential climate change impacts to the American pika that include results of testing alternative models of climate-mediated extirpations.

Salzer et al. (2009) report "Great Basin bristlecone pine (Pinus longaeva) at 3 sites in western North America near the upper elevation limit of tree growth showed ring growth in the second half of the 20th century that was greater than during any other 50-year period in the last 3,700 years." The authors suggest the primary factor for this is increasing temperatures.

Cayan et al. (2001) document earlier blooming of lilacs and honeysuckles correlated to increasing spring temperatures.

2.2.3.4 Agriculture

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.

Lobell et al. (2011) present the findings of a global analysis of crop production impacts due to past climate change. The authors developed statistical models comparing 1980–2008 actual production levels for the four largest commodity crops (corn, wheat, soybeans, and rice) to theoretical levels without climate change. Their results indicate respective 3.8 and 5.5% decreases in worldwide corn and wheat production and approximately no net change for soybeans and rice. Significant changes in U.S. production levels were not found, and this is attributed to relatively low increases in temperatures in our agricultural regions.

The authors attribute the modeled impacts to changes in temperature rather than precipitation, and they acknowledge that their analysis does not account for adaptations by growers or the effect of elevated CO_2 on crop yields.

Nardone et al., 2010 discusses the effects of climate change on livestock following the "theory of global warming." Topics include impaired production due to increased temperatures, desertification of rangelands, impacts to grain availability, and adaptability of animal genotypes.

Nelson (2012) explores some of the policy issues associated with ground water use in the California central valley for agriculture. They note that typically only voluntary approaches to limiting or regulating ground water extraction are used, whether or not the local problems with excessive ground water depletion are severe or not, and without regard to the possible impacts of overpumping.

Hanson et al. (2012) report on the development of a new physically based model of water use in California's central valley, which links global models of the climate and projections of climate change with fully integrated surface and ground water models. A sample application using simulated temperature and precipitation changes through the end of the century shows reduced surface water deliveries and increased ground water pumping, with the possibility of associated land subsidence, less water for riparian ecosystems, and altered flows in the Sacramento-San Joaquin River delta. Recent work suggests that the GRACE satellites may be able to provide remotely-sensed estimates of ground water changes in the region (Scanlon et al. 2012).

2.2.3.5 Forest Fires and Wildfires

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 U.S., 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 in Westerling et al. (2006), which documents large increases in fire season duration and fire frequency, especially at mid-elevations, in the Western U.S. Coincident with trends toward warmer and drier climate in the Western U.S. 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, 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 to 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. (2011) predict there will be 12 to 74% more fires in California by 2085, based on 3 GCMs and the A2 scenario.

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 U.S. 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 U.S. 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. Root (2012) cautions that increased wildfires can lead to unexpected results on some fire-adapted species, for example if fires become so frequent that juvenile plants do not have time to produce seeds. Westerling and Bryant (2008) projected California wildfire risks for SRES A2 and B1 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."

Moritz et al. (2012) used projections from 16 different GCMs to formulate a comprehensive look at global fire patterns. Those projections focused on two timeframes: 2010–2039 and 2070–2099. The results indicated climate change will result in an increase in the frequency of wildfires in the Western U.S. in the next 30 years, and across the entire U.S. at the end of the century. Westerling et al. (2011b) find that statewide, California wildfire areas burned could increase 36 to 72% under the higher GHG emissions scenarios, and by 2085 could increase more than 100% in northern California forests.

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

> “Global sea level rose at a rate of 1.7 millimeters/year during the 20th century. The rate has increased to over 3 millimeters/year in the past 20 years and scientific studies suggest high confidence (>9 in 10 chance) that global mean sea level will rise 0.2 to 2 meters by the end of this century” (*Burkett and Davidson* 2012).

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 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 due to thermal expansion alone of approximately 3 to 10 cm (or 1 to 4 inches) by roughly 2035 relative to 1980–1999 conditions. These projections are based on CMIP3 models’ simulation of ocean response to atmospheric warming under a collection of 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. National Research Council (2012) provides a comprehensive review of global sea level rise and how it will affect the west coast of the U.S. Ice loss processes ignored in IPCC 2007 are included in the NRC report, leading to approximately a doubling of the projected sea level rise (50 to 140 cm by 2100).

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 study conducted by Yin et al. (2011) suggests that the acceleration of outlet glacier melting in Greenland and Antarctica is closely linked to subsurface ocean layer temperatures. Additionally, using 19 climate models, they were able to project ocean temperatures through 2200. These models showed the potential for maximum ocean temperature increases around Greenland to be 1.7 to 2.0 °C by the end of the 21st century. The same modeling around Antarctica showed maximum ocean temperature increases of 0.5 to 0.6 °C by the year 2100. Both of these results represent ocean temperature increases greater than what was previously thought, indicating the potential for even greater sea level rises in the future. Because ocean temperatures require centuries to come into equilibrium with warmer surface forcing, sea level rise can continue long after land temperatures stop rising (Wigley, 2005).

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 ISB estimated a range of sea level rise at Golden Gate of 1.6 to 4.6 feet (50 to 140 cm) by the end of the century (CALFED ISB 2007). Likewise, the CA DWR applied this approach using the 12 future climate projections selected by the 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. The San Francisco Bay Conservation and Development Commission used two sea level rise projections (a 16-inch (40 cm) sea level rise by mid-century and a 55-inch (140 cm) rise in sea level by the end of the century) for a vulnerability assessment presented in SFBCDC 2011. 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 to 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.

Bromirski et al. (2011) specifically studied the Pacific coast in regard to sea level rise. The study notes that, from approximately 1930–1980, sea levels along the Pacific coast of North America rose at a rate equivalent to the global rate of change (2 millimeters per year). Between 1980 and 2009, however, sea levels remained relatively constant according to tide gauge and satellite altimetry measurements. Contributing factors to this regional variance include a shift from cold to warm phase of the PDO that occurred in the mid-1970s, which was followed by a shift in wind stress patterns. The shift in wind stress patterns likely has suppressed the previously observed rising trend (Bromirski et al. 2011).

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.

Given the uncertainty in global sea level rise projections, and the aforementioned critique of the assumptions in the IPCC AR4 analysis, Parris et al. (2012) developed four plausible scenarios of sea level rise, which can be applied in conjunction with analyses of local conditions. They mention the following:

> "Based on a large body of science, we identify four scenarios of global mean SLR ranging from 0.2 meters (8 inches) to 2.0 meters (6.6 feet) by 2100. These scenarios provide a set of plausible trajectories of global mean SLR for use in assessing vulnerability, impacts, and adaptation strategies. None of these scenarios should be used in isolation, and experts and coastal managers should factor in locally and regionally specific information on climatic, physical, ecological, and biological processes and on the culture and economy of coastal communities."

Konikow (2011) discusses the relationship between sea level rise and ground water depletion and suggest a better understanding of this relationship is needed to better predict future rates of sea level rise. According to the author, the 1900–2008 global ground water depletion was approximately 4,500 cubic kilometers (3.6 million acre-feet) which would be equivalent to a 12.6 millimeter rise in sea level.

2.3 Lower Colorado Region

Numerous studies have been conducted on the potential consequences of climate change for water resources in Reclamation's LC Region. This section summarizes findings from recent studies (1994–2012) demonstrating evidence of regional climate change during the 20th century and exploring water and environmental resources impacts associated with various climate change scenarios.[16] A recent summary of historical and projected climate changes that includes the LC Region is given in the Southwest Climate Change Assessment (Overpeck et al. 2012), part of the U.S. National Climate Assessment.

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 U.S. spring temperatures increased 1 to 3 °C between the 1970s and 1980s. Based on data available from the Western Climate Mapping Initiative,[17] the change in 11-year annual mean during the 20th century is roughly +1.2 °C for the Upper Colorado River Basin and +1.7 °C for the Lower Colorado River Basin.[18] 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 to 2 °C for most of the LC Region for 1900–2002, and 2 to 4 °C spring minimum temperature increases throughout most of the LC Region (2004; 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. Salzer and Kipfmueller (2005) report that the highest annual maximum temperatures in the last 2000 years, for the southern Colorado Plateau, have occurred in the late 20th century. 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

[16] 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 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).

[17] Available online at: http://www.cefa.dri.edu/Westmap/.

[18] 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).

May. Moreover, Weiss and Overpeck (2005) note an increase in the length of the frost-free season in the heart of the Sonoran Desert, which corroborates similar findings in a study of U.S. trends in numbers of frost days and dates of first and last frosts (Easterling 2002). For the LC Region, the number of winter and spring frost days in the second half of the 20th century decreased, the date of the last spring frost arrived earlier in the year, and the date of the first fall frost arrived 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. Woodhouse et al. (2010) also present information on Southwest temperatures concurrent with drought that is based on paleoclimate and model data. 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 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 Cooperative Observer Program (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 precipitation trends from 1916–2003 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 U.S. 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.

Dettinger et al. (2011) discuss the significance of unusually large variations in annual precipitation and streamflow totals in California relative to the rest of the U.S. These variations mostly reflect the unusually small average number of wet days per year needed to accumulate most of the State's annual precipitation totals (ranging from 5 to 15). Whether or not a few large storms arrive can make the difference between a wet year and a drought. California receives some of the largest 3-day storm totals in the country, and its largest storms generally are fueled by landfalling ARs. The fractions of precipitation and streamflow totals at stations across California contribute 20 to 50% of the State's precipitation and streamflow. The authors discuss the prospects for long-lead forecasts of these fractions and the significance of improving this forecasting. Coincident with these trends, the Western U.S. 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 SWE in snowfall and precipitation measurements at 207 Western U.S. National Weather Service cooperative observer stations (Knowles et al. 2007). Knowles et al. found that declines in the ratio of SWE in snowfall 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 multidecadal variability, such as shifts in the Pacific Decadal Oscillation, only partly could 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. Pierce et al. (2008) analyzed data from 548 snow courses in the Western U.S. over the period 1950–1999, and found a general decrease in the fraction of winter precipitation that is retained in the spring snowpack, including a significant decline in the Colorado Rockies. Pederson et al. (2011) also found reduced snowpack across the entire North American cordillera since between the 1980s and late 1990s/early 2000s using tree-ring reconstructions. These correlations imply that warming results in less April 1 SWE because of the increased frequency of melt events, and are consistent with evidence of declining spring snowpack across North America in the IPCC AR4 (IPCC 2007). Observations show that spring snow cover extent in North America has set record lows in 3 of the past 5 years (Derksen and Brown, 2012).

Brown and Mote (2009) performed a Northern Hemisphere snowpack sensitivity study and compared the results to observed conditions (1966–2007 NOAA satellite dataset) and snow cover simulations from the CMIP3. Annual snow cover duration was found to be the most sensitive variable and especially so in maritime climates with high snowfall, such as the Western U.S. coastal mountain areas. Both observed conditions and CMIP3 simulations support this finding with the largest decreases in historical annual snow cover duration occurring in the midlatitudinal coastal areas where seasonal mean air temperatures range from -5 to +5 °C. The least sensitive areas were found to be in the interior regions with relatively cold and dry winters where precipitation plays a larger role in snow cover variability, in agreement with Bales et al. (2006). 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. Fritze et al. (2011) found shifts from snowmelt-dominated to rain-dominated regimes have occurred for particularly sensitive basins in the Western U.S., with the upshot of a higher frequency of winter flooding, a decrease in soil moisture during the dry season, and longer summer and fall low-flow periods. These shifts have been most pronounced in the Sierra Nevada and in northeastern New Mexico. 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).

Kapnick and Hall (2010) looked at the interannual variability in snowpack in an attempt to interpret the causes of recent snowpack trends in western North America. Of particular interest in this analysis is the impact of temperatures in the mid to late portion of the snow season (March through May). There is little impact in the early part of the snow season (February) when temperatures rarely rise above freezing. That is also the key part of the season when stations that exhibit an increase in April 1 SWE receive an increase in accumulation. Their final conclusion is that recent snowpack changes across western North America are due to regional-scale warming. This has implications for future warming regimes, and indicates a possible loss of late season snowpack and an earlier melt season.

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[19] (Stewart et al. 2005). Lundquist et al. (2009) find that in recent decades, the fraction of annual streamflow from late spring to summer runoff has declined 10 to 25%, and that snowmelt-driven runoff arrives 1 to 3 weeks earlier over the majority of the mountainous Western U.S. Earlier melt and center of mass have implications for reservoir storage and low flows following peak runoff.

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

Regonda et al. (2005) evaluated 1950–1999 data from 89 stream gauges in the Western U.S. and report 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. Kapnick and Hall (2012) find that the sensitivity of the snowpack to temperature increases varies over the snow season, peaking in March through May, but is quite small in February.

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, and has grown five-fold since the mid 19th century (Painter et al. 2012a). 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. Likewise, although the increase in dust is a human effect on climate, it would not be influenced by changes in GHG emissions. Recent advances in satellite-based remote measurement of dust on snow hold promise in increasing the ability to understand the effects of this mechanism on snowpack in the Western U.S. (Painter et al. 2012b).

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.

Villarini et al. (2009) analyzed annual peak discharge records from 50 stations in the U.S. with 100 years of record and attempted to document reduced stationarity. However, their results were not 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.”

Deser et al. (2010 and 2012) urged climate scientists to make clear the important role of natural climate variability in future trends over North America when communicating the results of climate change projections with stakeholders and other decision makers. Among the implications of this work is that future scenarios developed from climate models are likely to reflect some mix of forced and internal variability, with the internal variability larger for precipitation than surface air temperature, over mid-latitude regions like western North America.

Another implication is that natural variability is likely to remain important for future precipitation trends and variations for mid-latitude regions, like North America, for at least the next half century. Unfortunately, there is some evidence that the CMIP5 global climate models may underestimate decadal to multi-decadal precipitation variability in western North America, complicating projections of future precipitation changes and drought in this region (Ault et al. 2012).

Focusing on changes in precipitation extremes, the former CCSP issued SAP 3.3 (CCSP 2008), wherein chapter 3 focuses on mechanisms for observed changes in extremes 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 U.S., although very small trends (1931–1996) were shown for the climate divisions of the LC Region. It should be noted, however, that 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. Dominguez et al. (2012) found that an ensemble of global climate models downscaled by regional models predict more extreme precipitation events over most of the LC Region, with daily events at the 20- and 50-year return periods increasing by 12 to 14%. Kunkel et al. (2012) show statistically significant increases in North American monsoon extreme precipitation, defined as daily precipitation events exceeding a threshold for a 1-in-5-year occurrence, in California and Nevada.

A variety of factors are likely to affect future precipitation extremes, including changes in temperature, precipitation efficiency, and vertical velocity (O'Gorman and Schneider, 2009; Muller et al., 2011), and the ability of warmer atmospheric conditions to sustain a higher equilibrium pressure of water vapor. Some researchers have tried to draw connections between changes in precipitation extremes and atmospheric moisture holding capacity. The latter is a significant factor when considering climate change impacts to the overall hydrologic cycle because warmer air has greater capacity to hold moisture. Santer et al. (2007) report data from the satellite-based SSM/I show that the total atmospheric moisture content over oceans has increased by 0.41 kg/m^2 per decade between 1988 and 2005. The authors performed a detection and attribution analysis comparing output from 22 GCMs under multiple forcing scenarios to the observed SSM/I data. They report a statistically significant correlation between the observed pattern of increasing water vapor and that expected to be found from anthropogenic forcing of the climate. It is suggested these findings together with related work on continental-scale river runoff, zonal mean rainfall, and surface specific humidity, indicate there is an emerging anthropogenic signal in both the moisture content of Earth's atmosphere and in the cycling of moisture between atmosphere, land, and ocean. An anthropogenic signal consistent with an intensified hydrological cycle can already be identified in the ocean salinity field (Terray et al. 2012; Durack et al. 2012; Pierce et al. 2012a), supporting this view.

In a follow-up study, Santer et al. (2009) performed a detection and attribution analysis to determine if the anthropogenic water vapor fingerprint is insensitive to current GCM uncertainties. The authors report the fingerprint is robust to current model uncertainties, dissimilar to the dominant noise patterns. They also report that the ability to identify an anthropogenic influence on observed multidecadal changes in water vapor is not affected by ‘‘model screening’’ based on model quality , a result also found for climate simulations focusing specifically on the Western U.S. (Pierce et al. 2009). However, Seager et al. (2012a) note that the global average tendency towards an intensified hydrological cycle may not be evident in all locations, depending on the particular changes in precipitation and evaporation in a region and how they might be affected by a teleconnected ENSO response. This is particularly true in the LC Region, which is affected by ENSO variability.

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 U.S. Groisman and Knight (2008) show that the mean duration of prolonged dry spells in the Southwestern U.S. 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 2000 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 Woodhouse et al. 2010) 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. A recent caution on the use of the PDSI in such studies is that Sheffield et al. (2012) and Hoerling et al. (2012) find that the PDSI may be an inappropriate measure of drought that arises from climate change, due to an overly-simplistic dependence of potential evaporation on temperature.

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 paleodrought is that drought and precipitation in the LC Region are 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 tropical SST variations 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 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 LC 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. Nowak et al. (2012) analyze decadal to multidecadal variability in Colorado River streamflow at Lees Ferry, and find ~64 year and ~15 year modes of variability. The former is associated with changes in runoff efficiency accomplished by changes in temperature, while the latter is associated with changes in moisture delivery to the region. Correlations suggest that the Atlantic multidecadal oscillation is associated with Upper Colorado River Basin temperature fluctuations.

Cook et al. (2008, 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.

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 GHG 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 U.S. 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 U.S., 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 35 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 U.S.; 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 U.S. and weak or absent at the scale of regional scale drainages with the exception of the Columbia River Basin (Hidalgo et al. 2009). Pierce and Cayan (2012) explored this idea further, quantifying the systematic increase in detectability of changes in snow variables when averaging across increasingly larger regions of the Western U.S.

Fritze et al., 2011 investigated changes in western North American streamflow timing over the 1948–2008 period. Their results indicate that streamflow has continued to shift to earlier in the water year, most notably for those basins with the largest snowmelt runoff component. But an acceleration of these streamflow timing changes for the recent warm decades is not clearly indicated. Most coastal rain-dominated and some interior basins have experienced later timing.

While the trends in Western U.S. riverflow, winter air temperature, and snowpack might be explained partially by anthropogenic influences on climate, annually averaged precipitation trends arising from anthropogenic forcing are not necessarily well separated from zero in this region. Worldwide, both observed mean (Zhang et al., 2007) and extreme (Min et al., 2011) precipitation trends show signs of the influence of human forcing of the climate, but climate models produce a notably weaker signal than is seen in the observations. 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 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 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. Looking to the future, even when substantial regional averaging is used, a significant signal of precipitation change does not emerge over the U.S. as a whole by 2100 (Mahlstein et al., 2012).

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 [Yin 2005; Salathé 2006; Seager et al. 2007]), atmospheric circulation over North America, and precipitation and temperature responses in the Western U.S. 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 U.S. (Cayan et al. 2001).

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

In 2011, as part of its responsibilities under section 9503 of the SECURE Water Act,[20] Reclamation reported on climate change implications for water supplies and related water resources within eight major Western U.S. river basins, including LC Region's Colorado River Basin. The report (Reclamation 2011) includes an original assessment of natural hydrology impacts under projected climate conditions, informed by the same downscaled climate projection summarized in appendix B (Reclamation 11c).

Focusing on the broader Western U.S. region, Reclamation (2011b) reports that projections of future precipitation indicate that the northwestern and north-central portions of the U.S. may gradually become wetter while the southwestern and south-central portions gradually become drier, albeit with substantial fluctuations on interannual to decadal timescales due to natural variability (Deser et al., 2010 and 2012). It is noted that these summary statements reflect regionally averaged

[20] The Omnibus Public Lands Act (Public Law 111-11) Subtitle F – SECURE Water.

changes and that projected changes have geographic variation; they vary through time; and the progression of change through time varies among climate projection ensemble members. What this means is that, going forward in time, different regions are likely to continue to experience the kind of interannual to interdecadal variations in precipitation that they have experienced in the past. For the next few decades, these variations are likely to be superimposed upon background trends that in most cases are likely to be subtle compared with the variations.

These projected changes in climate have implications for hydrology. Warming trends contribute to a shift in cool season precipitation towards more rain and less snow (Knowles et al. 2007), which causes increased rainfall-runoff volume during the cool season accompanied by less snowpack accumulation. The shift of precipitation from snow to rain, which falls more quickly and so is carried a shorter distance by winds, could also exaggerate rain shadows in the mountainous west (Pavelsky et al., 2012). Projections of future hydrology (Reclamation 2011) suggest that warming and associated loss of snowpack will occur over much of the Western U.S. However, not all locations are projected to experience similar changes. Analyses suggest that losses to snowpack will be greatest where the baseline climate is closer to freezing thresholds (e.g., lower lying valley areas and lower altitude mountain ranges) (Bales et al. 2006). Analyses also suggest that, in high-altitude and high-latitude areas, cool-season snowpack actually could increase during the 21st century (e.g., Columbia headwaters in Canada, Colorado headwaters in Wyoming). A review of these processes, with application to the Colorado Rocky Mountains, is given in Rangwala and Miller (2012). Pierce and Cayan (2012) use 13 downscaled global climate models to quantify the influence of mechanisms that contribute to changes in end-of-century peak snowpack: increased precipitation, increased melting, and the conversion of precipitation from snow to rain. The Colorado Rockies have the smallest projected decrease in spring snowpack of the Western U.S. regions examined in their study, since greater melting and the conversion of snow to rain by 2100 is partially offset by increasing winter precipitation.

Projected changes in surface water runoff are more complex than projections of snowpack. Hydrologic projections introduced in Reclamation (2011b) suggest that geographic trends may emerge. The Southwestern U.S. to the southern Rockies may experience gradual annual runoff declines during the 21st century, and the northwest to north-central U.S. may experience little change through mid-21st century with increases projected for the late-21st century. With respect to seasonal runoff, warming is projected to affect snowpack conditions both in terms of cool season accumulation and warm season melt. Without changes to overall precipitation quantity, these changes in snowpack dynamics would lead to increases in cool season rainfall-runoff and decreases in warm season snowmelt-runoff, leading to a season-varying sensitivity of runoff to warming (Das et al., 2011). The hydrologic projections indicate that the degree to which this expectation may occur varies by location in the Western U.S. For example, cool season runoff is projected to increase over the west coast basins from California to Washington and over the north-central U.S., but with little change to slight decreases over the Southwestern U.S. to southern Rockies. Warm season runoff is projected to experience substantial decreases over a region spanning southern Oregon, the Southwestern U.S., and southern Rockies. In summary, the hydrologic projections featured in Reclamation (2011b) suggest that projected precipitation increases in the northern tier of the Western U.S. could counteract warming-related decreases in warm season runoff, whereas projected decreases in precipitation in the southern tier of the Western U.S. could amplify warming-related decreases in warm season runoff.

Focusing on Reclamation (2011b) results representative of LC Region conditions, **table 5** summarizes the CMIP3 projection median change from an ensemble of downscaled CMIP3 models run through VIC for various hydroclimate conditions in Colorado River subbasins. Generally speaking, the ensemble-median changes of **table 5** suggest that these subbasins will experience increasing mean-annual temperature and with precipitation change during the 21st century that varies from increases in more northerly subbasins to decreases in more southerly subbasins. These changes are projected to be accompanied by decreasing trend in spring SWE, decreasing trend in April-July runoff volume, and increasing trends in December-March and annual runoff volumes.[21]

While **table 5** summarizes the model ensemble's median change values, it is noted the models typically project a wide range of possible trends in precipitation for many midlatitude regions. The significance of this fact is that the uncertainty (or spread among ensemble members) is very large for precipitation projections for many parts of the U.S. over the next 10 to 60 years, at least (Deser et al. 2010 and 2012).

The projected climate change implications for water resources reported in Reclamation (2011b) are similar to those reported in prior assessments. A recent paper by the CBO (CBO 2009) presents an overview of the current understanding of the impacts of climate change in the U.S., including that warming will tend to be greater at high latitudes and in the interiors of the U.S. Global average warming values therefore tend to underestimate the warming the interior U.S. will experience (IPCC, 2007). 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. This change in precipitation intensity, in and of itself, can affect the snowpack (Kumar et al., 2012). A similar overview is included in the Interagency

[21] This study is complemented by the ongoing WaterSMART Colorado River Water Supply and Demand Study (http://www.usbr.gov/lc/region/programs/crbstudy.html). This study is informed by hydroclimate projections from Reclamation (2011b), along with other basis of future climate assumptions including paleoclimate proxies. At the time this synthesis was updated, the results from the WaterSMART study were still in development.

Climate Change Adaptation Task Force National Action Plan (CEQ, 2011), with emphasis on freshwater resources impacts and discussions of strategies to address these impacts. Lundquist et al. (2009) report similar findings on hydrologic impacts.

Table 5.—Summary of simulated changes from an ensemble of downscaled CMIP3 models run through VIC in decade-mean hydroclimate for several subbasins in the Colorado River Basin

Hydroclimate Metric (change from 1990s)	2020s	2050s	2070s
Green River near Greendale			
Mean Annual Temperature (°F)	1.8	3.8	5.2
Mean Annual Precipitation (%)	0.7	2.1	3.6
Mean April 1 SWE (%)[1]	-1.5	-3.7	-5.5
Mean Annual Runoff (%)	-2.3	-3.5	-2.4
Mean December–March Runoff (%)	-4.9	-4.0	-0.1
Mean April–July Runoff (%)	0.3	0.7	2.4
Mean Annual Maximum Week Runoff (%)	1.9	6.2	7.7
Mean Annual Minimum Week Runoff (%)	-12.0	-16.6	-20.2
Colorado River at Lees Ferry			
Mean Annual Temperature (°F)	1.8	3.8	5.2
Mean Annual Precipitation (%)	-0.6	-0.3	-0.1
Mean April 1 SWE (%)[1]	-3.1	-7.8	-11.0
Mean Annual Runoff (%)	-3.1	-8.5	-6.9
Mean December–March Runoff (%)	0.1	-1.1	4.9
Mean April–July Runoff (%)	-1.0	-7.4	-6.5
Mean Annual Maximum Week Runoff (%)	-2.8	-3.5	-8.0
Mean Annual Minimum Week Runoff (%)	-8.2	-13.0	-14.9
Colorado River above Imperial Dam			
Mean Annual Temperature (°F)	1.8	3.7	5.1
Mean Annual Precipitation (%)	-3.0	-8.6	-13.1
Mean April 1 SWE (%)[1]	-53.0	-48.6	-13.1
Mean Annual Runoff (%)	-1.7	-7.4	-7.7
Mean December–March Runoff (%)	3.5	-3.0	1.3
Mean April–July Runoff (%)	0.3	-6.6	-6.1
Mean Annual Maximum Week Runoff (%)	-3.0	-3.7	-8.3
Mean Annual Minimum Week Runoff (%)	-7.9	-12.3	-14.0

[1] The reported percentage changes in mean April 1st SWE have been updated to correct a reporting error in Reclamation (2011b). The error stemmed from reporting this change as the mean change in cell-specific changes from all 1/8-degree grid-cells within the given basin. Such a change metric does not equal the change in total basin SWE integrated across all grid-cells within the basin, which was the intended reporting metric and is now indicated by the updated percentage changes.

Focusing on the California portion of LC Region, Pierce et al. (2012b) report probabilistic projections of T and P change over California by the 2060s relative to a historical period (1985–1994) based on bias-corrected and downscaled output from 16 GCMs under a single GHG emissions scenario (SRES A2) with focus on changes in daily distributions of T and P. Similar to previous studies, the T climate change signal is more consistent geographically and across models than the P signal. The distribution of warmest days in July tends to increase uniformly, except along the North coast of the State. In the monthly average, July temperatures shift enough that that the hottest July found in any simulation over the historical period becomes a modestly cool July in the future period. The distribution of warmest days in January is little changed at the median or below, but becomes notably warmer on the few warmest days of the year. As a result, Januarys as cold as any found in the historical period are still found in the 2060s, but the median and maximum monthly average temperatures increase notably. Although the annual P changes are small compared to interannual or intermodal variability, the annual change is composed of seasonally varying changes in storm intensity and number of stormy days that are themselves much larger, but tend to cancel in the annual mean. Winters show modest wetter conditions in the north of the State, while spring and autumn show drying. Gershunov and Guirguis (2012) find that the increase in temperature is expected to be greater in nighttime minimum temperatures than in daytime maximums, potentially putting additional stresses on public health and energy resources.

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.[22] 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, although recent work shows that model agreement on precipitation changes is not always evaluated correctly (Power et al., 2012). 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 AR4 robustly predict that the Southwestern U.S. 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. Using a dynamically downscaled 111-year transient WRF-HadCM3 run (A2 SRES), Wi et al. (2012) found a statistically

[22] 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.

significant decrease in snowfall in all but the highest elevations and latitudes of the Colorado River Basin. The fraction of total precipitation falling as snow shows statistically significant declines in parts of the basin. They note that the strongest decrease in snowfall is seen at high elevations in the southern part of the basin and low elevations in the northern part of the basin. “The regions of most intense decreases in snow experience a decline of approximately 50% in snowfall throughout the 111-year simulation period. The regions of strongest declines in snowfall roughly correspond to the region of migration of the zero degree Celsius line and emphasize snowfall dependence on both altitude and latitude.” 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 GHG increases) projections showing 11 to 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 AR4 poorly simulate characteristics of the summer monsoon circulation, which is important to the LC Region (Lin et al. 2008); the IPCC AR4 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 (Max-Planck Institute [MPI] ECHAM5[23] and United Kingdom Meteorological Office [UKMO] Hadley Center for Climate Prediction and Research [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 LC Region will be dramatically amplified during La Niña conditions, which will be much more severe—warmer and drier—than during the historic period. Pierce et al. (2013) found that different methods of downscaling global climate model results, which is necessary due to the impact of topography on precipitation, have inconsistent effects on the summer monsoon precipitation in the LC Region. Projected changes in monsoon precipitation were linked to the particular downscaling method used, while winter precipitation change was more linked to the original global climate model used. Castro et al. (2012) note that dynamical downscaling of the North American monsoon region with WRF yielded only mixed and incremental increases in seasonal forecast

[23] The latest version of the Max Planck Institute for Meteorology climate model.

skill, re-emphasizing the difficulty that models have in capturing the North American monsoon process. Similarly, Cavazos and Arriaga-Ramirez (2012) found that statistically downscaling six global climate models over the Baja California-North American monsoon region yielded results that greatly underestimated precipitation variability on the interannual timescale.

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 U.S. 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 LC Region will exceed 1951–1999 levels from 2 to 5 times per decade between 2020–2039, depending on location in the LC 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 southwestern U.S. 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 (high) 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 NCAR Regional Climate Model Version 2.5 (RegCM2.5) 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.

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."

Temperature effects alone could cause significant impacts to hydrologic systems. Diffenbaugh and Ashfaq (2010) report on near-term GCM projections of future extreme temperature events in the U.S. and correlation to reduced soil moisture levels. Although the authors identified robust correlations between changes in temperature, precipitation, and soil moisture, the specific relationship between surface drying and intensified hot extremes is confounding since the predicted decreases in soil moisture could be a product of decreases in precipitation and/or increases in net surface radiation.

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, an effect already that is already observed (Min et al., 2011). Allan (2011) and Pall et al. (2011) both concur that there will be an increase in the frequency of intense rainfalls with warming. Dominguez et al. (2012) found that an ensemble of global climate models downscaled by regional models predict more extreme winter precipitation events, with daily events at the 20- and 50-year return periods increasing by 12 to 14%. 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 a more intense and extreme precipitation for the globe as a whole and over various regions. Watterson and Dix (2003) report a predicted worldwide average 14% increase in 30-year extreme daily precipitation for 2071–2100 compared to 1961–1990 based on simulations by the CSIRO Mark 2 GCM under A2 (high) and B2 (moderate) emissions scenarios. From a separate stochastic model study of the same GCM output, Watterson (2005) reports the interannual standard deviation of mean monthly precipitation increases with warming temperature. The 1961–1990 to 2071–2100 increases found were 9.0% for January and 11.5% for July. Min et al. (2011) proposed that some GCM simulations actually may underestimate the trend toward increased extreme precipitation events in the Northern Hemisphere, which suggests that extreme precipitation events may be stronger than projected. Chou and Lan (2012) note that the increase in precipitation extremes means that the annual range of precipitation will increase over much of the world. However, Dulière et al. (2011) caution the use of GCM simulations for local extreme precipitation projections since the resolution of these models is very coarse. For localized extreme precipitation events, it appears as though regional models retain the large-scale forcings and may preserve the mesoscale forcings and topographic interactions necessary to produce events at this finer scale. 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). Extreme runoff due to changes in the statistics of extreme events will present flood control challenges to varying degrees at many locations (e.g., Das et al., 2011).

A variety of factors are likely to affect future precipitation extremes, including changes in temperature, precipitation efficiency, and vertical velocity (O'Gorman and Schneider, 2009; Muller et al., 2011), and the ability of warmer atmospheric conditions to sustain a higher equilibrium pressure of water vapor.

Favre and Gershunov (2008), using a comparison of National Centers for Environmental Prediction (NCEP)-NCAR reanalysis data and Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (CERFACS) 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 LC 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), Christensen and Lettenmaier (2007), Miller et al. (2011), and Harding et al. (2012). Seager et al. (2012b) examined changes in seasonal and annual average precipitation, evaporation, and runoff for several Southwest river basins, using an ensemble of 16 CMIP5 models (RCP8.5 scenario). They focused on changes between the periods 2021–2040 and 1951–2000. For the Colorado River, they found 10% mean and median decreases in annual runoff, with agreement in the sign of change by more than 75% of the GCMs. They attribute the decrease to a projected increase in evaporation. They conclude as follows:

> "A reduction in Colorado River flow of 10% is comparable to the variability of decadal mean flows over the past century (for example, ref. 8 [Christensen and Lettenmaier, 2007] and Supplementary Information). Furthermore, a 1,200-year tree-ring reconstruction of Colorado River flow at Lee's Ferry (Meko et al. 2007) has the very lowest value of 20-year means (during the twelfth-century mega drought), about 15% lower than the long-term mean (see also ref. 28 [Woodhouse et al. 2010]). Hence, anthropogenic climate change is projected to lead to a potential reduction of Colorado River flow comparable to the most severe, but temporary, long-term decreases in flow recorded. These projected declines in surface-water availability for the coming two decades are probably of sufficient amplitude to place additional stress on regional water resources given the pressure of meeting agricultural demands as well as those of a growing population while needing to preserve riparian ecosystems."

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 (e.g., 6 to 45% by the middle of the 21st century), and Harding et al. (2012) emphasize the spread in projected runoff changes across the various climate models. The earlier studies were reviewed in Reclamation (2007), and the authors of that report offered some conclusions that put this projected runoff uncertainty into context. First, 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. In addition, 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; Harding et al. 2012).[24] 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.[25] 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 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 to 9% runoff reduction

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[24] 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.

[25] In addition to being complimented by appendix U, the Shortage Guidelines FEIS also was 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.

per degree Celsius increase in temperature—which implies a large range of runoff reductions, 4 to 18% by 2050. Based on their assessment of these and other factors, Hoerling et al. estimate 2050 Colorado River flow declines of 5 to 20%.

Miller et al. (2011) used a bias-corrected, statistically downscaled set of projected climate data to force the NWS River Forecasting System (RFS) hydrologic model that is utilized by the Colorado Basin River Forecasting Center (CBRFC) to derive projections of streamflow over the Green, Gunnison, and San Juan Rivers' headwater basins located within the Upper Colorado River Basin. The study evaluated the impact of changing climate to evapotranspiration rates and predicts how hydrologic processes change under varying climate conditions through 2099. The impact to evapotranspiration rates is taken into consideration and incorporated into developing streamflow projections over the Colorado River headwater basins. Results indicate decreased runoff in two of the three basins. A 6 to 13% average decrease in runoff is predicted over the Gunnison River Basin when compared to static evapotranspiration rates and a 10 to 15% average decrease in San Juan River Basin runoff. Over the Green River Basin, a 5 to 8% increase in basin runoff is projected through 2099. Also, the authors found evidence of nonstationary behavior over the Gunnison and San Juan River Basins. Ellis et al. (2008) used downscaled GCM temperature and precipitation changes as inputs to a water balance model for Arizona's Salt and Verde River Basins to assess runoff at mid-century; the Salt River is a tributary to the Colorado River. 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 multimodel ensemble mean runoff was 77.4% of 1961–1990 historical levels. Annually, the Salt-Verde system delivers >1.2 billion cubic meters (972,000 acre-feet) of water to downstream users.

It is important to recognize that these assessments of hydrologic impacts under climate change are sensitive to numerous uncertainties. Much attention has been given to the uncertainties introduced by climate projection selection, bias correction, and spatial downscaling. Some of these issues are explored for the Colorado River in Harding et al. (2012). Ashfaq et al. (2010) report on an evaluation of climate model bias effects and hydrologic impacts using a RegCM3 to drive a hydrological model (VIC) for the full contiguous U.S. In addition to showing the significance of climate model bias in predicting hydrologic responses, their results highlight the importance of daily temperature and precipitation extremes in predicting future hydrological effects of climate change. Recently, the uncertainties associated with the hydrologic analysis also have been garnering attention. Vano et al. (2012) applied multiple land-surface hydrologic models in the Colorado River Basin under multiple, common climate change scenarios. Their results showed that runoff response to these scenarios varied by model and stemmed from how the models feature a collective of plausible hydrologic process portrayals, where a certain combination of process portrayal choices led to a model's simulated runoff being more or less sensitive to climate change. Although these results are most applicable to the Colorado River Basin, it is still expected that application of the models in Vano et al. (2012) to other Western U.S. basins likewise would show model-dependent runoff sensitivity to climate change. Improving our understanding of these data and model uncertainties will help refine future estimates of climate change implications for hydrology.

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 U.S. 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 Final Environmental Impact Statement, Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead (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, four 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, 2009a; 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. Barnett and Pierce (2008) reported more severe potential operations impacts, but this study was later revised (Barnett and Pierce 2009a), modifying several original assessment assumptions (Barsugli et al. 2009; Barnett and Pierce 2009b) and leading to results more consistent with McCabe and Wolock (2007). Subsequently Rajagopalan et al. (2009) also predicted similar impacts to that of McCabe and Wolock (2007) and Barnett and Pierce (2009a). For these studies, the shortage risk on the whole system increases greatly in the 2020s and beyond. However, Barnett and Pierce (2009a) still note that the whole upper basin was in a deficit of 1 million acre-feet a year over the period 1997–2008, a value consistent with what would be expected from climate change according to several earlier studies, and that the 20th century average is "wet" compared to the longer-term flows in the basin revealed by tree rings. A reversion to the longer-term lower mean flow would exacerbate the effects of climate change on water availability in the Colorado River Basin.

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 IPCC AR4 and demonstrated increasing drought severity across the LC 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 the Ellis et al.(2008) 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 ground water 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 ground water drawdown, reduces the long-term sustainability of ground water resources (under some scenarios), and (4) adaptive policy with appropriate monitoring to track ground water 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 ground water surface flow model, maintaining ground water extraction at current rates and found that recharge will decrease 17 to 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 were 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

This section is organized under the following subheadings: Multiple Species/ Resources and Ecosystems; Fisheries and Aquatic Ecosystems; Individual Species/Resources; Agriculture; and Forest Fires. The literature covered includes both historical and projected future conditions.

2.3.3.1 Multiple Species/Resources and Ecosystems

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.[26] 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.

Parmesan (2006) provides a synthesis of recent studies pertaining to observed responses of wild biological species and systems to recent climate change. This author's literature search revealed 866 peer-reviewed papers that documented changes in species or systems that could be attributed at least in part to climate change. The synthesis focuses on advancing of spring events, variations in

[26] 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.

phenological responses between interacting species, species range shifts, range restricted species, pests and parasites, extinction, and evolutionary responses and genetic shifts.

Using meta-analysis, Chen et al. (2011) documented a change of elevation and latitude of terrestrial organisms as a result of climate variability. Using available studies of Europe, North America, Chile, Malasia, and the Marion Islands, range shifts were documented for 764 individual species responses for latitude adjustment and 1,367 species responses for elevation variability. The results of this analysis indicate that species have moved away from the equator at a median rate of 16.9 kilometers per decade. Additionally, species have moved to higher elevations at a median rate of 11.0 meters per decade.

The VEMAP[27] and other similar projects have increased our understanding of ecosystem dynamics under climate change; however, our understanding of the interactions between stresses on individual species at the ecosystem level is still relatively limited. Specific examples include the interaction between atmospheric CO_2 and soil water and nutrient limitations on plant productivity, carbon sequestration , and species composition ; the interactions between CO_2 and tropospheric O_3 on plant water-use efficiency; and the rates of plant species migration and ecosystem establishment under climate change (Aber et al. 2001). In general, vegetation models indicate that a moderate increase in future temperatures produces an increase in vegetation density and carbon sequestration across most of the U.S. with small changes in vegetation types, and large increases in future temperatures would cause losses of carbon with large shifts in vegetation types (Bachelet et al. 2001).

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 recently have occurred or are occurring in the U.S., and increased temperature and drought likely influenced these outbreaks. 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

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[27] Available online at: http://www.cgd.ucar.edu/vemap/.

cascading series of impacts such as decreased soil retention and increased aeolian and fluvial erosion. Williams et al. (2010) used a combination of tree-ring records, observed tree mortality and fire records, and projected climate changes from the NCAR CCSM model (A2 scenario) to establish linkages between aridity, increasing temperatures, decreased tree growth and tree morality due to drought, fire, and insect outbreaks. They estimate that the Southwest forest area could be reduced by greater than 50% with just a couple of more recurrences of drought and mortality similar to those in the 1984–2008 period. Especially vulnerable tree species are pinon pine (Pinus edulis), ponderosa pine (Pinus ponderosa), and Douglas fir (Pseudotsuga menziesii). Moreover, Williams et al. (2013) note that by the 2050s mean forest drought stress, which is influenced by vapor-pressure deficit (VPD; largely controlled by temperature), will exceed that of the most severe droughts in the past 1,000 years. They projected mid-21st century VPD using an ensemble of 10 CMIP3 models (A2 scenario) corroborated by an ensemble of NARCCAP dynamically downscaled models for 2042–2069. Bentz et al. (2010) report that "models suggest a movement of temperature suitability to higher latitudes and elevations and identify regions with a high potential for bark beetle outbreaks and associated tree mortality in the coming century." Moreover, Bentz et al. (2010) project increased population success for mountain pine beetle and spruce beetle, with high potential for beetle outbreaks and associated tree mortality across the LC Region during the 21st century. Their analyses were based on input of simulated climate from a single GCM (Canadian Regional Climate Model; A2 scenario) into beetle models.

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. 2007; Painter et al. 2010).

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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 to 75% (CCSP 2009). Robinson et al. (2008) describe and compare several ecological models that estimate vegetation development (productivity or vegetation type) under climate change.

Projected declines in winter precipitation in the LC Region likely will affect distribution and survivorship of antelope and other mammal populations. Research by Ault and others (2011) shows that the average timing of plant phenology events, such as bud formation and flowering, is occurring 1.5 days earlier per decade across western North America). They note that the major modes of atmospheric circulation only account for about one-third of the trend. 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). However Crimmins et al. (2011) found that flowering phenology along an elevational gradient in south-central Arizona shows a strong association with the amount and timing of July precipitation. 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 Community Climate System Model (CCSM3) and Geophysical Fluid Dynamics Laboratory Coupled Model Version 2.1 (GFDL CM2.1) in projections of bird species richness in California, and noted that, in the future, most of the portion of California in the LC 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.

Shaw et al. (2009) provides an assessment of the potential impacts of climate change on selected ecosystem services and their associated economic value in California. The GCM based assessment focuses on the social cost and the market value of carbon sequestration, the profits associated with the production of natural forage, and the consumer surplus of skiing and salmon fishing. Other ecosystem services that currently lack quantitative models and the impact of climate change on California's biodiversity are also discussed. The authors report that climate change will likely affect the abundance, production, distribution, and quality of ecosystem services throughout California. Specific impacts include water delivery to support human consumption and wildlife, climate stabilization through carbon sequestration, and the fish supply for commercial and recreational sport fishing.

2.3.3.2 Fisheries and Aquatic Ecosystems

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 U.S., including Western U.S. 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 U.S.

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). Marcarelli et al. (2010) estimated past and future hydrographs and patterns of ecosystem metabolism for a Western U.S. river and analyzed the impacts of climate change and water use. The reported combined hydrologic-related impacts, measured in terms of gross primary production and ecosystem respiration, are indicative of the potentially important role hydrologic regime plays in controlling ecosystem function.

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.

2.3.3.3 Individual Species/Resources

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 and 2011) 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.

Peery et al. (2012) found highly reduced 21st century spotted owl (Strix occidentalis) survival and reproductive output and high extinction risk, based on projections from four CMIP3 GCMs (CNRM-CM3, CSIROMk3.0, ECHam5, MIROC3.2), under three SRES scenarios (B1, A1B, A2). Warm, dry conditions were negatively associated with owl survival in Arizona. Southern California owl populations had low extinction risk, due to projected cold, wet springs.

Salzer et al. (2009) report "Great Basin bristlecone pine (Pinus longaeva) at 3 sites in western North America near the upper elevation limit of tree growth showed ring growth in the second half of the 20th century that was greater than during any other 50-year period in the last 3,700 years." The authors suggest the primary factor for this is increasing temperatures.

Cayan et al. (2001) document earlier blooming of lilacs and honeysuckles correlated to increasing spring temperatures.

Cole et al. (2010) project a substantially contracted range for Joshua tree (Yucca brevifolia), compared to its 20th-century range, due to projected rapidly increasing temperatures. They used five individual CMIP3 GCMs and an ensemble of 22 CMIP3 GCMs, all statistically downscaled, to project 21st century temperature and precipitation (Garfin et al. 2010). The future range of Joshua tree is projected to decline by 90% throughout the southern portions of its current range.

2.3.3.4 Agriculture

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). 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.

Lobell et al. (2011) present the findings of a global analysis of crop production impacts due to past climate change. The authors developed statistical models comparing 1980–2008 actual production levels for the four largest commodity crops (corn, wheat, soybeans, and rice) to theoretical levels without climate change. Their results indicate respective 3.8 and 5.5% decreases in worldwide corn and wheat production, and approximately no net change for soybeans and rice. Significant changes in U.S. production levels were not found, and this is attributed to relatively low increases in temperatures in our agricultural regions. The authors attribute the modeled impacts to changes in temperature rather than precipitation, and they acknowledge that their analysis does not account for adaptations by growers or the effect of elevated CO_2 on crop yields. Frisvold and Konyar (2012) examine how six states in the Colorado River region might be affected by a reduced water supply, and find that under their model assumptions, rationing incurs the financial largest losses, while allowing changes to crops and irrigation techniques reduced the losses. Losses were reduced further still when irrigators passed on the increased cost to buyers. Although agriculture in the region as a whole was resilient to the reduction in water supply, cotton and alfalfa were particularly vulnerable.

Nardone et al., 2010 discusses the effects of climate change on livestock following the “theory of global warming.” Topics include impaired production due to increased temperatures, desertification of rangelands, impacts to grain availability, and adaptability of animal genotypes.

Based on input of projected climate changes from a single climate model (GFDL, A2 scenario) to the Statewide Agricultural Production Model, for the time period centered on 2050, Medellin-Azuara et al. (2011) project agricultural economic losses for southern California. They find that projected changes in water supply are more likely than temperature increases to affect crop production. In southern California (Imperial Valley, Palo Verde, Coachella, San Diego, and Ventura), they project reduced acreage in corn, cotton, alfalfa, field crops, grain, and irrigated pasture and increases in orchard crops and tomatoes—both of which are expected to thrive in southern California due to higher tolerance for warm temperatures.

Tree crops, many of which have chilling hour requirements (e.g., pecans, almonds, apricots), and for which production requires large up-front capital investments, may require relocation in the projected warmer climate of southern California and southern Arizona (Frisvold et al. 2013).

Frisvold and Konyar (2011) found that, if less water was available for agriculture in Arizona, then reducing cotton and alfalfa crops would be an effective adaptation strategy. They also found that central Arizona would see the largest crop output reduction, due to junior water rights status; in contrast, western Arizona, with its senior water rights and emphasis on high-value crops would remain an important specialty crop production center.

2.3.3.5 Forest Fires and Wildfires

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 U.S., 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 in Westerling et al. (2006), which documents large increases in fire season duration and fire frequency, especially at mid-elevations, in the Western U.S. Coincident with trends toward warmer and drier climate in the Western U.S. 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. Using satellite imagery and aerial survey data, Williams et al. 2010 estimate that during 1997–2008 approximately 18% of southwestern forest area (excluding woodlands) experienced mortality due to bark beetles or wildfire. 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 U.S. 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 U.S. 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 LC 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. 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). Root (2012) cautions that increased wildfires can lead to unexpected results on some fire-adapted species, for example if fires become so frequent that juvenile plants do not have time to produce seeds.

Moritz et al. (2012) used projections from 16 different GCMs to formulate a comprehensive look at global fire patterns. Those projections focused on two timeframes: 2010–2039 and 2070–2099. The results indicated climate change will results in an increase in the frequency of wildfires in the Western U.S. in the next 30 years, and across the entire U.S. at the end of the century.

Litschert et al. (2012) estimate a doubling of mean burned area in the southern Rocky Mountains from 2010–2070, based on two GCMs and the B1 and A2 scenarios. Westerling et al. (2011) predict there will be 12 to 74% more fires in California by 2085 with LC Region increases at the low end of the range, based on 3 GCMs and the A2 scenario. Spracklen et al. (2009) project an increase in area burned of 43%, by 2050, for Arizona and New Mexico.

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

> "Global sea level rose at a rate of 1.7 millimeters/year during the 20th century. The rate has increased to over 3 millimeters/year in the past 20 years and scientific studies suggest high confidence (>9 in 10 chance) that global mean sea level will rise 0.2 to 2 meters by the end of this century" *(Burkett and Davidson* 2012).

The IPCC AR4 from Working Group I (chapter 10, "Sea Level Change in the 21st Century" [IPCC 2007]) provides projections of global average sea level rise that primarily represent thermal expansion associated with global air temperature projections from current 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 due to thermal expansion alone of approximately 3 to 10 cm (or 1 to 4 inches) by roughly 2035 relative to 1980–1999 conditions. These projections are based on CMIP3 models' simulation of ocean response to atmospheric warming under a collection of 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. National Research Council (2012) provides a comprehensive review of global sea level rise and how it will affect the west coast of the U.S. Ice loss processes ignored in IPCC 2007 are included in the NRC report, leading to approximately a doubling of the projected sea level rise (50 to 140 cm by 2100).

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). 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 to 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.

Bromirski et al. (2011) specifically studied the Pacific coast in regard to sea level rise. Their study notes that, from approximately 1930–1980, sea levels along the Pacific coast of North America rose at a rate equivalent to the global rate of change (2 millimeters per year [mm/yr]). In the last 100 years, sea level has risen along the Southwest coast by 6.7 to 7.9 inches, according to the National Research Council (NRC, 2012). Between 1980 and 2009, however, they report Pacific coast sea levels remained relatively constant according to tide gauge and satellite altimetry measurements. Contributing factors to this regional variance include a shift from cold to warm phase of the PDO that occurred in the mid-1970s, which was followed by a shift in wind stress patterns. The shift in wind stress patterns has likely suppressed the previously observed rising trend. In 2008, observations show that the mean annual wind stress curl dropped to levels equal to those observed before the 1970s shift. Assuming this wind stress curl drop persists for an extended period, a potential result is an associated rise in sea level at or exceeding the global rate of sea level rise along the Pacific coast (Bromirski et al. 2011).

Given the uncertainty in global sea level rise projections, and the aforementioned critique of the assumptions in the IPCC AR4 analysis, Parris et al. (2012) developed four plausible scenarios of sea level rise, which can be applied in conjunction with analyses of local conditions. They mention the following:

> "Based on a large body of science, we identify four scenarios of global mean SLR ranging from 0.2 meters (8 inches) to 2.0 meters (6.6 feet) by 2100. These scenarios provide a set of plausible trajectories of global mean SLR for use in assessing vulnerability, impacts, and adaptation strategies. None of these scenarios should be used in isolation, and experts and coastal managers should factor in locally and regionally specific information on climatic, physical, ecological, and biological processes and on the culture and economy of coastal communities."

Konikow (2011) discusses the relationship between sea level rise and ground water depletion and suggest a better understanding of this relationship is needed to better predict future rates of sea level rise. According to the author, the 1900–2008 global ground water depletion was approximately 4,500 cubic kilometers (3.6 million acre-feet) which would be equivalent to a 12.6 millimeter rise in sea level.

2.4 Upper Colorado Region

Numerous studies have been conducted on the potential consequences of climate change for water resources in Reclamation's UC Region. This section summarizes findings from recent studies (1994–2012) demonstrating evidence of regional climate change during the 20th century and exploring water and environmental resources impacts associated with various climate change scenarios.[28] A recent summary of historical and projected climate changes that includes the UC Region is given in the Southwest Climate Change Assessment (Overpeck et al. 2012), part of the U.S. National Climate Assessment.

2.4.1 Historical Climate and Hydrology

In the Upper Colorado River Basin, streamflow is mostly snow melt dominated at present. Temperature increases will likely change the timing of snowmelt and runoff. Reservoirs on upper tributaries to the Colorado River are more sensitive to timing or snowmelt as compared to the large reservoirs on the mainstem. The annual volume in the large reservoirs is most critical, with timing being a secondary concern.

Over the course of the 20th century, it appears that all areas of the UC Region became warmer, but annual precipitation trends are less evident. Cayan et al. (2001) report that Western U.S. spring temperatures increased 1 to 3 °C (1.8 to 5.4 °F) between 1970 and 1998. Based on data available from the Western Climate Mapping Initiative,[29] 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. Rangwala and Miller (2010) report trends in surface air temperature for the San Juan Mountains of the UC Region from 1895–2005. Results show a net warming of 1 °C between 1895–2005 with most warming during 1990–2005.

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[28] 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 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.

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

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 1999. These multi-decadal fluctuations in temperature are usually interpreted as the result of multi-decadal climate modes such as the PDO in addition to a long-term warming trend. 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 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. The UC Region in general lies between a region of projected drying to the south and a region of projected wetter conditions to the north (IPCC, 2007). 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 1916–2003 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 U.S. 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 PDO. 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 ensure 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) are performed adequately. This breakpoint or shift is further substantiated by Kalra and Ahmad, 2011.

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 paleodrought, is that drought and precipitation in the UC Region are 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 UC 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. Nowak et al. (2012) analyze decadal to multidecadal variability in Colorado River streamflow at Lees Ferry, and find ~64 year and ~15 year modes of variability. The former is associated with changes in runoff efficiency accomplished by changes in temperature, while the latter is associated with changes in moisture delivery to the region. Correlations suggest that the Atlantic multidecadal oscillation is associated with Upper Colorado River Basin temperature fluctuations.

Recent work by Ben Cook and colleagues (Cook et al. 2010) demonstrates that the Pacific Ocean is the primary driver of drought in the UC 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. (2008, 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.

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 GHG 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.

Matter et al. (2010) report on the application of a new methodology to characterize historical time series of UC Region temperature, precipitation, and streamflow. The method is based on complementary temperature and precipitation patterns, and the authors report statistically significant indictors of relative magnitude of upcoming precipitation and runoff that are evident in the fall.

Regarding the Rio Grande Basin, D'Antonio (2006) reports that, in northern New Mexico, 1995–2004 annual average temperatures have been more than 2 ºF (1.1 ºC) above 1961–1990 values. Rangwala and Miller (2010) report trends in surface air temperature for the San Juan Mountains of the UC Region from 1895–2005. Results show a net warming of 1 ^{o}C between 1895–2005 with most warming during 1990–2005.

Coincident with these trends, the Western U.S. and UC Region also experienced a general decline in spring snowpack, reduced fractions of winter precipitation occurring as snowfall, and earlier snowmelt runoff. Observations show that spring snow cover extent in North America has set record lows in 3 of the past 5 years (Derksen and Brown, 2012). Reduced snowpack and snowfall fractions are indicated by analyses of 1948–2001 SWE measurements at 173 Western U.S. stations (Knowles et al. 2007). Pierce et al. (2008) analyzed data from 548 snow courses in the Western U.S. over the period 1950–1999, and found a general decrease in the fraction of winter precipitation that is retained in the spring snowpack, including a significant decline in the Colorado Rockies. Pederson et al. (2011) also found reduced snowpack across the entire North American cordillera since the 1980s using tree-ring reconstructions. Brown and Mote (2009) performed a Northern Hemisphere snowpack sensitivity study and compared the results to observed conditions (1966–2007 NOAA satellite dataset) and snow cover simulations from the CMIP3. Annual snow cover duration was found to be the most sensitive variable and especially so in maritime climates with high snowfall, such as the Western U.S. coastal mountain areas. Both observed conditions and CMIP3 simulations support this finding with the largest decreases in historical annual snow cover duration occurring in the midlatitudinal coastal areas where seasonal mean air temperatures range from -5° to +5° C. The least sensitive areas were found to be in the interior regions with relatively cold and dry winters where precipitation plays a larger role in snow cover variability, in agreement with Bales et al. (2006). These elevation, latitude, and processes dependencies lend considerable local texture to the historical snowpack response in the UC Region (Harpold et al. 2012). Kapnick and Hall (2012) found that the sensitivity of the snowpack to temperature increases varies over the snow season, peaking in March through May, but is quite small in February.

Lundquist et al. (2009) find that in recent decades, the fraction of annual streamflow from late spring to summer runoff has declined 10 to 25%, and that snowmelt-driven runoff arrives 1 to 3 weeks earlier over the majority of the mountainous Western U.S. Stewart et al. (2005) examined the timing of runoff in a network of 302 western gauges and found that the center of mass of streamflow has shifted earlier by 1 to 4 weeks in many of the records. 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 U.S. 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

(8,125 feet) showed little change in peak streamflow or in monthly SWE (at least for March 1 and April 1, and May 1 does show a signal up to about 3,000 meters [9,750 feet]). 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.

Kapnick and Hall (2010) looked at the interannual variability in snowpack in an attempt to interpret the causes of recent snowpack trends in western North America. Of particular interest in this analysis is the impact of temperatures in the mid to late portion of the snow season (March through May). There is little impact in the early part of the snow season (February) when temperatures rarely rise above freezing. That is also the key part of the season when stations that exhibit an increase in April 1 SWE receive an increase in accumulation. Their final conclusion is that recent snowpack changes across western North America are due to regional-scale warming. This has implications for future warming regimes, and indicates a possible loss of late season snowpack and an earlier melt season.

Studies that document decreasing snowpack and earlier runoff in the Colorado River Basin include Harpold et al. (2012), Clow (2010), Hamlet et al. (2005), and Stewart et al. (2004). Harpold et al. (2012) found that the duration of snow cover decreased in 11 of 13 drainage regions, and snowmelt center of mass advanced 1 to 4 days per decade in 6 of 13 regions. There were significant trends toward a faster snowmelt center of mass and shorter duration of snow cover in the highest-elevation regions (>2800 m) of the Colorado River Basin, suggesting that winter T and P may not be the primary driver of change. Other findings include drier and warmer winters in the Colorado River and Rio Grande Basins. The changes in snowmelt timing also were variable, with a shorter snowmelt center of mass and less maximum SWE in the Colorado River and Rio Grande Basins. 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.

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 advances in satellite-based remote measurement of dust on snow hold promise in increasing the ability to understand the effects of this mechanism on snowpack in the Western U.S. (Painter et al. 2012b).

Villarini et al. (2009) analyzed annual peak discharge records from 50 stations in the U.S. with 100 years of record and attempted to document reduced stationarity. However, their results were not 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.”

Deser et al. (2010 and 2012) to urge climate scientists to make clear the important role of natural climate variability in future trends over North America when communicating the results of climate change projections with stakeholders and other decision makers. Among the implications of this work is that future scenarios developed from climate models are likely to reflect some mix of forced and internal variability, with the internal variability larger for precipitation than surface air temperature, over mid-latitude regions like western North America. Another implication is that natural variability is likely to remain important for future precipitation trends and variations for mid-latitude regions, like North America, for at least the next half century. Unfortunately, there is some evidence that the CMIP5 global climate models may underestimate decadal to multi-decadal precipitation variability in western North America, complicating projections of future precipitation changes and drought in this region (Ault et al. 2012).

Focusing on changes in precipitation extremes, the former CCSP issued SAP 3.3 (CCSP 2008), wherein chapter 3 focuses on mechanisms for observed changes in extremes 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 U.S., 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. Dominguez et al. (2012) found that an ensemble of global climate models downscaled by regional models predict more extreme precipitation events over most of the UC Region, with daily events at the 20- and 50-year return periods increasing by 12 to 14%.

A variety of factors are likely to affect future precipitation extremes, including changes in temperature, precipitation efficiency, and vertical velocity (O’Gorman and Schneider, 2009; Muller et al., 2011), and the ability of warmer atmospheric conditions to sustain a higher equilibrium pressure of water vapor. Some researchers have tried to draw connections between changes in precipitation extremes and atmospheric moisture holding capacity. The latter is a significant factor when considering climate change impacts to the overall hydrologic cycle because warmer air has greater capacity to hold moisture. Santer et al. (2007) report data from the satellite-based SSM/I show that the total atmospheric moisture content over oceans has increased by 0.41 kg/m^2 per decade between 1988 and 2005. The authors performed a detection and attribution analysis comparing output from 22 GCMs under multiple forcing scenarios to the observed SSM/I data. They report a statistically significant correlation between the observed pattern of increasing water vapor and that expected to be found from anthropogenic forcing of the climate. It is suggested these findings together with related work on continental-scale river runoff, zonal mean rainfall, and surface specific humidity indicate there is an emerging anthropogenic signal in both the moisture content of earth's atmosphere and in the cycling of moisture between atmosphere, land, and ocean. An anthropogenic signal consistent with an intensified hydrological cycle can already be identified in the ocean salinity field (Terray et al. 2012; Durack et al. 2012; Pierce et al. 2012a), supporting this view. In a follow-up study, Santer et al. (2009) performed a detection and attribution analysis to determine if the anthropogenic water vapor fingerprint is insensitive to current GCM uncertainties. The authors report the fingerprint is robust to current model uncertainties, dissimilar to the dominant noise patterns. They also report that the ability to identify an anthropogenic influence on observed multidecadal changes in water vapor is not affected by ‘‘model screening’’ based on model quality, a result also found for climate simulations focusing specifically on the Western U.S. (Pierce et al. 2009). However, Seager et al. (2012a) note that the global average tendency towards an intensified hydrological cycle may not be evident in all locations, depending on the particular changes in precipitation and evaporation in a region and how they might be affected by a teleconnected ENSO response. This is a important issue in the Colorado River Basin, which is significantly affected by ENSO variability.

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 U.S. 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 U.S., 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 streamflow center of timing for 1950–1999 co-vary. They concluded, with a high statistical significance, that 35 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 U.S., 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 U.S. and weak or absent at the scale of regional scale drainages with the exception of the Columbia River Basin (Hidalgo et al. 2009). Pierce and Cayan

(2012) systematically explored the effect of using ever-larger averaging areas on the statistical significance of trends in snow measures across the Western U.S., and confirmed that there is a tradeoff between how early a trend can be detected and how large the area to be averaged over is.

Fritze et al., 2011 investigated changes in western North American streamflow timing over the 1948–2008 period. Their results indicate that streamflow has continued to shift to earlier in the water year, most notably for those basins with the largest snowmelt runoff component. But an acceleration of these streamflow timing changes for the recent warm decades is not clearly indicated. Most coastal rain-dominated and some interior basins have experienced later timing.

While the trends in Western U.S. riverflow, winter air temperature, and snowpack might be partially explained by anthropogenic influences on climate, annually averaged precipitation trends arising from anthropogenic forcing are not necessarily well separated from zero in this region (e.g., Dettinger 2005). Worldwide, both observed mean (Zhang et al., 2007) and extreme (Min et al., 2011) precipitation trends show signs of the influence of human forcing of the climate, but climate models produce a notably weaker signal than is seen in the observations. 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 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. A recent caution on the use of the PDSI in such studies is that Sheffield et al. (2012) and Hoerling et al. (2012) find that the PDSI may be an inappropriate measure of drought that arises from climate change, due to an overly-simplistic dependence of potential evaporation on temperature. Looking to the future, even when substantial regional averaging is used, a significant signal of precipitation change does not emerge over the U.S. as a whole by 2100 (Mahlstein et al., 2012).

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 [Yin 2005; Salathé 2006; Seager et al. 2007]), atmospheric circulation over North America, and precipitation and temperature responses in the Western U.S. 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 U.S. (Cayan et al. 2001).

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 (e.g., Mote et al. 2005; Barnett et al. 2005). 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

In 2011, as part of its responsibilities under section 9503 of the SECURE Water Act,[30] Reclamation reported on climate change implications for water supplies and related water resources within eight major Western U.S. river basins, including UC Region's Colorado River and Rio Grande Basins. The report (Reclamation 2011) includes an original assessment of natural hydrology impacts under projected climate conditions, informed by the same downscaled climate projection summarized in appendix B (Reclamation 2011c).

Focusing on the broader Western U.S. region, Reclamation (2011b) reports that projections of future precipitation indicate that the northwestern and north-central portions of the U.S. may gradually become wetter while the southwestern and south-central portions gradually become drier, albeit with substantial fluctuations on interannual to decadal timescales due to natural variability (Deser et al. 2010 and 2012). It is noted that these summary statements reflect regionally averaged changes and that projected changes have geographic variation; they vary through time; and the progression of change through time varies among climate projection ensemble members. What this means is that, going forward in time, different regions are likely to continue to experience the kind of interannual to interdecadal variations in precipitation that they have experienced in the past. For the next few decades, these variations are likely to be superimposed upon background trends that in most cases are likely to be subtle compared with the variations.

These projected changes in climate have implications for hydrology. Warming trends contribute to a shift in cool season precipitation towards more rain and less snow (Knowles et al. 2007), which causes increased rainfall-runoff volume during the cool season accompanied by less snowpack accumulation. The shift of

[30] The Omnibus Public Lands Act (Public Law 111-11) Subtitle F – SECURE Water.

precipitation from snow to rain, which falls more quickly and so is carried a shorter distance by winds, could also exaggerate rain shadows in the mountainous west (Pavelsky et al., 2012). The warming may also reduce the incidence of surface hailstorms in Colorado as the melting level migrates to higher elevations (Mahoney et al. 2012). Projections of future hydrology (Reclamation 2011) suggest that warming and associated loss of snowpack will occur over much of the Western U.S. However, not all locations are projected to experience similar changes. Analyses suggest that losses to snowpack will be greatest where the baseline climate is closer to freezing thresholds (e.g., lower lying valley areas and lower altitude mountain ranges) (Bales et al. 2006). Analyses also suggest that, in high-altitude and high-latitude areas, cool-season snowpack actually could increase during the 21st century (e.g., Columbia headwaters in Canada, Colorado headwaters in Wyoming). A review of these processes, with application to the Colorado Rocky Mountains, is given in Rangwala and Miller (2012). Pierce and Cayan (2012) use 13 downscaled global climate models to quantify the influence of mechanisms that contribute to changes in end-of-century peak snowpack: increased precipitation, increased melting, and the conversion of precipitation from snow to rain. The Colorado Rockies have the smallest projected decrease in spring snowpack of the Western U.S. regions examined in their study, since greater melting and the conversion of snow to rain by 2100 is partially offset by increasing winter precipitation.

Projected changes in surface water runoff are more complex than projections of snowpack. Hydrologic projections introduced in Reclamation (2011b and 2011c) suggest that geographic trends may emerge. The Southwestern U.S. to the southern Rockies may experience gradual annual runoff declines during the 21st century. With respect to seasonal runoff, warming is projected to affect snowpack conditions both in terms of cool season accumulation and warm season melt. Without changes to overall precipitation quantity, these changes in snowpack dynamics would lead to increases in cool season rainfall-runoff and decreases in warm season snowmelt-runoff, leading to a season-varying sensitivity of runoff to warming (Das et al., 2011). The hydrologic projections indicate that the degree to which this expectation may occur varies by location in the Western U.S. For example, cool season runoff is projected to increase over the west coast basins from California to Washington and over the north-central U.S., but with little change to slight decreases over the Southwestern U.S. to southern Rockies. Warm season runoff is projected to experience substantial decreases over a region spanning southern Oregon, the Southwestern U.S., and southern Rockies. In summary, the hydrologic projections featured in Reclamation (2011b) suggest that projected precipitation increases in the northern tier of the Western U.S. could counteract warming-related decreases in warm season runoff, whereas projected decreases in precipitation in the southern tier of the Western U.S. could amplify warming-related decreases in warm season runoff.

Focusing on Reclamation (2011b) results representative of UC Region conditions, **tables 5 (section 2.3.2) and 6** summarize the projection median change from an ensemble of downscaled CMIP3 models run through VIC for various hydroclimate conditions in Colorado River and Rio Grande subbasins, respectively. Generally speaking, the ensemble-median changes of **tables 5 and 6** suggest that these subbasins will experience increasing mean-annual temperature and with precipitation change during the 21st century that varies from increases in more northerly subbasins to decreases in more southerly subbasins. These changes are projected to be accompanied by decreasing trend in spring SWE, decreasing trend in April–July runoff volume, and increasing trends in December–March and annual runoff volumes.[31]

While **table 6** summarizes the model ensemble's median change values, it is noted the models typically project a wide range of possible trends in precipitation for many midlatitude regions. The significance of this fact is that the uncertainty (or spread among ensemble members) is very large for precipitation projections for many parts of the U.S. over the next 10 to 60 years, at least (Deser et al. 2010 and 2012).

The projected climate change implications for water resources reported in Reclamation (2011b) are similar to those reported in prior assessments. A recent paper by the CBO (CBO 2009) presents an overview of the current understanding of the impacts of climate change in the U.S., including that warming will tend to be greater at high latitudes and in the interiors of the U.S. Global average warming values therefore tend to underestimate the warming the interior U.S. will experience (IPCC, 2007).

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. This change in precipitation intensity, in and of itself, can affect the snowpack (Kumar et al., 2012). A similar overview is included in the Interagency Climate Change Adaptation Task Force National Action Plan (CEQ 2011), with emphasis on freshwater resources impacts and discussions of strategies to address these impacts. Lundquist et al. (2009) report similar findings on hydrologic impacts.

[31] This study is complemented by the recently completed WaterSMART Colorado River Water Supply and Demand Study (http://www.usbr.gov/lc/region/programs/crbstudy.html). This study is informed by hydroclimate projections from Reclamation (2011b), along with other basis of future climate assumptions including paleoclimate proxies. .

Table 6.—Summary of Simulated Changes in Decadal Hydroclimate for several subbasins in the Rio Grande Basin from an ensemble of downscaled CMIP3 models run through VIC

Hydroclimate Metric (change from 1990s)	2020s	2050s	2070s
Rio Chama near Abiquiu			
Mean Annual Temperature (°F)	1.9	3.8	5.3
Mean Annual Precipitation (%)	-1.1	-2.3	-2.5
Mean April 1 SWE (%)[1]	-7.9	-18.4	-25.9
Mean Annual Runoff (%)	-0.2	-7.3	-11.0
Mean December–March Runoff (%)	4.8	5.5	8.6
Mean April–July Runoff (%)	-1.3	-13.9	-21.7
Mean Annual Maximum Week Runoff (%)	-4.3	-9.5	-14.9
Mean Annual Minimum Week Runoff (%)	-12.1	-19.2	-23.9
Rio Grande near Otowi			
Mean Annual Temperature (°F)	1.9	3.7	5.2
Mean Annual Precipitation (%)	-1.5	-2.5	-2.4
Mean April 1 SWE (%)[1]	-4.4	-10.2	-13.9
Mean Annual Runoff (%)	-4.4	-14.4	-19.9
Mean December–March Runoff (%)	-3.1	-10.4	-12.0
Mean April–July Runoff (%)	-2.5	-15.9	-21.8
Mean Annual Maximum Week Runoff (%)	-9.3	-20.3	-25.3
Mean Annual Minimum Week Runoff (%)	-11.7	-21.6	-26.3
Rio Grande at Elephant Butte Dam			
Mean Annual Temperature (°F)	1.9	3.7	5.1
Mean Annual Precipitation (%)	-0.9	-2.3	-1.9
Mean April 1 SWE (%)[1]	-4.4	-10.4	-14.3
Mean Annual Runoff (%)	-4.1	-13.5	-16.4
Mean December–March Runoff (%)	-3.6	-8.9	-10.9
Mean April–July Runoff (%)	-1.6	-15.4	-20.0
Mean Annual Maximum Week Runoff (%)	-6.1	-15.7	-18.8
Mean Annual Minimum Week Runoff (%)	-9.6	-18.2	-22.4

The reported percentage changes in mean April 1st SWE have been updated to correct a reporting error in Reclamation (2011b). The error stemmed from reporting this change as the mean change in cell-specific changes from all 1/8-degree grid-cells within the given basin. Such a change metric does not equal the change in total basin SWE integrated across all grid-cells within the basin, which was the intended reporting metric and is now indicated by the updated percentage changes.

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.[32] 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 2006). The UC Region lies between the subtropics, where 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 U.S.) 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). Power et al. (2012) have pointed out that the earlier CMIP3 generation of global climate models agree on the projected precipitation change in the UC Region in consistently projecting that the change is likely to be small, and the fact that the model projections are distributed around a mean of near zero should not be misinterpreted as a sign of disagreement in the projections. 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. Gutmann et al. (2012) examine statistical versus dynamical downscaling in the UC Region, and find that that a high resolution (2 km) simulation by the WRF weather model better match snow observations in Colorado than does a reconstruction using Parameter-Elevation Regression on Independent Slopes Model (PRISM) statistical techniques. Although more work remains to be done, they believe this may be due to the WRF model's inclusion of key dynamical processes that influence precipitation and snow over topography. Similar results for the central Rockies are found by Silverman et al. (2012).

Much summer precipitation in the UC Region is associated with the North American monsoon, which is poorly simulated in most climate models (Lin et al. 2008; Gutzler et al. 2005). Pierce et al. (2013) found that different methods of downscaling global climate model results, which is necessary due to the impact of topography on precipitation, have inconsistent effects on the summer monsoon precipitation. Projected changes in monsoon precipitation were linked to the

[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.

particular downscaling method used, while winter precipitation change was more linked to the original global climate model used. Castro et al. (2012) note that dynamical downscaling the North American monsoon region with WRF yielded only mixed and incremental increases in seasonal forecast skill, re-emphasizing the difficulty that models have in capturing the North American monsoon process. Similarly, Cavazos and Arriaga-Ramirez (2012) found that statistically downscaling six global climate models over the Baja California-North American monsoon region yielded results that greatly underestimated precipitation variability on the interannual timescale.

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."

Other notable studies on future climate projections over the 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 U.S. 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.

Sheppard et al. (2002), who examined moisture variations in the Southwest (a region that encompasses part of the UC 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 Colorado River Basin (e.g., Cook et al. 2004; Hughes and Diaz 2008; MacDonald et al. 2008 and Woodhouse et al. 2010). Paleoclimate studies pertaining more to the UC Region of the Colorado River Basin include Woodhouse et al. 2006, Meko et al. 2007, Gangopadhyay et al. 2009, and Gangopadhyay and McCabe 2010. 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. A recent caution on the use of the PDSI in such studies is that Sheffield et al. (2012) and Hoerling et al. (2012) find that the PDSI may be an inappropriate measure of drought that arises from climate change, due to an overly-simplistic dependence of potential evaporation on temperature.

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.

Temperature effects alone could cause significant impacts to hydrologic systems. Diffenbaugh and Ashfaq (2010) report on near-term GCM projections of future extreme temperature events in the U.S. and correlation to reduced soil moisture levels. Although the authors identified robust correlations between changes in temperature, precipitation, and soil moisture, the specific relationship between surface drying and intensified hot extremes is confounding since the predicted decreases in soil moisture could be a product of decreases in precipitation and/or increases in net surface radiation.

Switching the 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, an effect already that is already observed (Min et al., 2011). Allan (2011) and Pall et al. (2011) both concur that there will be an increase in the frequency of intense rainfalls with warming. Dominguez et al. (2012) found that an ensemble of global climate models downscaled by regional models predict more extreme winter precipitation events, with daily events at the 20- and 50-year return periods increasing by 12 to 14%. 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. Watterson and Dix (2003) report a predicted worldwide average of a 14% increase in 30-year extreme daily precipitation for 2071–2100 compared to 1961–1990 based on simulations by the CSIRO Mark 2 GCM under A2 (high) and B2 (moderate) emissions scenarios. From a separate stochastic model study of the same GCM output, Watterson (2005) reports the interannual standard deviation of mean monthly precipitation increases with warming temperature. The 1961–1990 to 2071–2100 increases found were 9.0% for January and 11.5% for July. Min et al. (2011) proposed that some GCM simulations may actually underestimate the trend towards increased extreme precipitation events in the Northern Hemisphere, which suggests that extreme precipitation events may be stronger than projected. Chou and Lan (2012) note that the increase in precipitation extremes means that the annual range of precipitation will increase over much of the world. However, Dulière et al. (2011) caution the use of GCM simulations for local extreme precipitation projections as the resolution of these models is very coarse. For localized extreme precipitation events, it appears as though regional models retain the large-scale forcings and may preserve the mesoscale forcings and topographic interactions necessary to produce events at this finer scale. Extreme runoff due to changes in the statistics of extreme events will present flood control challenges to varying degrees at many locations (e.g., Das et al., 2011).

A variety of factors are likely to affect future precipitation extremes, including changes in temperature, precipitation efficiency, and vertical velocity (O'Gorman and Schneider, 2009; Muller et al., 2011), and the ability of warmer atmospheric conditions to sustain a higher equilibrium pressure of water vapor.

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), Christensen and Lettenmaier (2007), Miller et al. (2011), and Harding et al. (2012). 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 (e.g., 6 to 45% reductions in natural flow at Lees Ferry), and Harding et al. (2012) emphasize the spread in projected runoff changes across the various climate models. The earlier studies were reviewed in Reclamation (2007), and the authors of that report offered some conclusions that put this projected runoff uncertainty into context. First, 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 the 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; Harding et al. 2012). 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% runoff reduction overstates potential Colorado River losses. Using different 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 to 9% runoff reduction per degree Celsius increase in temperature—which implies a large range of runoff reductions, 4 to 18% by 2050. Based on their assessment of these and other factors, Hoerling et al. estimate 2050 Colorado River flow declines of 5 to 20%. Vano et al. (2012) evaluated five hydrology models with regard temperature sensitivity as well as changes related to precipitation (elasticity). The authors found that the annual elasticity of modeled runoff (fractional change in annual runoff divided by fractional change in annual precipitation) at Lees Ferry ranged from two to six for the different models. Annual temperature sensitivities (percent change in annual runoff per degree change in annual temperature) ranged from declines of 2% to as much as 9% per degree Celsius increase at Lees Ferry.

Miller et al. (2011) used a bias-corrected, statistically downscaled set of projected climate data to force the NWS RFS hydrologic model that is utilized by the CBRFC to derive projections of streamflow over the Green, Gunnison, and San Juan Rivers' headwater basins located within the Colorado River Basin. The study evaluated the impact of changing climate to evapotranspiration rates and predicts how hydrologic processes change under varying climate conditions through 2099. The impact to evapotranspiration rates is taken into consideration and incorporated into the development of streamflow projections over the Colorado River headwater basins. Results indicate decreased runoff in two of the three basins. A 6 to 13% average decrease in runoff is predicted over the Gunnison River Basin when compared to static evapotranspiration rates and a 10 to 15% average decrease in San Juan River Basin runoff. Over the Green River Basin, a 5 to 8% increase in basin runoff is projected through 2099. Also, the authors found evidence of nonstationary behavior over the Gunnison and San Juan River Basins.

While many studies report on the mean trends of GCM projections, Harding et al. (2012) discusses the variability of streamflow in the Upper Colorado River Basin that was estimated using a multi-model ensemble approach wherein the downscaled outputs of 112 future climate projections from 16 global climate models (GCMs) were used to drive a macroscale hydrology model. Mostly as a function of precipitation projections, the results show a wide range in predicted changes in Colorado River flow ranging from approximately plus to minus 30% change by mid-century.

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

It is important to recognize that these assessments of hydrologic impacts under climate change are sensitive to numerous uncertainties. Much attention has been given to the uncertainties introduced by climate projection selection, bias correction and spatial downscaling. Some of these issues are explored for the Colorado River in Harding et al. (2012). Ashfaq et al. (2010) report on an evaluation of climate model bias effects and hydrologic impacts using a RegCM3 to drive a hydrological model (VIC) for the full contiguous U.S. In addition to showing the significance of climate model bias in predicting hydrologic responses, their results highlight the importance of daily temperature and precipitation extremes in predicting future hydrological effects of climate change. Recently, the uncertainties associated with the hydrologic analysis have also been garnering attention. Vano et al. (2012) applied multiple land-surface hydrologic models in the Colorado River Basin under multiple, common climate change scenarios. Their results showed that runoff response to these scenarios varied by model and stemmed from how the models feature a collective of plausible hydrologic process portrayals, where a certain combination of process portrayal choices led to a model's simulated runoff being more or less sensitive to climate change. Although these results are most applicable to the Colorado River Basin, it is still expected that application of the models in Vano et al. (2012) to other

Western U.S. basins would likewise show model-dependent runoff sensitivity to climate change. Improving our understanding of these data and model uncertainties will help refine future estimates of climate change implications for hydrology.

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 U.S. 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, four 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, 2009a; 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. Barnett and Pierce (2008) reported more severe potential operations impacts, but this study was later revised (Barnett and Pierce 2009a), modifying several original assessment assumptions (Barsugli et al. 2009; Barnett and Pierce 2009b) and leading to results more consistent with McCabe and Wolock (2007). Subsequently, Rajagopalan et al. (2009) also predicted similar impacts as to McCabe and Wolock (2007) and Barnett and Pierce (2009a). For these studies, the risk of shortage on the whole system increases greatly in the 2020s and beyond. However, Barnett and Pierce (2009a) still note that the whole upper basin was in a deficit of 1 million acre-feet a year over the period 1997–2008, a value consistent with what would be expected from climate change according to several earlier studies, and that the 20th century average is “wet” compared to the longer-term flows in the basin revealed by tree rings. A reversion to the longer-term lower mean flow would exacerbate the effects of climate change on water availability in the Colorado River Basin.

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

This section is organized under the following subheadings: Multiple Species/Resources and Ecosystems; Fisheries and Aquatic Ecosystems; Individual Species/Resources; Agriculture; and Forest Fires. The literature covered includes both historical and projected future conditions.

2.4.3.1 Multiple Species/Resources and Ecosystems

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.

Parmesan (2006) provides a synthesis of recent studies pertaining to observed responses of wild biological species and systems to recent climate change. This author's literature search revealed 866 peer-reviewed papers that documented changes in species or systems that could be attributed at least in part to climate

[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.

change. The synthesis focuses on advancing of spring events, variations in phenological responses between interacting species, species range shifts, range restricted species, pests and parasites, extinction, and evolutionary responses and genetic shifts.

Using meta-analysis, Chen, et.al. (2011) documented a change of elevation and latitude of terrestrial organisms as a result of climate variability. Using available studies of Europe, North America, Chile, Malasia, and the Marion Islands, range shifts were documented for 764 individual species responses for latitude adjustment and 1,367 species responses for elevation variability. The results of this analysis indicate that species have moved away from the equator at a median rate of 16.9 kilometers per decade. Additionally, species have moved to higher elevations at a median rate of 11.0 meters per decade.

Research by Ault and others (2011) shows that the average timing of plant phenology events, such as bud formation and flowering, is occurring 1.5 days earlier per decade across western North America. They note that the major modes of atmospheric circulation only account for about one-third of the trend.

The VEMAP[34] and other similar projects have increased our understanding of ecosystem dynamics under climate change; however, our understanding of the interactions between stresses on individual species at the ecosystem level is still relatively limited. Specific examples include the interaction between atmospheric CO_2 and soil water and nutrient limitations on plant productivity, carbon sequestration , and species composition; the interactions between CO_2 and tropospheric O_3 on plant water-use efficiency; and the rates of plant species migration and ecosystem establishment under climate change (Aber et al. 2001). In general, vegetation models indicate that a moderate increase in future temperatures produce an increase in vegetation density and carbon sequestration across most of the U.S. with small changes in vegetation types and large increases in future temperatures that would cause losses of carbon with large shifts in vegetation types (Bachelet et al. 2001).

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 U.S., and increased temperature and drought likely influenced these outbreaks. Climate change has affected forest insect species range and abundance through changes in insect survival rates, increases in life cycle

[34] Available online at: http://www.cgd.ucar.edu/vemap/.

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. Bentz et al. (2010) report that “models suggest a movement of temperature suitability to higher latitudes and elevations and identify regions with a high potential for bark beetle outbreaks and associated tree mortality in the coming century.” Although recent studies on mountain pine beetle infestations in the central Rockies show less than expected water resources impacts, the associated physical processes are not well understood; and it’s expected that the picture will change as new research and monitoring is conducted (Lukas and Gordon, 2010).

Hurd and Coonrod (2007) report that the greatest climate change-related risk in New Mexico is to ecosystems. They report that reduced snowpack, 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.

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).

Robinson et al. (2008) describe and compare several ecological models that estimate vegetation development (productivity or vegetation type) under climate change.

2.4.3.2 Fisheries and Aquatic Ecosystems

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 U.S., including Western U.S. 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 U.S.

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). Marcarelli et al. (2010) estimated past and future hydrographs and patterns of ecosystem metabolism for a Western U.S. river and analyzed the impacts of climate change and water use. The reported combined hydrologic related impacts, measured in terms of gross primary production and ecosystem respiration, are indicative of the potentially important role hydrologic regime plays in controlling ecosystem function.

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.

2.4.3.3 Individual Species/Resources

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 and 2011) report study findings associated with potential climate change impacts to the American pika that include results of testing alternative models of climate-mediated extirpations.

Salzer et al. (2009) report "Great Basin bristlecone pine (Pinus longaeva) at 3 sites in western North America near the upper elevation limit of tree growth showed ring growth in the second half of the 20th century that was greater than during any other 50-year period in the last 3,700 years." The authors suggest the primary factor for this is increasing temperatures.

Cayan et al. (2001) document earlier blooming of lilacs and honeysuckles correlated to increasing spring temperatures.

2.4.3.4 Agriculture

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.

Lobell et al. (2011) present the findings of a global analysis of crop production impacts due to past climate change. The authors developed statistical models comparing 1980–2008 actual production levels for the four largest commodity crops (corn, wheat, soybeans, and rice) to theoretical levels without climate change. Their results indicate respective 3.8 and 5.5% decreases in worldwide corn and wheat production, and approximately no net change for soybeans and rice. Significant changes in U.S. production levels were not found, and this is attributed to relatively low increases in temperatures in our agricultural regions. The authors attribute the modeled impacts to changes in temperature rather than precipitation, and they acknowledge their analysis does not account for adaptations by growers or the effect of elevated CO_2 on crop yields. Frisvold and Konyar (2012) examine how six states in the Colorado River region might be affected by a reduced water supply, and find that under their model assumptions, rationing incurs the largest financial losses, while allowing changes to crops and irrigation techniques reduced the losses. Losses were reduced further still when irrigators passed on the increased cost to buyers. Although agriculture in the region as a whole was resilient to the reduction in water supply, cotton and alfalfa were particularly vulnerable.

Nardone et al., 2010 discusses the effects of climate change on livestock following the “theory of global warming.” Topics include impaired production due to increased temperatures, desertification of rangelands, impacts to grain availability, and adaptability of animal genotypes.

2.4.3.5 Forest Fires and Wildfires

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 U.S., 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 in Westerling et al. (2006), which document large increases in fire season duration and fire frequency, especially at mid-elevations, in the Western U.S. Coincident with trends toward warmer and drier climate in the Western U.S. 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. Using satellite imagery and aerial survey data, Williams et al. 2010 estimate that during 1997–2008 approximately 18% of southwestern forest area (excluding woodlands) experienced mortality due to bark beetles or wildfire. 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 U.S. 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 U.S. with the exception of the Pacific Northwest and with the greatest increase in the northern Rockies, Great Basin, and the Southwest. Westerling et al. (2011a) find that the projected increase in wildfires could substantially change the flora and fauna of the greater Yellowstone region by mid-century. 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 pinyon-juniper and spruce-fir forest ecosystems resulting from climate change. Root (2012) cautions that increased wildfires can lead to unexpected results on some fire-adapted species, for example if fires become so frequent that juvenile plants do not have time to produce seeds.

Moritz et al. (2012) used projections from 16 different GCMs to formulate a comprehensive look at global fire patterns. Those projections focused on two timeframes: 2010–2039 and 2070–2099. The results indicated climate change will results in an increase in the frequency of wildfires in the Western U.S. in the next 30 years, and across the entire U.S. at the end of the century.

Litschert et al. (2012) estimate a doubling of mean burned area in the southern Rocky Mountains from 2010–2070, based on two GCMs and the B1 and A2 scenarios. Spracklen et al. (2009) project an increase in area burned of 43%, by 2050, for Arizona and New Mexico.

2.5 Great Plains Region

Numerous studies have been conducted on the potential consequences of climate change for water resources in Reclamation's GP Region. This section summarizes findings from recent studies (1994–2012) demonstrating evidence of regional climate change during the 20th and early 21st centuries and exploring water and environmental resources impacts associated with various climate change scenarios.[35]

2.5.1 Historical Climate and Hydrology

It appears that all areas of the GP Region became warmer since the beginning of the 20th century, and some areas received more winter precipitation during the 20th century. Cayan et al. (2001) report that Western U.S. spring temperatures increased 1 to 3 °C (1.8 to 5.4 °F) between the 1970s and late 1990s. Based on data from the USHCN, temperatures increased 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.[36] 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 southern Great Plains. Regonda et al. (2005) report increased winter precipitation trends during 1950–1999 at many Western U.S. sites, including numerous sites in the western GP Region, but a consistent GP Region-wide trend is not apparent. NOAA Technical Report NESDIS 142-4, "Regional Climate Trends and Scenarios for the U.S. National Climate Assessment: Part 4. Climate of the Great Plains" (Kunkel et al. 2012) was produced in support of the third National Climate Assessment (NCA). This report used historical COOP data to describe long-term trends of temperature and precipitation for areas within the GP Region. Temperatures in the northern GP Region generally have risen faster than other

[35] 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 U.S. and/or areas of the GP Region west of the 100th meridian.

[36] Trend calculations described in the U.S. Environmental Protection Agency's 2009 U.S. and Global Mean Temperature and Precipitation. 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.

areas within the GP Region. In fact, North Dakota's increase of 0.26°F per decade over the last 130 years is the greatest such rise for any state. All but 3 of the 20 years previous to 2012 were above the 1901–1960 average. Based upon the gridded climate division version of the COOP data (NCDC CDDv2), the greatest statistically significant seasonal increase in temperature since the beginning point of that dataset in 1895 has occurred during winter in the northern Great Plains (+0.33°F winter, +0.20°F summer and +0.20°F annual). Increases over the same period for the southern Great Plains are generally less (+0.14°F winter and +0.09°F annual), with no statistically significant increases discovered in the summer and fall seasons. The NCDC CDDv2 precipitation dataset indicates greater variability in the southern Great Plains versus the northern Great Plains for the 1895–2011 period. None of those trends were statistically significant, however. 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). Pierce et al. (2008) analyzed data from 548 snow courses in the Western U.S. over the period 1950–1999, and found a general decrease in the fraction of winter precipitation that is retained in the spring snowpack. Reduced snowpack and snowfall ratios are indicated by analyses of 1948–2001 SWE measurements at 173 Western U.S. stations (Knowles et al. 2007). Pederson et al. (2011) also found reduced snowpack across the entire North American cordillera between the 1980s and late 1990s/early2000s using tree-ring reconstructions. Schlaepfer et al. (2012) demonstrated the importance of precipitation seasonality over the form of precipitation for ecosystem water balance. Brown and Mote (2009) performed a Northern Hemisphere snowpack sensitivity study and compared the results to observed conditions (1966–2007 NOAA satellite dataset) and snow cover simulations from the CMIP3. Annual snow cover duration was found to be the most sensitive variable and especially so in maritime climates with high snowfall, such as the Western U.S. coastal mountain areas. Both observed conditions and CMIP3 simulations support this finding with the largest decreases in historical annual snow cover duration occurring in the midlatitudinal coastal areas where seasonal mean air temperatures range from -5° to +5° C. The least sensitive areas were found to be in the interior regions with relatively cold and dry winters where precipitation plays a larger role in snow cover variability. Observations show that spring snow cover extent in North America has set record lows in 3 of the past 5 years (Derksen and Brown, 2012). Kapnick and Hall (2012) found that the sensitivity of the snowpack to temperature increases varies over the snow season, peaking in March through May, but is quite small in February.

Lundquist et al. (2009) find that in recent decades, the fraction of annual streamflow from late spring to summer runoff has declined 10 to 25%, and that snowmelt-driven runoff arrives 1 to 3 weeks earlier over the majority of the mountainous Western U.S. Stewart et al. (2005) examined the timing of runoff in a network of 302 western gauges and found that the center of mass of streamflow has shifted earlier by 1 to 4 weeks in many of the records. 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 U.S. 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 to 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.

Kapnick and Hall (2012) looked at the interannual variability in snowpack in an attempt to interpret the causes of recent snowpack trends in western North America, including the northwest GP Region. Of particular interest in this analysis is the impact of temperatures in the mid to late portion of the snow season (March through May). There is little impact in the early part of the snow season (February) when temperatures rarely rise above freezing. That is also the key part of the season when stations that exhibit an increase in April 1 SWE receive an increase in accumulation. Their final conclusion is that recent snowpack changes across western North America and the northwest GP Region are due to regional-scale warming. This has implications for future warming regimes, and indicates a possible loss of late season snowpack and an earlier melt season.

Kunkel et al. (2009) studied snowfall seasons across the conterminous U.S. from 1900–1901 to 2006–2007. They found no seasons with statistically significant trends in high-extreme (90^{th} percentile) snowfall years, either for the U.S. as a whole or regionally. They did find statistically significant trends in low-extreme (10^{th} percentile) seasonal snowfall for the north-central region, including Montana, Nebraska, North Dakota, South Dakota, and Wyoming. Since the 1950–1951 snow season, significant increases in low-extreme snowfall years occurred in the southern region, which includes Kansas, Oklahoma, and Texas. November-March temperatures were highly significantly correlated with the annual percentages, negatively with the low-extreme snow seasons.

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. Painter et al. (2012a) concluded that high dust concentration can advance the melt-out date by up to 51 days. 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.

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.

Villarini et al. (2009) analyzed annual peak discharge records from 50 stations in the U.S. with 100 years of record and attempted to document reduced stationarity. However, their results were not 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.”

Irrigation from the Ogallala Aquifer has possibly impacted rainfall patterns across the GP Region according to Harding and Snyder (2012a). They used a forecast model to simulate the effects of irrigation on nine April-October periods. The periods were broken down into groups of three from pluvial (wet), drought and normal simulations. During normal and wet periods, significant precipitation increases were found. During drought periods, significant decreases resulted. Based on those results, they demonstrated a point where irrigation decreases or suppresses convection during drought periods, but enhance convection during normal or pluvial periods. In a companion study (Harding and Snyder, 2012b), they determined that water losses from evapotranspiration overwhelm any precipitation increases due to irrigation. Therefore, irrigation promotes net water loss over the GP Region.

Deser et al. (2010 and 2012) to urge climate scientists to make clear the important role of natural climate variability in future trends over North America when communicating the results of climate change projections with stakeholders and other decision makers. Among the implications of this work is that future scenarios developed from climate models are likely to reflect some mix of forced and internal variability, with the internal variability larger for precipitation than surface air temperature, over mid-latitude regions like western North America. Another implication is that natural variability is likely to remain important for future precipitation trends and variations for mid-latitude regions, like North America, for at least the next half century. Unfortunately, there is some evidence that the CMIP5 global climate models may underestimate decadal to multi-decadal precipitation variability in western North America, complicating projections of future precipitation changes and drought in this region (Ault et al. 2012).

Focusing on changes in precipitation extremes, the former CCSP issued SAP 3.3 (CCSP 2008), wherein chapter 3 focuses on mechanisms for observed changes in extremes and reports heavy precipitation events averaged over North America have increased over the past 50 years (Gutowski et al. 2008). A variety of factors are likely to affect future precipitation extremes, including changes in temperature, precipitation efficiency, and vertical velocity (O'Gorman and Schneider, 2009; Muller et al., 2011), and the ability of warmer atmospheric conditions to sustain a higher equilibrium pressure of water vapor.

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 U.S., 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). A more recent evaluation of increasing precipitation intensities is presented in Groisman et al., 2012.

Other research has suggested that warming-induced increases in thunderstorm activity of the GP Region (and most of the contiguous U.S.) (Changnon 2001) led to an increase in heavy precipitation events between 1900 and 2002 (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. The western GP Region is highly reliant upon the Ogallala aquifer, which has seen significant declines since it has been pumped for agricultural uses beginning in the 1940s. Kutsu et al. (2010) identified widespread negative streamflow trends across the High Plains over the Ogallala aquifer. The streamflow depletions occur despite the recent precipitation increases in the GP Region (Garbrecht et al., 2004). Therefore, their results link the streamflow depletions much more strongly to changes in ground water levels and not changes in precipitation. Some researchers have tried to draw connections between changes in precipitation extremes and atmospheric moisture holding capacity. The latter is a significant factor when considering climate change impacts to the overall hydrologic cycle because warmer air has greater capacity to hold moisture. Santer et al. (2007) report data from the SSM/I show that the total atmospheric moisture content over oceans has increased by 0.41 kg/m^2 per decade between 1988 and 2005. The authors performed a detection and attribution analysis comparing output from 22 GCMs under multiple forcing scenarios to the observed SSM/I data. They report a statistically significant correlation between the observed pattern of increasing water vapor and that expected to be found from anthropogenic forcing of the climate. It is suggested that these findings, together with related work on continental-scale river runoff, zonal mean rainfall, and surface specific humidity, indicate there is an emerging anthropogenic signal in both the moisture content of earth's atmosphere and in the cycling of moisture between atmosphere, land, and ocean. An anthropogenic signal consistent with an intensified hydrological cycle can already be identified in the ocean salinity field (Terray et al. 2012; Durack et al. 2012; Pierce et al. 2012a), supporting this view. In a follow-up study, Santer et al. (2009) performed a detection and attribution analysis to determine if the anthropogenic water vapor fingerprint is insensitive to current GCM uncertainties. The authors report that the fingerprint is robust to current model uncertainties, dissimilar to the dominant noise patterns. They also report that the ability to identify an anthropogenic influence on observed multidecadal changes in water vapor is not affected by ‘‘model screening’’ based on model quality, a result also found for climate simulations focusing specifically on the Western U.S. (Pierce et al. 2009). However, Seager et al. (2012a) note that the global average tendency towards an intensified hydrological cycle may not be evident in all locations, depending on the particular changes in precipitation and evaporation in a region and how they might be affected by a teleconnected ENSO response.

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 U.S. 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 U.S., 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 U.S., 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 U.S. and weak or absent at the scale of regional scale drainages with the exception of the Columbia River Basin (Hidalgo et al. 2009). Pierce and Cayan (2012) systematically explored the effect of using ever-larger averaging areas on the statistical significance of trends in snow measures across the Western U.S., and confirmed that there is a tradeoff between how early a trend can be detected and how large the area to be averaged over is.

While the trends in Western U.S. riverflow, winter air temperature, and snowpack might be partially explained by anthropogenic influences on climate, and worldwide trends in observed mean (Zhang et al. 2007) and extreme (Min et al. 2011) precipitation trends show signs of the influence of human forcing of the climate, climate models produce a notably weaker precipitation change signal than is seen in the observations. 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. A recent caution on the use of the PDSI in such studies is that Sheffield et al. (2012) and Hoerling et al. (2012) (who examined the GP Region specifically) find that the PDSI may be an inappropriate measure of drought that arises from climate change, due to an overly-simplistic dependence of potential evaporation on temperature. Looking to the future, even when substantial regional averaging is used, a significant signal of precipitation change does not emerge over the U.S. as a whole by 2100 (Mahlstein et al., 2012).

Kunkel et al. (2007) urged caution in interpreting temporal variations in SWE studies using data from the COOP network due to inhomogeneities in observational practices. There was less concern for studies in the Western U.S. 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 1920–1921 to 2006–2007 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.

Fritze et al., 2011 investigated changes in western North American streamflow timing over the 1948–2008 period. Their results indicate that streamflow has continued to shift to earlier in the water year, most notably for those basins with the largest snowmelt runoff component. But an acceleration of these streamflow timing changes for the recent warm decades is not clearly indicated. Most coastal rain-dominated and some interior basins have experienced later timing.

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 [Yin 2005; Salathé 2006; Seager et al. 2007]), atmospheric circulation over North America, and precipitation and temperature responses in the Western U.S. They found that, during the transition to spring, following a Northern Annular Mode (also called Arctic Oscillation (AO)) 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 U.S. (Cayan et al., 2001).

There is growing evidence of a linkage between the warming of the globe, arctic sea ice decline and extreme winters across the eastern two-thirds of the U.S., including the GP Region. Cohen et al. (2007) found a dynamical linkage and predictability between Eurasian snowcover and strongly negative AO regimes. Follow-up studies (Cohen et al. 2010, Cohen et al. 2012, Liu et al. 2012) described a connection between recent cold, snowy winters in North America (including the GP Region) and extensive fall Eurasian snowcover and the resulting negative AO. Further, they argued this type of scenario is consistent with a warming planet. Warming of the atmosphere allows it to hold more moisture which can lead to more autumn snowfall, leading to the afore-mentioned negative AO. Further, the reduction in Arctic sea ice has led to more atmospheric water vapor content available being available for winter storms across areas of the Northern Hemisphere, including the eastern GP Region (Liu et al. 2012).

Kunkel et al. (2004) found an increase in the frost-free season length from 1895–2000 of approximately 2 weeks, with a larger increase in the Western U.S.

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 (e.g., Mote et al. 2005; Barnett et al. 2005). 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

In 2011, as part of its responsibilities under section 9503 of the SECURE Water Act,[37] Reclamation reported on climate change implications for water supplies and related water resources within eight major Western U.S. river basins, including GP Region's Missouri River Basin. The report (Reclamation 2011) includes an original assessment of natural hydrology impacts under projected climate conditions, informed by the same downscaled climate projection summarized in appendix B (Reclamation 2011c).

Focusing on the broader Western U.S. region, Reclamation (2011b) reports that projections of future precipitation indicate that the northwestern and north-central portions of the U.S. may gradually become wetter while the southwestern and south-central portions gradually become drier, albeit with substantial fluctuations

[37] The Omnibus Public Lands Act (Public Law 111-11) Subtitle F – SECURE Water.

on interannual to decadal timescales due to natural variability (Deser et al. 2010 and 2012). It is noted that these summary statements reflect regionally averaged changes and that projected changes have geographic variation; they vary through time; and the progression of change through time varies among climate projection ensemble members. What this means is that, going forward in time, different regions are likely to continue to experience the kind of interannual to interdecadal variations in precipitation that they have experienced in the past. For the next few decades, these variations are likely to be superimposed upon background trends that in most cases are likely to be subtle compared with the variations.

These projected changes in climate have implications for hydrology. Warming trends contribute to a shift in cool season precipitation towards more rain and less snow (Knowles et al. 2007), which causes increased rainfall-runoff volume during the cool season accompanied by less snowpack accumulation. The shift of precipitation from snow to rain, which falls more quickly and so is carried a shorter distance by winds, could also exaggerate rain shadows in the mountainous west (Pavelsky et al., 2012). Projections of future hydrology (Reclamation 2011) suggest that warming and associated loss of snowpack will occur over much of the Western U.S. However, not all locations are projected to experience similar changes. Analyses suggest that losses to snowpack will be greatest where the baseline climate is closer to freezing thresholds (e.g., lower lying valley areas and lower altitude mountain ranges) (Bales et al. 2006). Analyses also suggest that, in high-altitude and high-latitude areas, cool-season snowpack actually could increase during the 21st century (e.g., Columbia headwaters in Canada, Colorado headwaters in Wyoming).

Pierce and Cayan (2012) used 13 downscaled global climate models to quantify the influence of mechanisms that contribute to changes in end-of-century peak snowpack: increased precipitation, increased melting, and the conversion of precipitation from snow to rain. The authors systematically explored climate-model projected changes by 2100 in six different snow-related variables over the Western U.S., and found that statistically significant linear trends are seen earliest in the fraction of winter precipitation that falls as snow, followed by SWE/P, and 5 to 20 years later by SWE. Least sensitive of all snow measures examined was total seasonal snowfall, which is strongly linked to precipitation. Different regions have different balances of mechanisms, although in the Western U.S. as a whole the conversion of precipitation from snow to rain dominates.

Projected changes in surface water runoff are more complex than projections of snowpack. Hydrologic projections introduced in Reclamation (2011b) suggest that geographic trends may emerge. The Southwestern U.S. to the southern Rockies may experience gradual annual runoff declines during the 21st century and the northwest to north-central U.S. may experience little change through mid-21st century with increases projected for the late-21st century. With respect to seasonal runoff, warming is projected to affect snowpack conditions both in terms of cool season accumulation and warm season melt. Without changes to overall precipitation quantity, these changes in snowpack dynamics would lead to increases in cool season rainfall-runoff and decreases in warm season snowmelt-runoff, leading to a season-varying sensitivity of runoff to warming (Das et al., 2011). The hydrologic projections indicate that the degree to which this expectation may occur varies by location in the Western U.S. For example, cool season runoff is projected to increase over the west coast basins from California to Washington and over the north-central U.S., but with little change to slight decreases over the Southwestern U.S. to southern Rockies. Warm season runoff is projected to experience substantial decreases over a region spanning southern Oregon, the Southwestern U.S., and southern Rockies. In summary, the hydrologic projections featured in Reclamation (2011b) suggest that projected precipitation increases in the northern tier of the Western U.S. could counteract warming-related decreases in warm season runoff, whereas projected decreases in precipitation in the southern tier of the Western U.S. could amplify warming-related decreases in warm season runoff.

Focusing on Reclamation (2011b) results representative of the GP Region conditions, **table 7** summarizes the projection median change from an ensemble of downscaled CMIP3 models run through VIC for various hydroclimate conditions in Missouri River subbasins. Generally speaking, the ensemble-median changes of **table 7** suggest that these subbasins will experience increasing mean-annual temperature and with precipitation change during the 21st century that varies from increases in more northerly subbasins to generally no change in more southerly subbasins. These changes are projected to be accompanied by decreasing trend in spring SWE decreasing trend in April–July runoff volume, and increasing trends in December–March and annual runoff volumes.

While **table 7** summarizes the model ensemble's median change values, it is noted the models typically project a wide range of possible trends in precipitation for many midlatitude regions. The significance of this fact is that the uncertainty (or spread among ensemble members) is very large for precipitation projections for many parts of the U.S. over the next 10 to 60 years, at least (Deser et al. 2010 and 2012).

The projected climate change implications for water resources reported in Reclamation (2011b) are similar to those reported in prior assessments. A paper by the CBO (CBO 2009) presents an overview of the current understanding of the impacts of climate change in the U.S. Their findings indicate that warming will tend to be greater at high latitudes and in the interiors of the U.S. 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.

Table 7.—Summary of simulated changes in decade-mean hydroclimate for several subbasins in the Missouri River Basin from an ensemble of downscaled CMIP3 models run through VIC

Hydroclimate Metric (change from 1990s)	2020s	2050s	2070s
Missouri River at Canyon Ferry			
Mean Annual Temperature (°F)	1.6	3.4	4.8
Mean Annual Precipitation (%)	1.9	4.5	6.6
Mean April 1 SWE (%)[1]	-4.0	-9.0	-12.0
Mean Annual Runoff (%)	0.8	2.1	6.2
Mean December–March Runoff (%)	4.2	13.6	28.4
Mean April–July Runoff (%)	0.4	1.8	3.6
Mean Annual Maximum Week Runoff (%)	4.5	7.6	12.5
Mean Annual Minimum Week Runoff (%)	-4.1	-5.4	-7.2
Milk River at Nashua, Montana			
Mean Annual Temperature (°F)	1.4	3.3	4.6
Mean Annual Precipitation (%)	2.8	7.3	7.9
Mean April 1 SWE (%)[1]	-8.0	-18.0	-28.0
Mean Annual Runoff (%)	8.2	8.5	12.9
Mean December–March Runoff (%)	11.9	20.1	32.5
Mean April–July Runoff (%)	7.6	8.2	10.6
Mean Annual Maximum Week Runoff (%)	9.8	12.7	17.3
Mean Annual Minimum Week Runoff (%)	1.7	1.0	1.4
South Platte River near Sterling, Colorado			
Mean Annual Temperature (°F)	1.8	3.6	5.0
Mean Annual Precipitation (%)	0.0	0.6	2.1
Mean April 1 SWE (%)[1]	-1.0	-3.0	-5.0
Mean Annual Runoff (%)	-8.5	-13.9	-17.5
Mean December–March Runoff (%)	-7.8	-12.2	-11.4
Mean April–July Runoff (%)	-7.2	-10.8	-9.9
Mean Annual Maximum Week Runoff (%)	1.8	-3.4	-2.3
Mean Annual Minimum Week Runoff (%)	-16.3	-23.5	-29.3
Missouri River at Omaha			
Mean Annual Temperature (°F)	1.6	3.5	4.8
Mean Annual Precipitation (%)	3.4	6.6	8.5
Mean April 1 SWE (%)[1]	-2.0	-6.0	-8.0
Mean Annual Runoff (%)	3.7	9.7	12.6
Mean December–March Runoff (%)	5.2	13.0	19.6
Mean April–July Runoff (%)	5.5	12.3	15.1
Mean Annual Maximum Week Runoff (%)	5.9	12.8	15.6
Mean Annual Minimum Week Runoff (%)	-0.7	1.3	1.1

[1] The reported percentage changes in mean April 1st SWE have been updated to correct a reporting error in Reclamation (2011b). The error stemmed from reporting this change as the mean change in cell-specific changes from all 1/8-degree grid-cells within the given basin. Such a change metric does not equal the change in total basin SWE integrated across all grid-cells within the basin, which was the intended reporting metric and is now indicated by the updated percentage changes.

A similar overview is included in the Interagency Climate Change Adaptation Task Force National Action Plan (CEQ 2011), with emphasis on freshwater resources impacts and discussions of strategies to address these impacts. Lundquist et al. (2009) report similar findings on hydrologic impacts. 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.[38]

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.[39] 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). However Power et al. (2012) have pointed out that in fact there is model consistency in projected precipitation changes in many of these regions; the consistently projected value is that precipitation changes will be small relative to natural variability. 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). 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 U.S. 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.

Brikowski, 2008 reports on streamflow declines and reservoir impacts in the Great Plains caused by the combined impacts of ground water mining and climate change. Although these impacts were historically related to ground water mining,

[38] See http://www.nar.ucar.edu/2008/ESSL/sp2/#03.

[39] 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.

the correlation to climate change has increased since the mid-1980s. GCM based predictions of streamflow and reservoir performance indicate a 70% chance of steady decline after 2007 at four Kansas reservoirs evaluated by the study.

Temperature effects alone could cause significant impacts to hydrologic systems. Diffenbaugh and Ashfaq (2010) report on near-term GCM projections of future extreme temperature events in the U.S. and correlation to reduced soil moisture levels. Although the authors identified robust correlations between changes in temperature, precipitation, and soil moisture, the specific relationship between surface drying and intensified hot extremes is confounding since the predicted decreases in soil moisture could be a product of decreases in precipitation and/or increases in net surface radiation.

The Palmer Drought Severity Index (PDSI) gives indications of a semi-permanent state of severe drought over the GP Region in coming decades when fed climate change projections of rising temperatures and decreasing precipitation amounts. Hoerling et al. (2012) looked at the difference between projections of PDSI and soil moisture through the 21st century and found that the PDSI projections do lead to prolonged severe drought conditions. The soil moisture projections, however, point to a more modest drying with a much smaller change in drought frequency. In their view, if prolonged severe drought occurs in the near future of the GP Region, it will be due to lengthy periods of precipitation deficits.

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, an effect already that is already observed (Min et al., 2011). Allan (2011) and Pall et al. (2011) both concur that there will be an increase in the frequency of intense rainfalls with warming. Dominguez et al. (2012) found that an ensemble of global climate models downscaled by regional models predict more extreme winter precipitation events, with daily events at the 20- and 50-year return periods increasing by 12 to 14%. 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. Watterson and Dix (2003) report a predicted worldwide average 14% increase in 30-year extreme daily precipitation for 2071–2100 compared to 1961–1990 based on simulations by the CSIRO Mark 2 GCM under A2 (high) and B2 (moderate) emissions scenarios. From a separate stochastic model study of the same GCM output, Watterson (2005) reports the interannual standard deviation of mean monthly precipitation increases with warming temperature. The 1961–1990 to 2071–2100 increases found were 9.0% for January and 11.5% for July. Min et al. (2011) proposed that some GCM simulations actually may underestimate the trend towards increased extreme precipitation events in the Northern Hemisphere, which suggests that extreme precipitation events may be stronger than projected. Chou and Lan (2012) note that the increase in precipitation extremes means that the annual range of precipitation will increase over much of the world. However, Dulière et al. (2011) caution the use of GCM simulations for local extreme precipitation projections because the resolution of these models is very coarse. For localized extreme precipitation events, it appears as though regional models retain the large-scale forcings and may preserve the mesoscale forcings and topographic interactions necessary to produce events at this finer scale. Extreme runoff due to changes in the statistics of extreme events will present flood control challenges to varying degrees at many locations (e.g., Das et al., 2011).

A variety of factors are likely to affect future precipitation extremes, including changes in temperature, precipitation efficiency, and vertical velocity (O'Gorman and Schneider, 2009; Muller et al., 2011), and the ability of warmer atmospheric conditions to sustain a higher equilibrium pressure of water vapor.

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 U.S. (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 percentiles. For the fourth basin (Gunnison), greater flow rates were projected for roughly the upper tercile. 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).

It is important to recognize that these assessments of hydrologic impacts under climate change are sensitive to numerous uncertainties. Much attention has been given to the uncertainties introduced by climate projection selection, bias correction, and spatial downscaling. Some of these issues are explored for the Colorado River in Harding et al. (2012). Ashfaq et al. (2010) report on an evaluation of climate model bias effects and hydrologic impacts using a RegCM3 to drive a hydrological model (VIC) for the full contiguous U.S. In addition to showing the significance of climate model bias in predicting hydrologic responses, their results highlight the importance of daily temperature and precipitation extremes in predicting future hydrological effects of climate change. Recently, the uncertainties associated with the hydrologic analysis have also been garnering attention. Vano et al. (2012) applied multiple land-surface hydrologic models in the Colorado River Basin under multiple, common climate change scenarios. Their results showed that runoff response to these scenarios varied by model and stemmed from how the models feature a collective of plausible hydrologic process portrayals, where a certain combination of process portrayal choices led to a model's simulated runoff being more or less sensitive to climate change. Although these results are most applicable to the Colorado River Basin, it is still expected that application of the models in Vano et al. (2012) to other Western U.S. basins would likewise show model-dependent runoff sensitivity to climate change. Improving our understanding of these data and model uncertainties will help refine future estimates of climate change implications for hydrology.

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 U.S. 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 that 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 U.S. 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

This section is organized under the following sub-headings: Multiple Species/Resources and Ecosystems; Fisheries and Aquatic Ecosystems; Individual Species/Resources; Agriculture; and Forest Fires. The literature covered includes both historical and projected future conditions.

2.5.3.1 Multiple Species/Resources and Ecosystems

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.[40] 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.

Parmesan (2006) provides a synthesis of recent studies pertaining to observed responses of wild biological species and systems to recent climate change. This author's literature search revealed 866 peer-reviewed papers that documented changes in species or systems that could be attributed at least in part to climate change. The synthesis focuses on advancing of spring events, variations in

[40] 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.

phenological responses between interacting species, species range shifts, range restricted species, pests and parasites, extinction, and evolutionary responses and genetic shifts.

Using meta-analysis, Chen, et.al. (2011) documented a change of elevation and latitude of terrestrial organisms as a result of climate variability. Using available studies of Europe, North America, Chile, Malasia, and the Marion Islands, range shifts were documented for 764 individual species responses for latitude adjustment and 1,367 species responses for elevation variability. The results of this analysis indicate that species have moved away from the equator at a median rate of 16.9 kilometers per decade. Additionally, species have moved to higher elevations at a median rate of 11.0 meters per decade.

Research by Ault and others (2011) shows that the average timing of plant phenology events, such as bud formation and flowering, is occurring 1.5 days earlier per decade across western North America. They note that the major modes of atmospheric circulation only account for about one-third of the trend.

The VEMAP[41] and other similar projects have increased our understanding of ecosystem dynamics under climate change; however, our understanding of the interactions between stresses on individual species at the ecosystem level is still relatively limited. Specific examples include the interaction between atmospheric CO_2 and soil water and nutrient limitations on plant productivity, carbon sequestration , and species composition; the interactions between CO_2 and tropospheric O_3 on plant water-use efficiency; and the future rates of plant species migration and ecosystem establishment under climate change (Aber et al. 2001). In general, vegetation models indicate that a moderate increase in future temperature would produce an increase in vegetation density and carbon sequestration across most of the U.S. with small changes in vegetation types and large increases in future temperature would cause losses of carbon with large shifts in vegetation types (Bachelet et al. 2001).

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 U.S., and increased temperature and drought likely influenced these outbreaks. 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

[41] Available online at: http://www.cgd.ucar.edu/vemap/.

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. Bentz et al. (2010) report that "models suggest a movement of temperature suitability to higher latitudes and elevations and identify regions with a high potential for bark beetle outbreaks and associated tree mortality in the coming century."

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 (Ryan et al. 2008). 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.

Dunnell and Travers, 2011 report that as spring temperatures in the northern Great Plains have increased and the growing season has lengthened, some spring flowering species have advanced their first flowering time, some fall species have delayed their first flowering, and some species have not changed. Given the importance of flowering timing for reproductive success, the changing climate in the Great Plains is expected to have long-term ecological and evolutionary consequences for native plant species.

Robinson et al. (2008) describe and compare several ecological models that estimate vegetation development (productivity or vegetation type) under climate change.

2.5.3.2 Aquatic Species/Resources and Ecosystems

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 U.S., including Western U.S. 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 U.S.

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).

Marcarelli et al. (2010) estimated past and future hydrographs and patterns of ecosystem metabolism for a Western U.S. river and analyzed the impacts of climate change and water use. The reported combined hydrologic related impacts, measured in terms of gross primary production and ecosystem respiration, are indicative of the potentially important role hydrologic regime plays in controlling ecosystem function.

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.

Covich et al. (1997) summarize available information on patterns of spatial climate variability and identify 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 impacts, respectively, to terrestrial and aquatic ecosystems based on two GCM-based climate change scenarios. 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.

2.5.3.3 Individual Species/Resources

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 and 2011) 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.

Although recent studies on mountain pine beetle infestations in the central Rockies show less than expected water resources impacts, the associated physical processes are not well understood; and it's expected that the picture will change as new research and monitoring is conducted (Lukas and Gordon, 2010).

McCarty (2001) reports night time temperature increases in northeastern Colorado resulting in a significant decline in the dominant native grass.

Cayan et al. (2001) document earlier blooming of lilacs and honeysuckles correlated to increasing spring temperatures.

2.5.3.4 Agriculture

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.

Lobell et al. (2011) present the findings of a global analysis of crop production impacts due to past climate change. The authors developed statistical models comparing 1980–2008 actual production levels for the four largest commodity crops (corn, wheat, soybeans, and rice) to theoretical levels without climate change. Their results indicate respective 3.8 and 5.5% decreases in worldwide corn and wheat production, and approximately no net change for soybeans and rice. Significant changes in U.S. production levels were not found, and this is attributed to relatively low increases in temperatures in our agricultural regions. The authors attribute the modeled impacts to changes in temperature rather than precipitation, and they acknowledge that their analysis does not account for adaptations by growers or the effect of elevated CO_2 on crop yields.

North Dakota's growing season is reported as 12 days longer than a century ago (Badh et al. 2009). In a later study, Badh and Akyuz (2010) looked at the accumulation of growing degree days (GDD) for corn across the northern Great Plains, including North Dakota, South Dakota and Nebraska, using a base temperature of 50° F. A significant increase in GDD accumulation was found for North Dakota from 1870–2009; no significant change was found in the other northern Great Plains states, however.

Ojima and Lacket (2002) discuss Great Plains ecosystem and agricultural impacts based on two GCM-based climate change scenarios. Two topics somewhat unique to this document are potential reduction in soil quality due to increased decomposition rates of soil organic matter and increased crop destruction by hail events. This report also discusses that an increased level of plant production was predicted by vegetation models under both GCM scenarios after 100 years (1994–2100) although there was a slight depression in productivity simulated during the first 30 years under one of the two GCM scenarios.

Ko et al. (2011) used agricultural system models to determine the impact of past and future climate change on dryland wheat, millet and corn production in the western GP Region of Colorado. Their results indicate that the negative effects of temperature increases over the next century exceed the benefits that might occur with elevated CO_2 concentrations. Wheat yields are expected to decrease somewhat as climate change continues, but corn and millet yields are projected to decrease at a statistically significant level.

Mader et al. (2009) studied the impact of climate change on the livestock production systems in the central U.S., including Nebraska and Kansas. Their work projects the potential for increasing economic losses in the summer, and suggests the necessity for mitigation of economic losses through changes in management practices.

Nardone et al., 2010 discusses the effects of climate change on livestock following the "theory of global warming." Topics include impaired production due to increased temperatures, desertification of rangelands, impacts to grain availability, and adaptability of animal genotypes.

2.5.3.5 Forest Fires and Wildfires

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 U.S., 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 in Westerling et al. (2006), which document large increases in fire season duration and fire frequency, especially at mid-elevations, in the Western U.S. Coincident with trends toward warmer and drier climate in the Western U.S. 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. Using satellite imagery and aerial survey data, Williams et al. 2010 estimate that during 1997–2008 approximately 18% of southwestern forest area (excluding woodlands) experienced mortality due to bark beetles or wildfire. 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 U.S. 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 U.S. 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 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. 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 GP Region resulting from climate change. Root (2012) cautions that increased wildfires can lead to unexpected results on some fire-adapted species, for example if fires become so frequent that juvenile plants do not have time to produce seeds.

Moritz et al. (2012) used projections from 16 different GCMs to formulate a comprehensive look at global fire patterns. Those projections focused on two timeframes: 2010–2039 and 2070–2099. The results indicated climate change will results in an increase in the frequency of wildfires in the Western U.S. in the next 30 years, and across the entire U.S. at the end of the century.

Litschert et al. (2012) estimate a doubling of mean burned area in the southern Rocky Mountains from 2010–2070, based on two GCMs and the B1 and A2 scenarios. Spracklen et al. (2009) project an increase in area burned of 43%, by 2050, for Arizona and New Mexico.

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

> "Global sea level rose at a rate of 1.7 millimeters/year during the 20th century. The rate has increased to over 3 millimeters/year in the past 20 years and scientific studies suggest high confidence (>9 in 10 chance) that global mean sea level will rise 0.2 to 2 meters by the end of this century" *(Burkett and Davidson* 2012).

The IPCC AR4 from Working Group I (chapter 10, "Sea Level Change in the 21st Century" [IPCC 2007]) provides projections of global average sea level rise that primarily represent thermal expansion associated with global air temperature projections from current 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 CMIP3 models' simulation of ocean response to atmospheric warming under a collection of 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 study conducted by Yin et al. (2011) suggests that the acceleration of outlet glacier melting in Greenland and Antarctica is closely linked to subsurface ocean layer temperatures. Additionally, using 19 GCMs, they were able to project ocean temperatures through 2200. These models showed the potential for maximum ocean temperature increases around Greenland to be 1.7 to 2.0 °C by the end of the 21st century. The same modeling around Antarctica showed maximum ocean temperature increases of 0.5 to 0.6 °C by the year 2100. Both of these results represent ocean temperature increases greater than what was previously thought, indicating the potential for even greater sea level rises in the future. Because ocean temperatures require centuries to come into equilibrium with warmer surface forcing, sea level rise can continue long after land temperatures stop rising (Wigley, 2005).

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). 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 to 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.

Sea level rise in the Gulf of Mexico is a particular concern for the Texas coastal areas. Donohgue (2011) studied long-term tide gauges along the northern Gulf of Mexico coast for the last 100 years and found general agreement with global sea level increases. The data indicate sea level rises of as much as 6.39 mm/year near Galveston Pier, Texas, and as little as 1.93 inches at Port Mansfield, Texas. Should sea level rises approach rates of those during the last deglacial era, as predicted by several recent model projections, then in-place drowning and overstepping of the Gulf Coast shorelines would result.

Given the uncertainty in global sea level rise projections, and the aforementioned critique of the assumptions in the IPCC AR4 analysis, Parris et al. (2012) developed four plausible scenarios of sea level rise, which can be applied in conjunction with analyses of local conditions. They mention the following:

> "Based on a large body of science, we identify four scenarios of global mean SLR ranging from 0.2 meters (8 inches) to 2.0 meters (6.6 feet) by 2100. These scenarios provide a set of plausible trajectories of global mean SLR for use in assessing vulnerability, impacts, and adaptation strategies. None of these scenarios should be used in isolation, and experts and coastal managers should factor in locally and regionally specific information on climatic, physical, ecological, and biological processes and on the culture and economy of coastal communities."

Konikow (2011) discusses the relationship between sea level rise and ground water depletion and suggest a better understanding of this relationship is needed to better predict future rates of sea level rise. According to the author, the 1900–2008 global ground water depletion was approximately 4,500 cubic kilometers (3.6 million acre-feet) which would be equivalent to a 12.6 millimeter rise in sea level.

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 ground water. 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 ground water primarily is based on information from the 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 U.S." applicability. Further, many of the climate change impacts evident in recent studies are common among regions. Consequently, there are many common themes in each region-specific summary that follows.

3.1 Pacific Northwest Region

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; Hay et al. 2011; Lutz et al. 2012). Projected reductions in late spring and summer snowmelt runoff largely are balanced by increases in winter and early spring runoff as more precipitation is projected to fall as rain rather than snow.

While trends toward increasing precipitation in the PN Region are plausible, it is also likely that the region will continue to experience substantial interannual to interdecadal variability in precipitation, and to a lesser extent, temperature. Natural resource managers should continue to seek operations that are robust to a wide range of hydrologic conditions (wet or dry, extreme high or low flows, etc.) while preparing for a future with less springtime snowpack and snowfed runoff for most PN watersheds.

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 will not 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.

Hoekema et al. (2010) report on the use of the Snake River Planning Model, a local water resource management tool, to evaluate climate change impacts in the Payette River Basin using the output from three GCMs under three emissions scenarios. Based on the evaluation results, the authors suggest that the current water management practices in this basin are robust enough to mitigate impacts through 2050. The evaluation results include a worst case increase in irrigation shortages by 9% and an average annual 2050 irrigation shortage of 17,500 acre-feet.

3.1.2 Flood Control

In Western U.S. 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 (e.g., Das et al. 2011). 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 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).

Chapter 4 of the WACCIA (Hamlet et al. 2010) evaluates potential changes in the seasonality and annual amount of PN hydropower production and changes in energy demand in a warming climate by linking simulated streamflow scenarios produced by a hydrology model to a simulation model of the Columbia River hydro system. Energy demand, and potential changes therein, are assessed estimates of heating degree days (HDD) and cooling degree days (CDD) for both the 20th century climate and projections of climate in three future periods (2010–2039, 2030–2059, and 2070–2099) and two emissions scenarios (IPCC A1B and B1). The gridded HDD and CDD values were combined with population projections to create energy demand indices that respond both to climate, future population, and changes in air conditioning market penetration. This analysis found substantial changes in the amount and seasonality of energy supply and demand in the PNW are likely to occur over the next century in response to warming, precipitation changes, and population growth. In the 2020s, regional hydropower production increased by 0.5 to 4% in winter and decreased by 9 to 11% in summer, with annual reductions of 1 to 4%. Slightly larger increases in winter, and summer decreases, were projected for the 2040s and 2080s. In the absence of warming, population growth was projected to result in considerable increases in heating energy demand, however, the combined effects of warming and population growth were projected to result in net increases that are approximately one-half those associated with population growth alone. On the other hand, population growth combined with warming greatly increased the projected demand for cooling energy, notwithstanding that by the 2080s, total cooling energy requirements will still be substantially lower than heating energy demand.

Markoff and Cullen (2008) found that, in the absence of adaptation, annual hydropower production in the PN Region is much more likely to decrease than to increase. They also found that economic impacts of hydropower changes could be on the order of hundreds of millions of dollars per year.

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 primarily are 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.

Wenger et al. (2011) has reported climate change effect on Western U.S. trout species. Instead of analyzing the effect on fishery habitat due to temperature alone, this study analyses the effects of temperature, flow regime, and biotic interactions, all of which are estimated under differing climate change scenarios. The study reports a decline of suitable native cutthroat trout habitat of 28% in the 2040s and 58% by the 2080s. Nonnative brook trout habitat is expected to be reduced by 44 and 77% in the 2040s and 2980s, respectively. Rainbow and brown trout are expected to see a more modest reduction of suitable habitat in the 2040 and 2080 time periods. Rainbow trout habitat is projected to decline 13% in the 2040s and 35% in the 2080s. Brown trout habitat is estimated to realize a 16 and 48% reduction, respectively, over the same time period.

Text from the draft NCA, chapter 21, page 725, for the Pacific Northwest:

> “Several aspects of hydrologic change, such as increased flooding in mixed rain-snow basins, region-wide increased winter flows and summer temperatures, and decreased summer flows, will threaten many freshwater species, particularly salmon, steelhead, and trout. Rising temperatures will increase disease and/or mortality in several iconic salmon species, including spring/summer Chinook and sockeye, especially in the interior Columbia and Snake River Basins (Mantua et al. 2010)—although some streams are less sensitive to warming because of the temperature buffering provided by snowmelt and ground water (Mohseni et al. 1999). By the 2080s, suitable

> habitat for the four trout species of the interior Western U.S. is projected to decline 47% on average compared to 1978–1997 (Wenger et al. 2011). Some Northwest streams (Isaak et al. 2011) and lakes have already warmed, on average, over the past three decades, contributing to changes such as earlier Columbia River sockeye salmon migration (Crozier et al. 2011) and earlier blooms of algae in Lake Washington (Winder and Schindler 2004). As species respond to climate change in diverse ways, there is a potential for ecological mismatches to occur – such as in the timing of the emergence of predators and their prey (Winder and Schindler 2004)."

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.

A recent preliminary report for the U.S. Environmental Protection Agency's (EPA's) Global Change Research Program "20 Watersheds Project" (Johnson et al. 2011) describes the overall structure of the ongoing effort (methods, sites, models, and scenarios) and discusses preliminary results. The goal of this work is to provide an improved understanding on a number of uncertainties associated with assessments of climate change impacts on water quality, including the use of different climate models, downscaling tools and methods, watershed models, land-use change scenarios, and process representations. Preliminary results from 5 of the 20 study sites suggest that sensitivity to climate change differs for mean flow, flow extremes, and sediment/nutrient loading, reflecting the different combination of hydrometeorological processes and spatial and temporal scales involved in each. Also, there is a strong sensitivity of the modeled flow and water quality endpoints to the climate model, downscaling approach, and combination of climate variables applied in the watershed simulations. At the scale of the large watersheds studied so far, sensitivity to climate change dominates over sensitivity to urban development, but it appears this will not necessarily be true at smaller spatial scales or for watersheds with larger amounts of urban development.

3.1.6 Ground Water

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 ground water 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 ground water resources. However, warmer, wetter winters could increase the amount of water available for ground water recharge. It is has not been demonstrated how much of this additional winter runoff can be captured and utilized without using artificial recharge schemes.

Earman and Dettinger (2011) discuss four ways that climate change could affect ground water systems: changes in precipitation amounts; the temporal distribution of precipitation; changes in the form of precipitation; and potential changes in evaporation, transpiration, and pumping rates. The response of the aquifer to each of these potential change mechanisms likely will be different depending of the physical characteristics.

Tague et al. (2008) show that differences in ground water dynamics can be as important as topographic differences in snow regimes in determining the response of mountain landscapes to changing climate. Their results show that within the Cascade Range, local variations in bedrock geology and concomitant differences in volume and seasonal fluxes of subsurface water will likely result in significant spatial variability in responses to climate forcing. Specifically, watersheds dominated by porous, volcanic, High Cascade geology that supports deep ground water connections to surface water will show greater absolute reductions in summer streamflow with predicted temperature increases.

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 U.S. is for agricultural irrigation. Between 80 and 90% of the consumptive use water demand in the U.S. is for irrigation (Schaible and Aillery, 2012). 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 conditions lead to uncertainties in future irrigation demands.

Using the Precipitation Runoff Modeling System to simulate the Natches River Basin in Washington and the Flathead River Basin in Montana, Hay et al. (2011) found that soil moisture on an annual basis decreased under climate change conditions, which may indicate an overall increase in agricultural demands. Interestingly, the model showed higher soil moisture levels during the winter month primarily due to increased snowpack melting and changes in precipitation.

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. Water conservation measures may offset potential increases in per capita water usage regardless of climate change-related increases in domestic water demands. Although the use of new water efficient appliances and fixtures will increase through institutional measures and mandates, socioeconomic factors will impact water conservation. EPA (2010) describes the activities of eight large U.S. water utilities who have conducted climate vulnerability assessments, including projections of future domestic water demands.

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 . Avery et al. (2011) reports on research into the water demands of thermoelectric energy production in the context of climate variability and change.

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 also could 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; Hidalgo et al. 2009; Null et al. 2010; Hay et al. 2011). While there will continue to be large interannual to interdecadal variations in precipitation, there is not a majority consensus among contemporary climate projections that precipitation might increase over the MP Region (Dettinger 2005; Pierce et al. 2012b). 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). And, this assumes existing storage capacity to retain the winter runoff for summer release. 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 earlier runoff by nearly a month, 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 will not 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.

Joyce et al. (2009) evaluated the Sacramento River Basin and Delta export region using a regional planning model driven by output from three GCMs under three emissions scenarios. These authors predict a general decrease in water supply reliability with most acute water shortages in the western San Joaquin Valley and Tulare Basin.

Wang et al. (2011) shows potential climate change impacts to the operation of the State Water Project and Central Valley Project at the mid-century and late-century points. The study incorporated the current planning model, CALSIM II, and used six GCMs and two emission scenarios to bracket potential impacts in conjunction with a three-step perturbation method to isolate the impacts of changes in annual inflow, pattern shifts, and sea level rise. The results show that, for mid-century (2030–2059), annual inflow changes contribute most to climate change impacts to the system: an approximate south of Delta export reduction of 9% and an approximate 20% north of Delta Reservoir carryover storage volume. By the late-century (2070–2099), an estimated sea level rise of 61 cm plays an important role in system climate change impacts: a south of Delta export reduction of about 21% and a north of Delta carryover storage volume reduction of approximately 36%.

3.2.2 Flood Control

In Western U.S. 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 (Das et al. 2011). 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 the respective 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.

Wenger et al. (2011) has reported climate change effect on Western U.S. trout species. Instead of analyzing the effect on fishery habitat due to temperature alone, this study analyses the effects of temperature, flow regime, and biotic interactions, all of which are estimated under differing climate change scenarios. The study reports a decline of suitable native cutthroat trout habitat of 28% in the 2040s and 58% by the 2080s. Nonnative brook trout habitat is expected to be reduced by 44 and 77% in the 2040s and 2980s, respectively. Rainbow and brown trout are expected to see a more modest reduction of suitable habitat in the

2040 and 2080 time periods. Rainbow trout habitat is projected to decline 13% in the 2040s and 35% in the 2080s. Brown trout habitat is estimated to realize a 16 and 48% reduction, respectively, over the same time period.

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.

A recent preliminary report for EPA's Global Change Research Program "20 Watersheds Project" (Johnson et al. 2011) describes the overall structure of the ongoing effort (methods, sites, models, and scenarios) and discusses preliminary results. The goal of this work is to provide an improved understanding on a number of uncertainties associated with assessments of climate change impacts on water quality, including the use of different climate models, downscaling tools and methods, watershed models, land-use change scenarios, and process representations. Preliminary results from 5 of the 20 study sites suggest that sensitivity to climate change differs for mean flow, flow extremes, and sediment/nutrient loading, reflecting the different combination of hydrometeorological processes and spatial and temporal scales involved in each. Also, there is a strong sensitivity of the modeled flow and water quality endpoints to the climate model, downscaling approach, and combination of climate variables applied in the watershed simulations. At the scale of the large watersheds studied so far, sensitivity to climate change dominates over sensitivity to urban development, but it appears this will not necessarily be true at smaller spatial scales or for watersheds with larger amounts of urban development.

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, especially 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 Ground Water

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 ground water 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 ground water resources. However, warmer wetter winters could increase the amount of water available for ground water recharge. It has not been demonstrated how much of this additional winter runoff can be captured and utilized without using artificial recharge schemes.

Earman and Dettinger (2011) discuss four ways that climate change could affect ground water systems: changes in precipitation amounts; the temporal distribution of precipitation; changes in the form of precipitation; and potential changes in evaporation, transpiration, and pumping rates. The response of the aquifer to each of these potential change mechanisms likely will be different depending of the physical characteristics.

Joyce et al. (2009) predict overexploitation of ground water resources to meet climate change induced increasing agricultural demands in the San Joaquin River Basin. This prediction is an outcome of evaluations of a regional water planning model based on six GCMs and two emissions scenarios. Nelson (2012) explores some of the policy issues associated with ground water use in the California central valley. They note that typically only voluntary approaches to limiting or regulating ground water extraction are used, whether or not the local problems with excessive ground water depletion are severe or not, and without regard to the possible impacts of overpumping.

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 U.S. is for agricultural irrigation. Between 80 and 90% of the consumptive use water demand in the U.S. is for irrigation (Schaible and Aillery, 2012). 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 conditions lead to uncertainties in future irrigation demands. Frisvold and Konyar (2012) examined scenarios of how agriculture in the Southwestern States might adopt to the impacts of climate change on the water supply, and found that while overall agriculture in the region was resilient to modest decreases in water supply, particular crops (cotton, alfalfa) were vulnerable.

Joyce et al. (2009) predict increasing agricultural water demands and decreasing water supply reliability in the San Joaquin Valley under climate change. The authors developed a regional model based on six GCMs and two emissions scenarios. Current operations and changing agricultural management strategies such as improved irrigation efficiencies and cropping pattern shifts were both modeled. Their results indicate that the modeled management changes will only partially offset increasing demands, and decreased reliability will occur. Using the Precipitation Runoff Modeling System to simulate the Feather and Sagehen River Basins in California, and Sprague River Basin in Oregon, Hay et al. (2011) found that soil moisture on an annual basis decreased under climate change conditions, which may indicate an overall increase in agricultural demands. Interestingly, the model showed higher soil moisture levels during the winter month, primarily due to increase snowpack melting and changes in precipitation.

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 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. Water conservation measures may offset potential increases in per capita water usage regardless of climate change related increases in domestic water demands. Although the use of new water efficient appliances and fixtures will increase through institutional measures and mandates, socioeconomic factors will impact water conservation. EPA (2010) describes the activities of eight large U.S. water utilities who have conducted climate vulnerability assessments, including projections of future domestic water demands.

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. Avery et al., 2011 reports on research into the water demands of thermoelectric energy production in the context of climate variability and change.

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), although the spread of projections across different models is large (Harding et al. 2012). 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. And, it must also be expected that historical interannual and interdecadal precipitation variations are likely to continue.

Warming also could 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 will not 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.

A number of studies have examined the effect of climate change on the Colorado River water supply system (McCabe and Wolock 2007; Barnett and Pierce 2008, 2009a; Rajagopalan et al. 2009). The general picture is that currently scheduled delivery increases, combined with decreasing inflow to the reservoir system and greater evapotranspiration losses from climate change, would increase the probability and likely duration of delivery shortages in coming decades. A natural reversion to the lower long-term mean flow in the Colorado River suggested by tree ring records, if it happened, would exacerbate this situation.

3.3.2 Flood Control

In Western U.S. reservoir systems with flood control objectives in currently snowmelt-dominated basins, warming without precipitation change could result in increased winter and early spring runoff volumes to manage during flood control operations (e.g., Das et al. 2011). 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 and early spring 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 change 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 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).

A recent preliminary report for EPA's Global Change Research Program "20 Watersheds Project" (Johnson et al. 2011) describes the overall structure of the ongoing effort (methods, sites, models, and scenarios) and discusses preliminary results. The goal of this work is to provide an improved understanding on a number of uncertainties associated with assessments of climate change impacts on water quality, including the use of different climate models, downscaling tools and methods, watershed models, land-use change scenarios, and process representations. Preliminary results from 5 of the 20 study sites suggest that sensitivity to climate change differs for mean flow, flow extremes, and sediment/nutrient loading, reflecting the different combination of hydrometeorological processes and spatial and temporal scales involved in each. Also, there is a strong sensitivity of the modeled flow and water quality endpoints to the climate model, downscaling approach, and combination of climate variables applied in the watershed simulations. At the scale of the large watersheds studied so far, sensitivity to climate change dominates over sensitivity to urban development, but it appears this will not necessarily be true at smaller spatial scales or for watersheds with larger amounts of urban development.

3.3.6 Ground Water

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 ground water 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 ground water resources. However, warmer, wetter winters could increase the amount of water available for ground water recharge. Projected ground water 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.

Earman and Dettinger (2011) discuss four ways that climate change could affect ground water systems: changes in precipitation amounts; the temporal distribution of precipitation; changes in the form of precipitation; and potential changes in evaporation, transpiration, and pumping rates. The response of the aquifer to each of these potential change mechanisms likely will be different depending of the physical characteristics.

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.

Agricultural water demands include those associated with crop irrigation and livestock consumption. The predominant water demand in the Western U.S. is for agricultural irrigation. Between 80 and 90% of the consumptive use water demand in the U.S. is for irrigation (Schaible and Aillery, 2012). 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 conditions lead to uncertainties in future irrigation demands. Frisvold and Konyar (2012) examined scenarios of how agriculture in the Southwestern States might adopt to the impacts of climate change on the water supply, and found that while overall agriculture in the region was resilient to modest decreases in water supply, particular crops (cotton, alfalfa) were vulnerable.

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 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).

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. The authors discuss that snowmaking during the early and late ski season may not be feasible due to high temperatures as early as 2050, thus reducing associated water demands.

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. Water conservation measures may offset potential increases in per capita water usage regardless of potential climate change-related increases in domestic water demands. Although the use of new water efficient appliances and fixtures will increase through institutional measures and mandates, socioeconomic factors will impact water conservation. EPA (2010) describes the activities of eight large U.S. water utilities who have conducted climate vulnerability assessments, including projections of future domestic water demands. Aggarwal et al. (2012) examined how temperatures influence household water use in Phoenix, AZ, and concluded that each degree F rise in nighttime temperatures increased water use by 1.4%, although this value depends on the size of the lot and any pool.

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. Avery et al., 2011 reports on research into the water demands of thermoelectric energy production in the context of climate variability and change.

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 also could 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 (Hay et al. 2011). 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 gradually would decrease over time, albeit with substantial year-to-year and decade-to-decade fluctuations due to natural climate variability (Deser et al. 2012). 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 (e.g., Das et al. 2011). 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 will not 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; Pierce and Cayan 2012), 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).

A number of studies have examined the effect of climate change on the Colorado River water supply system (McCabe and Wolock 2007; Barnett and Pierce 2008, 2009a; Rajagopalan et al. 2009). The general picture is that currently scheduled delivery increases, combined with decreasing inflow to the reservoir system and greater evapotranspiration losses from climate change, would increase the probability and likely duration of delivery shortages in coming decades. A natural reversion to the lower long-term mean flow in the Colorado River suggested by tree ring records, if it happened, would exacerbate this situation.

3.4.2 Flood Control

In Western U.S. 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 Region 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.

Wenger et al. (2011) report on climate change impacts on Western U.S. trout species. Instead of analyzing the effect on fish habitat due to temperature alone, this study analyses the effects of temperature, flow regime, and biotic interactions, all of which are estimated under differing climate change scenarios. The study reports a decline of suitable native cutthroat trout habitat of 28% in the 2040s and 58% by the 2080s. Nonnative brook trout habitat is expected to be reduced by 44 and 77% in the 2040s and 2980s, respectively. Rainbow and brown trout are expected to see a more modest reduction of suitable habitat in the 2040 and 2080 time periods. Rainbow trout habitat is projected to decline 13% in the 2040s and 35% in the 2080s. Brown trout habitat is estimated to realize a 16 and 48% reduction, respectively, over the same time period.

3.4.5 Water Quality

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

A recent preliminary report for EPA's Global Change Research Program "20 Watersheds Project" (Johnson et al. 2011) describes the overall structure of the ongoing effort (methods, sites, models, and scenarios) and discusses preliminary results. The goal of this work is to provide an improved understanding on a number of uncertainties associated with assessments of climate change impacts on water quality, including the use of different climate models, downscaling tools and methods, watershed models, land-use change scenarios, and process representations. Preliminary results from 5 of the 20 study sites suggest that sensitivity to climate change differs for mean flow, flow extremes, and sediment/nutrient loading, reflecting the different combination of hydrometeorological processes and spatial and temporal scales involved in each. Also, there is a strong sensitivity of the modeled flow and water quality endpoints to the climate model, downscaling approach, and combination of climate variables applied in the watershed simulations. At the scale of the large watersheds studied so far, sensitivity to climate change dominates over sensitivity to urban development, but it appears this will not necessarily be true at smaller spatial scales or for watersheds with larger amounts of urban development.

3.4.6 Ground Water

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 ground water 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 ground water resources. However, warmer wetter winters could increase the amount of water available for ground water recharge. It has not been demonstrated how much of this additional winter runoff can be captured and utilized without using artificial recharge schemes.

Earman and Dettinger (2011) discuss four ways that climate change could affect ground water systems: changes in precipitation amounts; the temporal distribution of precipitation; changes in the form of precipitation; and potential changes in evaporation, transpiration and pumping rates. The response of the aquifer to each of these potential change mechanisms will likely be different depending of the physical characteristics.

3.4.7 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 U.S. is for agricultural irrigation. Between 80 and 90% of the consumptive use water demand in the U.S. is for irrigation (Schaible and Aillery, 2012). 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 conditions lead to uncertainties in future irrigation demands. Frisvold and Konyar (2012) examined scenarios of how agriculture in the Southwestern States might adopt to the impacts of climate change on the water supply, and found that while overall agriculture in the region was resilient to modest decreases in water supply, particular crops (cotton, alfalfa) were vulnerable.

Using the Precipitation Runoff Modeling System to simulate the Yampa and East River Basins in Colorado, Hay et al. (2011) found that soil moisture on an annual basis decreased under climate change conditions, which may indicate an overall increase in agricultural demands. Interestingly, the model showed higher soil moisture levels during the winter month primarily due to increase snowpack melting and changes in precipitation.

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 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. Water conservation measures may offset potential increases in per capita water usage regardless of potential climate change related increases in domestic water demands. Although the use of new water efficient appliances and fixtures will increase through institutional measures and mandates, socioeconomic factors will impact water conservation. EPA (2010) describes the activities of eight large U.S. water utilities who have conducted climate vulnerability assessments, including projections of future domestic water demands.

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. Avery et al., 2011 reports on research into the water demands of thermoelectric energy production in the context of climate variability and change.

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 also could 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, particularly in the mountainous areas (Hay et al. 2011), 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). Regardless, annual precipitation will continue to vary at interannual and interdecadal time scales as it has in the past.

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 will not 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 likely would translate into reductions in storage capture and, likewise, reductions in water supply for warm season delivery.

3.5.2 Flood Control

In Western U.S. 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). Luizzo et al. (2009) studied the impact of climate change on water resources in a northeastern Oklahoma basin in the eastern GP Region. A hydrologic model was used to estimate the basin's surface and ground water using current data and future climate scenarios. An increase in precipitation was found across the basin. Their conclusions find that the increases in precipitation are translated much more strongly into surface water than ground water. Evapotranspiration is slightly affected. This leads to higher runoff rates and increased flood risks.

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 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.

Wenger et al. (2011) evaluate climate change impacts on Western U.S. trout species. Instead of analyzing the effect on fishery habitat due to temperature alone, this study analyses the effects of temperature, flow regime, and biotic interactions, all of which are estimated under differing climate change scenarios. The study reports a decline of suitable native cutthroat trout habitat of 28% in the 2040s and 58% by the 2080s. Nonnative brook trout habitat is expected to be reduced by 44 and 77% in the 2040s and 2980s, respectively. Rainbow and brown trout are expected to see a more modest reduction of suitable habitat in the 2040 and 2080 time periods. Rainbow trout habitat is projected to decline 13% in the 2040s and 35% in the 2080s. Brown trout habitat is estimated to realize a 16 and 48% reduction, respectively, over the same time period.

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.

A recent preliminary report for EPA's Global Change Research Program "20 Watersheds Project" (Johnson et al. 2011) describes the overall structure of the ongoing effort (methods, sites, models, and scenarios) and discusses preliminary results. The goal of this work is to provide an improved understanding on a number of uncertainties associated with assessments of climate change impacts on water quality, including the use of different climate models, downscaling tools and methods, watershed models, land-use change scenarios, and process representations. Preliminary results from 5 of the 20 study sites suggest that sensitivity to climate change differs for mean flow, flow extremes, and sediment/nutrient loading, reflecting the different combination of hydrometeorological processes and spatial and temporal scales involved in each. Also, there is a strong sensitivity of the modeled flow and water quality endpoints to the climate model, downscaling approach, and combination of climate variables applied in the watershed simulations. At the scale of the large watersheds studied so far, sensitivity to climate change dominates over sensitivity to urban development, but it appears this will not necessarily be true at smaller spatial scales or for watersheds with larger amounts of urban development.

3.5.6 Ground Water

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 ground water 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 ground water 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 ground water recharge. It has not been demonstrated how much of this additional winter runoff can be captured and utilized without using artificial recharge schemes.

Earman and Dettinger (2011) discuss four ways that climate change could affect ground water systems: changes in precipitation amounts; the temporal distribution of precipitation; changes in the form of precipitation; and potential changes in evaporation, transpiration, and pumping rates. The response of the aquifer to each of these potential change mechanisms will likely be different depending of the physical characteristics.

3.5.7 Water Demand

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Ojima and Lacket (2002) discuss climate change water demand impacts in the Great Plains under four scenarios. The impacts are addressed within the context of critical issues including managing the impacts, laws and institutional factors, and population growth and urban development plans. Using the Precipitation Runoff Modeling System to simulate the Starkweather River Basin in North Dakota, Hay et al. (2011) found that soil moisture on an annual basis decreased under climate change conditions, which may indicate an overall increase in agricultural demands.

Agricultural water demands include those associated with crop irrigation and livestock consumption. The predominant water demand in the Western U.S. is for agricultural irrigation. Between 80 and 90% of the consumptive use water demand in the U.S. is for irrigation (Schaible and Aillery, 2012). 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 conditions 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 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 20^{th} century; and it is projected that, by the end of the 21^{st} century, it will be more than 2 weeks longer than typical of the late 20^{th} century (Gutowski et al. 2008). Gunther et al. (2006) predict significant increases in 21^{st} 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. Water conservation measures may offset potential increases in per capita water usage regardless of potential climate change related increases in domestic water demands. Although the use of new water-efficient appliances and fixtures will increase through institutional measures and mandates, socioeconomic factors will impact water conservation. EPA (2010) describes the activities of eight large U.S. water utilities who have conducted climate vulnerability assessments, including projections of future domestic water demands.

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 also could 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 maps that summarize changes in climatological precipitation and temperature expressed by two generations of downscaled climate projections. Changes are assessed at three future periods (2010–2039, 2040–2060 and 2070–2099) relative to a common historical period in the climate simulations (1970–1999). 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

Contemporary global climate projections have been made available through the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (CMIP). CMIP phase 3 (CMIP3[42], available online at: http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php) has informed climate change impacts research since the release of the IPCC AR4 (IPCC 2007). The CMIP3 dataset features simulation of future climates using multiple global climate models, considering multiple future pathways for GHG emissions (i.e., the SRES emission scenarios from Nakićenović and Swart (2000)), 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). WCRP has recently released the next generation of global climate projections through CMIP phase 5 (CMIP5[43]), likewise produced using a collection of climate models, forced by a collection of GHG emissions scenarios, and from multiple initial climate states. However, CMIP5 projections differ from CMIP3 in that they were produced using next-generation climate models. The CMIP5 models as a set are generally higher resolution than the older CMIP3 models, and often have improved physical parameterizations that represent recent advancements in climate science.

As mentioned, the CMIP5 models are forced by a new set of future climate forcing scenarios called representative concentration pathways, or RCPs (van Vuuren et al. 2011). Without going into the specifics of how the SRES and RCP scenarios were developed, one may draw impressions about their aggregate implications for global climate by evaluating projected global mean air

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[42] Available online at: http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php.

[43] Available online at: http://cmip-pcmdi.llnl.gov/cmip5/.

temperature under each scenario (**figure 1**). It is evident that the RCPs considered in CMIP5 leads to global mean temperature responses that generally encompass CMIP3 responses associated with three SRES scenarios that are commonly referenced in the literature (B1, A1b and A2). The graphical results introduced later in this section focus on the same set of four RCP and three SRES scenarios as shown in **figure 1**. Within this context, it's clear that the CMIP5 results are informed by emissions scenarios and global mean temperature responses that are higher (RCP 8.5) and lower (RCP 2.6) than comparable extreme SRES paths in the CMIP3 results (A2 and B1, respectively). In particular RCP2.6 features a strong mitigation assumption, with emissions peaking in the middle of the century and then becoming negative later on, thus causing concentrations of GHGs and consequently temperature changes to decrease in the second part of the 21st Century. No such mitigation scenario was assumed among the SRES run by CMIP3. This helps build expectation that the family of CMIP5 results may include warmer and cooler projections than those featured among the CMIP3 results.

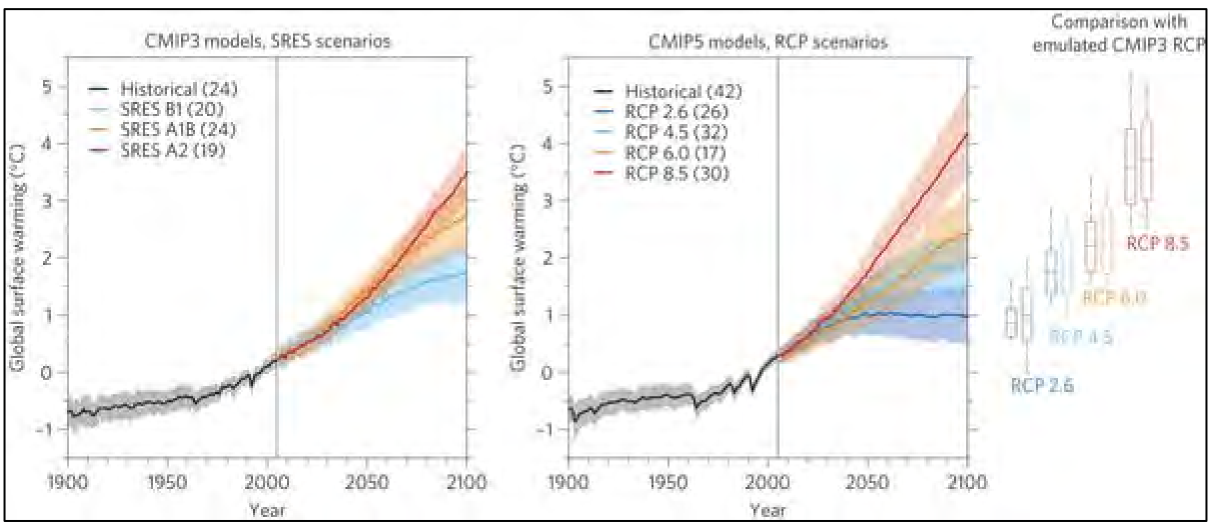

Figure 1.—Knutti, R. and J. Sedláček. 2012. "Robustness and uncertainties in the new CMIP5 climate model projections," Nature Climate Change, DOI:10.1038/nclimate1716.

Comparison of Global Mean Temperature Projections from CMIP3 and CMIP5. Global temperature change (mean and one standard deviation as shading) relative to 1986–2005 for the SRES scenarios run by CMIP3 and the RCP scenarios run by CMIP5. The number of models is given in brackets. The box plots (mean, one standard deviation, and minimum to maximum range) are given for 2080–2099 for CMIP5 (colors) and for the MAGICC model calibrated to 19 CMIP3 models (black), both running the RCP scenarios. (Figure courtesy of R. Knutti and J. Sedláček, 2012).

The collective of CMIP3 and CMIP5 global climate models simulate climate at spatial resolutions ranging from roughly 100 to 500 kilometers. Therefore, they are unable to resolve climate variations at much finer resolutions, which are relevant to analysis of hydrology, water resources, and environmental conditions. For example, 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 U.S. where there are strong gradients in temperature and associated hydrologic structure. To relate these global climate projections to such local conditions, a regionalization process is necessary, involving the translation of spatially coarse output from the global climate models to basin-scale information (i.e., "downscaling").

Many CMIP3 and CMIP5 projections have been downscaled for the contiguous U.S. using a statistical technique (i.e., monthly "bias correction and spatial disaggregation" (BCSD), described in Wood et al. 2002). Results have been made publically available (i.e., Archive)[44] along with information about the downscaling technique[45] as well as discussion of its limitations, strengths, and weaknesses relative to other downscaling methods.[46]

The Archive's BCSD CMIP3 ensemble represents 112 CMIP3 projections produced collectively by 16 CMIP3 climate models. Model inclusion in this archive was based on a criterion, applied in summer 2007, that each model must have simulated three different GHG emissions pathways (Nakićenović and Swart 2000) 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 degree (approximately [~]12 kilometers or ~7.5 miles) over the contiguous U.S. Harding et al. (2012) used these projections to examine the spread of model predictions of changes in Colorado River flow at Lees Ferry.

The Archive's BCSD CMIP5 ensemble represents 234 CMIP5 projections produced collectively by 37 CMIP5 climate models. Model inclusion in this archive was based on a criterion, applied in summer 2012, that each model should have simulated four of the new GHG emissions scenarios (i.e., Representative Concentration Pathways, described in van Vuuren et al. 2011) at least once (where multiple simulations reflect the simulations starting from different initial

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[44] "Bias-Corrected and Downscaled WCRP CMIP3 and CMIP5 Climate and Hydrology Projections" available online at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html.

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

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

condition estimates of the climate system [i.e., "runs" reflecting different initializations]). Each BCSD CMIP5 projection dataset has the same attributes as a BCSD CMIP3 projection dataset.

The downscaling technique features the subjective choice to compensate for climate model biases (bias-correction). 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 CMIP3 and CMIP5 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.

This method of bias correction was applied to 21st century temperature projections in a way such that the global model's temperature trend was preserved during the bias correction (i.e., so that the bias-corrected, downscaled projection has a 21st century warming trend that matches that of the original global model projection). In contrast, the method was applied to 21st century global model precipitation projections without preserving trend. Assessment of CMIP3 bias-corrected precipitation projections shows that this systematically led to wetter precipitation trends (by up to a few percent) in the bias-corrected, downscaled projections when compared to the original global model projections over much of the Western U.S. (Reclamation 2011c[47]). This bias-correction effect is small compared to the ensemble spread of projected trends. However, if one focuses on ensemble-median information and considers that runoff elasticity to climatological precipitation changes[48] exceeds 2 for many Western U.S. basins (e.g., 2 to 4 for the Upper Colorado River runoff at Lees Ferry [Vano et al. 2012]), it is apparent that just a few percent increase in projected future precipitation trend in the downscaled data (due to the bias correction technique) could lead to a significant increase in projected runoff in the downscaled data that is absent in the original global model projection. Or, in cases where the original global model projected a runoff decrease, this could lead to a reduction of the projected runoff decrease in the downscaled data.

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[47] Available online at: http://www.usbr.gov/WaterSMART/docs/west-wide-climate-risk-assessments.pdf.

[48] Runoff elasticity is defined here as the percentage change in mean-annual runoff given a percent change in mean-annual precipitation.

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 2011–2039 to 2070–2099. These changes in period-mean climate always are assessed relative to the same model's reference period of 1970–1999. Note that the historical data used to develop these maps are not "observed" historical climate data. They are simulated historical data included in the CMIP3 and CMIP5 simulations. In each historical simulation, a given GCM was forced by estimated time series atmospheric condition (1900–1999) and starting from an estimated initial climate condition in year 1900 (sometimes from multiple initial conditions, leading to multiple historical "runs").[49] As a result, the Archive contains a set of "historical climates" for both CMIP3 and CMIP5 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. Changes were computed using the following procedure:

- Use monthly BCSD precipitation and temperature sources (CMIP3 and CMIP5) and compute period-change in mean-annual precipitation (percent) and temperature (ºC) for each projection and grid cell.
- For models that have more than one projection available (i.e., starting at different initial conditions), pool changes for that climate model at every grid cell and compute the model's average change (i.e., model-specific change pattern).
- Pool model-specific change patterns for all available models and compute the ensemble-median (50th percentile) change (i.e., from 16 model-specific patterns in CMIP3 and from 37 model-specific patterns in CMIP5).
- Map the ensemble-median change by future period (2010–2039, 2040–2069, or 2070–2099) and source (CMIP3 or CMIP5). Then map difference in changes by source (CMIP5 minus CMIP3) for each future period.

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[49] For CMIP3 correspondence, see http://www-pcmdi.llnl.gov/ipcc/time_correspondence_summary.htm.
To understand CMIP5 correspondence, see "Ensemble Member" in http://cmip-pcmdi.llnl.gov/cmip5/docs/cmip5_data_reference_syntax_v0-25_clean.pdf.

Note that this procedure differs slightly from that used to generate appendix B maps in the first edition (Reclamation 2009) of this literature synthesis, which was left unchanged for the second edition. The earlier procedure assumed all projections to be equally plausible and, thus, the mapped changes were simply the ensemble-median of all projection-specific changes.[50] The equal plausibility assumption still holds in this updated procedure, but the modification is done to balance the climate models' influence on the mapped changes rather than let the more prolific climate modeling groups have their results cast greater influence on the changes shown. This is important since some models supply five times more simulations than other models, yet there is no evidence that models with more simulations are of systematically better quality.

4.3 Interpreting the Map Summaries for Each Region

It is recommended that the maps be interpreted as follows:

- All climate models informing the BCSD CMIP3 and CMIP5 projection ensembles have generally equal influence on the changes shown.
- All of the projections included in the BCSD CMIP3 and CMIP5 ensembles 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 change among all of the model-specific change patterns to get a sense about mean projected climate change at that point in the future.
- 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. The maps invite focus on climate change trends and deter attention from the reality that there are uncertainties about such projected trends. Uncertainties arise

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[50] The assumption of equal plausibility was supported by 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).

from the future scenarios of GHG emissions forcing future climate, climate model formulation (as described above), the model's simulation of internal natural variability, 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 2008, Reservoir Management Joint Operating Committee [RMJOC 2011], and Colorado Water Conservation Board [CWCB] 2012), 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 (as alluded to at the end of section 4.1).

Many scientists have expressed reservations about combining projection results from multiple emissions scenarios. For example, some regard the RCP2.6 as an optimistic and unlikely scenario, and therefore it should not be included in with projections from the other scenarios in order to characterize future climate possibilities for vulnerability assessment and adaptation planning purposes. Despite these cautions, the following graphics resources present results abstracted from the multi-emissions, multi-model ensemble of opportunity, noting that this is consistent with past practice in the impacts community and that there remains an absence of guidance from the climate science community on whether certain future emissions scenarios are indeed less likely than others that are available.

Even if the models were perfect, the actual climate change the Earth will experience will differ from the mean model-estimated climate change due to natural variability such as El Niño , La Niña, and the Pacific Decadal Oscillation (e.g., Deser et al. 2012). The smaller the region and the shorter the period being considered, the more natural variability will dominate; the larger the region and longer the time period, the more natural variability will be averaged out and human-caused climate change will dominate.

This summary of the ensemble median fails to convey the large spread among different ensemble members that indicates a wide range of climate sensitivities in different models, particularly for precipitation. The summary also does not address how projected changes are attributable to anthropogenically-forced trends and internal (natural) variability within the climate models. Focusing on the ensemble medians should not be misinterpreted as the predicted condition; rather, it is one of many plausible scenarios.

This summary focuses on annual changes. It is understood that many water and environmental resource systems depend not on just the change in annual climatology, but also changes in seasonal to monthly characteristics. Technical readers may refer to the monthly BCSD data sources supporting these graphical resources to develop similar assessments of seasonal to monthly changes.

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

- For *mean-annual precipitation*, BCSD CMIP3 ensemble median suggests a trend toward slightly wetter conditions by the early 21st century for northern portions of the region (i.e., Washington, northern Idaho, northern Oregon, and northwestern Montana), and toward more significantly wetter conditions by the late 21st century over the nearly the entire region. BCSD CMIP5 is similar to BCSD CMIP3 throughout the region, except with slightly less projected precipitation increase over the central to northern portions of the region by the late 21st century. More specifically, for these portions of the PN Region, the maps show that late 21st century projected changes in mean-annual precipitation are up to 3% less in BCSD CMIP5 compared to those in BCSD CMIP3.

- 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. BCSD CMIP5 differs slightly from BCSD CMIP3 in that projected warming in higher latitudes is expected to be slightly greater (i.e., by roughly 0.5 to 0.7 ºC).

The MP Region maps could be interpreted as follows:

- For *mean-annual precipitation*, BCSD CMIP3 suggests a tendency toward drier conditions developing over southern portions of the region (i.e., southern California 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 the late 21st century. In contrast, BCSD CMIP5 suggests a trend toward slightly wetter conditions throughout the region by the early 21st century, transitioning to more significant precipitation increases over much of the region by the late 21st century (particularly within the Great Basin). This leads to differences in MP Region precipitation trends from BCSD CMIP3 to CMIP5 being roughly 0 to +5% in the early 21st century transitioning to roughly 0 to +15% in the 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. BCSD CMIP3 and CMIP5 results are generally consistent with differences generally between plus or minus 0.3 ºC, and with a tendency towards cooler BCSD CMIP5 conditions over much of the region by late 21st century.

The LC Region maps could be interpreted as follows:

- For *mean-annual precipitation*, BCSD CMIP3 suggests an evolving tendency towards drier conditions for most of the region through the 21st century. BCSD CMIP5 suggests this tendency towards drier conditions is more confined to the southeastern portions of LC Region, with the remaining portion evolving toward wetter conditions. This leads to differences in LC Region precipitation trends from BCSD CMIP3 to CMIP5 similar to the ranges found for the MP Region.

- 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. Like the MP Region, BCSD CMIP3 and CMIP5 results are generally consistent with differences generally between plus or minus 0.3 ºC, and with a tendency towards cooler BCSD CMIP5 conditions over much of the region by the late 21st century.

The UC Region maps could be interpreted as follows:

- For *mean-annual precipitation*, BCSD CMIP3 suggests that, for much of the central and southern portions of the region (i.e., New Mexico, northeastern Arizona, southwestern Colorado, and southern Utah), there is an evolving tendency towards a drier condition during the 21st century. For the northern portions of region (northwestern Colorado, northern Utah, southwestern Wyoming), the projections suggest wetter conditions. BCSD CMIP5 suggests that the boundary of evolving drier versus wetter conditions shifts so that the area of evolving drier conditions is confined to generally the southeastern portions of the UC Region (i.e., the Rio Grande and Pecos Basins over New Mexico). This leads to differences in UC Region precipitation trends from BCSD CMIP3 to CMIP5 that differ markedly for the Colorado River Basin compared to the Rio Grande and Pecos Basins. For the Colorado River Basin, differences range from roughly 0 to +5% in the early 21st century transitioning to roughly 0 to +15% in the late 21st century. For the Rio Grande and Pecos Basins, the two CMIP sources offer more comparable results, with differences being generally within plus or minus 3% throughout much of the 21st century.

- For *mean-annual temperature*, the projections suggest mostly uniform amounts of warming throughout the region through the 21st century. BCSD CMIP3 and CMIP5 results are generally consistent with differences generally between plus or minus 0.3 ºC, and with a tendency towards cooler BCSD CMIP5 conditions over much of the region by the late 21st century, particularly over the Rocky Mountain headwaters of the Colorado and Rio Grande River Basins.

The GP Region maps could be interpreted as follows:

- In terms of *mean-annual precipitation*, a pronounced northeast-southwest gradient of projected precipitation changes exists for each future simulation period. BCSD CMIP3 suggests that much of the central and northern portions of the region (e.g., Missouri Basin, Kansas, northeastern Colorado, portions of Oklahoma and Texas) would experience trends towards 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). The northeast-southwest gradient exists in each simulation period, but becomes stronger as the 21st century advances, as does the magnitude of the precipitation increases or decreases. Throughout all three future periods a demarcation area persists from the lee of the Rockies in Wyoming down through southern Oklahoma and northern Texas, showing increases in the northeast and decreases in the southwest. BCSD CMIP5 suggests a similar northeast-southwest divide for evolving wetter versus drier conditions, and with the position of this divide being generally similar between the sources. There still exist large differences between the BCSD CMIP3 and CMIP5 depictions, especially in the northeast GP Region. For example, projected increases over South Dakota, Nebraska, and northern Kansas are roughly 0 to 7% less in BCSD CMIP5 compared to BCSD CMIP3.

- In terms of *mean-annual temperature*, the projected warming is generally uniform across the region and increasing through the 21st century. BCSD CMIP3 and CMIP5 results are generally consistent over the central and southern portions of GP Region, with differences generally between plus or minus 0.2 ºC. For the northern portion of GP Region, and especially the northeastern portion, BCSD CMIP5 projects warmer trends than BCSD CMIP3 by roughly 0.2 to 0.4 ºC in the early 21st century, transitioning to roughly 0.3 to 0.8 ºC in the late 21st century.

These results show that the BCSD CMIP3 and CMIP5 “ensembles of opportunity” express generally similar changes over large areas, but sometimes significantly different changes for more local regions. This is particularly notable in parts of the MP and UC regions, which generally lie beneath the transition zone between drier conditions to the south and wetter conditions to the north. The CMIP5 generation of models place the wetter/drier dividing line slightly more to the north than the CMIP3 models, leading to different climate projections for regions in the transition zone. The next level of inquiry is to understand why the projections differ and which are more reliable. Two potential factors are that CMIP5 projections are developed using a different collection of models—representing recent climate science advancements—and are forced by a collection of new climate forcing scenarios (Representative Concentration Pathways). Attributing the differences between CMIP5 and CMIP3 to these two factors remains a matter of research.

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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 Covered		Regions Covered				
	Global to Regional Climate Simulation and Analyses	Surface Water, Snowpack and Runoff	Sea Level Rise	Ecosystems, Wildfires and Agriculture	Water Quality	Ground Water	Drought	Water Demand	Reservoir System Operations	Extreme Precipitation, Floods and Flood Control	Hydroelectric Power	Historical	Future	PN	MP	LC	UC	GP
Aber et al. 2001				X									X	X	X	X	X	X
Adams et al. 2009				X									X			X	X	
Aggarwal et al. 2012								X				X				X		
Allan 2011										X			X	X	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	
Aneress et al. 2012				X								X	X	X	X	X	X	X
Andreadis and Lettenmaier 2006	X	X										X		X	X	X	X	X
Arismendi et al. 2012						X						X	X	X	X	X	X	X
Ashfaq et al. 2010	X	X											X	X	X	X	X	X
Ault et al. 2012	X						X					X	X	X	X	X	X	X
Ault et al. 2011	X			X								X		X	X	X	X	X
Bachelet et al. 2001	X			X									X	X	X	X	X	X
Badh and Akyuz 2010	X											X						X
Badh and Akyuz 2010	X											X						X
Badh et al. 2009	X											X						X
Bala et al. 2008	X											X	X	X	X	X	X	X
Baldocchi and Wong 2006				X				X					X		X	X		
Bales et al. 2006				X				X				X		X	X	X	X	X
Bardossy and Pegram 2012	X												X	X	X	X	X	X
Bark et al. 2009								X					X			X		

Peer-Reviewed Journal Articles

Journal Articles (Peer Reviewed)	Resource Theme(s)											Time Covered		Regions Covered				
	Global to Regional Climate Simulation and Analyses	Surface Water, Snowpack and Runoff	Sea Level Rise	Ecosystems, Wildfires and Agriculture	Water Quality	Ground Water	Drought	Water Demand	Reservoir System Operations	Extreme Precipitation, Floods and Flood Control	Hydroelectric Power	Historical	Future	PN	MP	LC	UC	GP
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. 2011				X								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		
Bentz et al. 2010				X									X	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
Brikowski 2008		X				X						X	X					X
Brooks et al. 2012			X									X			X			
Bromirski et al. 2011										X		X	X	X	X			

Peer-Reviewed Journal Articles																		
	Resource Theme(s)											Time Covered		Regions Covered				
Journal Articles (Peer Reviewed)	Global to Regional Climate Simulation and Analyses	Surface Water, Snowpack and Runoff	Sea Level Rise	Ecosystems, Wildfires and Agriculture	Water Quality	Ground Water	Drought	Water Demand	Reservoir System Operations	Extreme Precipitation, Floods and Flood Control	Hydroelectric Power	Historical	Future	PN	MP	LC	UC	GP
Brown et al. 2004	X			X									X	X	X	X	X	X
Brown and Mote 2009	X	X										X		X	X	X	X	X
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				
Castro et al. 2012	X												X			X	X	X
Cavazos and Arriga-Ramirez 2012	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
Chen et al. 2011				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	
Chou and Lan 2011	X												X	X	X	X	X	X
Christy 2012		X										X			X			
Church and White 2006			X									X			X			
Clement et al. 2011	X											X	X	X	X	X	X	X
Cloern et al. 2010		X	X	X	X								X		X			
Clow 2010		X										X					X	X
Cohen et al. 2012	X												X	X	X	X	X	X
Cohen et al. 2010	X												X	X	X	X	X	X

Peer-Reviewed Journal Articles

	Resource Theme(s)											Time Covered		Regions Covered				
Journal Articles (Peer Reviewed)	Global to Regional Climate Simulation and Analyses	Surface Water, Snowpack and Runoff	Sea Level Rise	Ecosystems, Wildfires and Agriculture	Water Quality	Ground Water	Drought	Water Demand	Reservoir System Operations	Extreme Precipitation, Floods and Flood Control	Hydroelectric Power	Historical	Future	PN	MP	LC	UC	GP
Cohen et al. 2007	X												X	X	X	X	X	X
Cole et al. 2010				X								X	X			X		
Conley and Kemp 2001				X								X						X
Cook et al. 2010							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
Crozier 2011	X			X								X	X	X				
Crozier et al. 2012				X									X	X				
Dai 2012							X					X	X	X	X	X	X	X
Dai 2006	X												X	X	X	X	X	X
Dai et al. 2009		X										X		X	X	X	X	X
Das et al. 2011		X								X			X		X			
Das et al. 2009		X										X		X	X	X	X	X
DeFalco et al. 2007				X									X			X		
Degu et al. 2011																		
Derksen and Brown 2012		X										X		X	X	X	X	X
Deser et al. 2012	X												X	X	X	X	X	X
Deser et al. 2010	X												X	X	X	X	X	X
Dettinger 2011										X			X		X			
Dettinger 2005	X												X		X	X		
Dettinger et al. 2011	X	X										X			X	X		

Peer-Reviewed Journal Articles

Journal Articles (Peer Reviewed)	Resource Theme(s): Global to Regional Climate Simulation and Analyses	Surface Water, Snowpack and Runoff	Sea Level Rise	Ecosystems, Wildfires and Agriculture	Water Quality	Ground Water	Drought	Water Demand	Reservoir System Operations	Extreme Precipitation, Floods and Flood Control	Hydroelectric Power	Time Covered: Historical	Future	Regions Covered: PN	MP	LC	UC	GP
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. 2010	X	X											X	X	X	X	X	X
Diffenbaugh et al. 2008	X												X	X	X	X	X	X
Diffenbaugh et al. 2005	X			X						X			X	X	X	X	X	X
Dominguez et al. 2012										X			X	X	X	X	X	X
Dominguez et al. 2010	X												X			X	X	X
Donoghue 2011			X									X	X					X
Duliere et al. 2011										X			X	X	X	X	X	X
Dunnell and Travers 2011				X								X						X
Dyer and Mote 2006		X										X		X	X	X	X	X
Earman and Dettinger 2011						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

Peer-Reviewed Journal Articles

Journal Articles (Peer Reviewed)	Resource Theme(s): Global to Regional Climate Simulation and Analyses	Surface Water, Snowpack and Runoff	Sea Level Rise	Ecosystems, Wildfires and Agriculture	Water Quality	Ground Water	Drought	Water Demand	Reservoir System Operations	Extreme Precipitation, Floods and Flood Control	Hydroelectric Power	Time Covered: Historical	Future	Regions Covered: PN	MP	LC	UC	GP
Ficke et al. 2007				X									X	X	X	X	X	X
Frank 2011				X									X					X
Frisvold and Konyar 2012				X				X					X			X	X	X
Fritze 2011		X										X		X	X	X	X	X
Gangopadhyay and McCabe 2010												X	X			X	X	
Gangopadhyay et al. 2009												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
Gershunovand Guirguis 2012	HEAT WAVES												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
Gleeson et al. 2011																		
Gober et al. 2010	X							X					X			X		
Goderniaux et al. 2009														X	X	X	X	X
Green 2011						X							X					
Groisman 2012										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

Peer-Reviewed Journal Articles

Journal Articles (Peer Reviewed)	Resource Theme(s)											Time Covered		Regions Covered				
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Gutmann et al. 2012	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
Hamlet and Lettenmaier 1999		X							X				X	X				
Hamlet et al. 2010											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
Hanson et al. 2012		X				X							X		X			
Harding et al. 2012a		X											X			X	X	
Harding et al. 2012b		X											X			X	X	
Harding and Snyder 2012a		X				X		X				X						X
Harding and Snyder 2012b		X											X			X	X	
Harou et al. 2010	X	X							X		X		X		X	X		
Harpold et al. 2012		X										X				X	X	X
Hay 2011																		
Hay et al. 2011		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	

Peer-Reviewed Journal Articles

Journal Articles (Peer Reviewed)	Resource Theme(s)											Time Covered		Regions Covered				
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Hoekema et al. 2010	X	X						X	X				X	X				
Hoerling et al. 2012		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
Isaak et al. 2011				X	X							X		X	X			
Islam et al. 2012								X					X					X
Johnson et al. 2005				X														X
Johnson et al. 2011	X	X			X								X	X	X	X	X	X
Joyce et al. 2009																		
Kalra and Ahmad 2011		X										X				X	X	
Kalra et al. 2008		X												X	X	X	X	X
Kapnick and Hall 2012		X										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
Knutti 2010	X												X	X	X	X	X	X
Ko et al. 2012				X								X	X					X

Peer-Reviewed Journal Articles																		
	Resource Theme(s)											Time Covered		Regions Covered				
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Konikow 2011						X						X		X	X	X	X	X
Kumar et al. 2012										X			X	X	X	X	X	X
Kunkel 2004				X								X		X	X	X	X	X
Kunkel 2003	X									X		X		X	X	X	X	X
Kunkel et al. 2012										X		X		X	X	X	X	X
Kunkel et al. 2009	X	X								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
Kunkel et al. 2003	X									X		X		X	X	X	X	X
Kunkel et al. 1998	X											X		X	X	X	X	X
Kustu et al. 2010		X				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	
Li et al. 2012										X			X	X	X	X	X	X
Lin et al. 2008	X												X	X	X	X	X	X
Litschert et al. 2012				X								X	X			X	X	X
Littell et al. 2010				X									X	X				
Littell et al. 2009	X			X									X	X				
Liu et al. 2012a		X										X	X	X	X	X	X	X

Peer-Reviewed Journal Articles

Journal Articles (Peer Reviewed)	Resource Theme(s)											Time Covered		Regions Covered				
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Liu et al. 2012a	X												X					X
Liuzzo et al. 2009		X				X							X					X
Loaiciga et al. 2000						X							X					X
Lobell et al. 2011	X			X								X		X	X	X	X	X
Logan et al. 2003				X									X	X	X	X	X	X
Luce and Holden 2009		X		X								X	X	X				
Lukas and Gordon 2010		X		X	X							X	X				X	X
Lundquist et al. 2009		X										X	X	X	X	X	X	X
Lutz et al. 2012		X										X		X				
MacDonald 2008	X	X										X				X		
MacDonald et al. 2008	X	X										X	X		X	X		
Madsen and Figdor 2007		X								X		X	X	X	X	X	X	X
Mahlstein et al. 2012	X												X	X	X	X	X	X
Mahoney et al. 2012										X			X				X	X
Mauget 2004		X										X						X
Maurer 2002		X										X		X	X	X	X	X
Mantua et al. 2009	X			X									X	X				
Marcarelli et al. 2010	X	X		X				X				X	X	X	X	X	X	X
Marinec and Rango 1989		X											X				X	
Markoff and Cullen 2008											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		

Peer-Reviewed Journal Articles

Journal Articles (Peer Reviewed)	Resource Theme(s): Global to Regional Climate Simulation and Analyses	Surface Water, Snowpack and Runoff	Sea Level Rise	Ecosystems, Wildfires and Agriculture	Water Quality	Ground Water	Drought	Water Demand	Reservoir System Operations	Extreme Precipitation, Floods and Flood Control	Hydroelectric Power	Time Covered: Historical	Future	Regions Covered: PN	MP	LC	UC	GP
Maurer et al. 2007		X										X			X			
McAfee and Russell 2008		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
McKenzie et al. 2004				X									X	X	X	X	X	X
McKinney et al. 2008				X								X				X		
Meehl et al. 2004	X												X	X	X	X	X	X
Meko et al. 2007	X	X										X					X	
Miller et al. 2011	X	X											X			X	X	
Miller and Schlegel 2006	X			X									X		X	X		
Milly et al. 2005		X											X	X	X	X	X	X
Min et al. 2011										X			X	X	X	X	X	X
Minder 2010	X	X											X	X				
Mohensi et al. 2003				X									X	X	X	X	X	X
Mohensi et al. 1999				X	X								X	X	X	X	X	X
Moritz et al. 2012				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

Peer-Reviewed Journal Articles

Journal Articles (Peer Reviewed)	Resource Theme(s)											Time Covered		Regions Covered				
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Mote et al. 2003		X		X									X	X				
Nardone et al. 2010				X			X						X	X	X	X	X	X
Nash and Gleick 1993	X	X											X			X	X	
Nash and Gleick 1991	X	X											X			X	X	
Nelson 2012						X						X	X		X	X		
Nelson et al. 2011	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
Ojima and Lackett 2002	X			X		X		X					X					X
Pagano et al. 2004	X											X		X	X	X	X	X
Painter et al. 2012a		X										X		X	X	X	X	X
Painter et al. 2012b		X										X				X	X	
Painter et al. 2010		X										X				X	X	
Painter et al. 2007		X												X	X	X	X	X
Pall et al. 2011										X			X	X	X	X	X	X
Pan et al. 2004	X												X					X
Passell et al. 2004		X										X					X	
Patricola and Cook 2012	X												X					X
Pavelsky et al. 2012		X											X		X			
Payne et al. 2004		X											X	X				
Pederson et al. 2011		X										X		X			X	
Peery et al. 2012				X									X			X	X	X

Peer-Reviewed Journal Articles

Journal Articles (Peer Reviewed)	Resource Theme(s)											Time Covered		Regions Covered				
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Peterson et al. 2008		X										X			X	X		
Pierce and Cayan 2012		X											X	X	X	X	X	X
Pierce et al. 2013										X			X		X	X		
Pierce, Ed. 2012										X			X		X	X		
Pierce et al. 2012a	X											X		X	X	X	X	X
Pierce et al. 2012b	X												X		X	X		
Peirce et al. 2011	X												X		X	X		
Peirce 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
Power et al. 2012	X	X											X	X	X	X	X	X
Purkey et al. 2008	X	X						X					X		X			
Raff et al. 2009										X			X	X	X		X	X
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 2012	X											X		X	X	X	X	X
Rangwala and Miller 2010	X											X					X	
Rangwala et al. 2012	X												X			X	X	X
Rasmusen et al. 2008																		

Peer-Reviewed Journal Articles

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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
Risley et al. 2010																		
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
Rothhausen and Conway 2011																		
Salzer et al. 2009				X								X			X			
Salzer and Kipfmueller 2005	X											X				X	X	
Santer et al. 2009												X		X	X	X	X	X
Santer et al. 2007	X											X		X	X	X	X	X
Scanlon et al. 2012						X						X			X			
Scanlon et al. 2007				X								X					X	X
Schalaepfer et al. 2012		X		X								X	X	X	X	X	X	X
Scroxton et al. 2011																		
Seager and Vecchi 2010	X												X		X	X	X	X
Seager et al. 2012a	X						X			X			X	X	X	X	X	X
Seager et al. 2012b		X										X				X	X	

Peer-Reviewed Journal Articles																		
	Resource Theme(s)											Time Covered		Regions Covered				
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Seager et al. 2007	X	X											X		X	X	X	X
Serrat-Capdevila et al. 2007	X	X											X			X		
Shaw et al. 2009	X	X		X								X	X		X	X		
Sheffield et al. 2012		X				X	X					X	X	X	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				
Sridar and Nayak 2010		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				
Stromberg et al. 2007				X								X	X			X		
Sun et al. 2007		X											X	X	X	X	X	X
Tague et al. 2012		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
Van Rheenen et al. 2004	X	X							X				X		X			
van Vuuren et al. 2011	X												X	X	X	X	X	X
Vano et al. 2012		X											X			X	X	

Peer-Reviewed Journal Articles

Journal Articles (Peer Reviewed)	Resource Theme(s)											Time Covered		Regions Covered				
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Vano et al. 2010	X								X				X	X				
Vermeer and Rahmstorf 2009			X									X	X		X			
Vicuna et al. 2010		X							X				X		X			
Villarini et al. 2009										X		x		X	X	X	X	X
Wagner et al. 2010	X		X	X									X		X			
Wang et al. 2011	X	X	X						X				X	X				
Washington et al. 2000	X											X	X	X	X	X	X	X
Watterson 2005												X	X	X	X	X	X	X
Watterson and Dix 2003	X	X										X	X	X	X	X	X	X
Weiss and Overpeck 2005	X											X				X		
Weiss et al. 2009	X	X										X				X	X	
Wenger et al. 2011				X									X	X	X		X	X
Westerling and Bryant 2008				X											X	X		
Westerling et al. 2011a				X									X		X	X		
Westerling et al. 2011b				X									X	X				X
Westerling et al. 2006				X								X		X	X	X	X	X
Wi et al. 2012		X										X				X	X	
Weiss et al. 2009		X		X			X					X				X	X	X
Wiens et al. 2009				X									X	X		X		
Wigley 2005	X		X										X	X	X	X	X	X
Williams et al. 2010				X								X	X			X	X	X
Williams et al. 2009				X									X				X	X
Williams et al. 2008				X								X	X			X		

Peer-Reviewed Journal Articles																		
	Resource Theme(s)											Time Covered		Regions Covered				
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Winder and Schindler 2004				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
Woodhouse et al. 2010	X											X	X	X	X	X	X	X
Woodhouse et al. 2006	X	X										X				X	X	
Wu et al. 2012		X										X	X	X				
Xia et al. 2012				X								X		X	X	X	X	X
Yin et al. 2011			X										X	X	X			
Yin et al. 2010			X										X		X	X		
Zang et al. 2007	X											X		X	X	X	X	X
Zhu and Newell 1998	X									X		X	X	X	X	X	X	X

Peer-Reviewed Synthesis Documents and Reports

Synthesis Documents and Reports (Peer Reviewed)	Resource Theme(s)											Time Covered		Regions Covered				
	Global to Regional Climate Simulation and Analyses	Surface Water, Snowpack and Runoff	Sea Level Rise	Ecosystems, Wildfires and Agriculture	Water Quality	Ground Water	Drought	Water Demand	Reservoir System Operations	Extreme Precipitation, Floods and Flood Control	Hydroelectric Power	Historical	Future	PN	MP	LC	UC	GP
Allan et al. 2005				X									X	X	X	X	X	X
Allan et al. 2005																		
Averyt et al. 2011								X				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															
Brekke et al. 2011	X	X		X	X			X	X	X	X		X	X	X	X	X	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
CEC 2009																		
CEQ 2011	X	X	X	X	X	X		X		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
CWCB 2012	X	X		X	X			X	X	X	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	
EPA 2010	X	X						X					X					
EPA 2009	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

Peer-Reviewed Synthesis Documents and Reports

Synthesis Documents and Reports (Peer Reviewed)	Resource Theme(s): Global to Regional Climate Simulation and Analyses	Surface Water, Snowpack and Runoff	Sea Level Rise	Ecosystems, Wildfires and Agriculture	Water Quality	Ground Water	Drought	Water Demand	Reservoir System Operations	Extreme Precipitation, Floods and Flood Control	Hydroelectric Power	Time Covered: Historical	Future	Regions Covered: PN	MP	LC	UC	GP
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				
NOAA 2013	X		X							X		X	X					X
NRC 2012			X									X	X	X	X	X		
Nakicenovic and Swart 2000	X												X	X	X	X	X	X
OCCRI 2010	X	X	X	X	X	X		X		X	X	X	X	X	X			
Overpeck et al. 2012		X		X						X		X	X			X	X	X
Parmesan 2006				X								X	X	X	X	X	X	X
Pierce (Ed) 2012 v. Root			X	X						X		X	X		X	X		
RMJOC 2011	X	X										X	X	X				
Reclamation 2011a	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X
Reclamation 2011b	X	X		X	X	X		X	X	X	X	X	X	X	X	X	X	X
Reclamation 2011c	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 2008	X	X	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
SFBCDC 2011			X									X	X		X			
Schaible and Aillery 2012								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 Covered		Regions Covered				
	Regional or Loca 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
Hoerling and Eischeid 2007	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
Travis 2007	X		X						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 projected changes in climatological precipitation and temperature expressed by two generations of downscaled climate projections, one using the earlier CMIP3 archive of global climate models and the other using the more recent CMIP5 archive (note that there was no CMIP4 archive).[1] The CMIP5 models generally have better resolution and upgraded physical parameterizations compared to the CMIP3 models. Climatological change is defined as change in 30-year mean annual condition. Changes are assessed at three future periods (2010–2039, 2040–2069, and 2070–2099) relative to a common historical period in the climate simulations (1970–1999). Downscaling is done using the statistical technique of bias correction and spatial disaggregation (BCSD; Wood et al. 2002). Chapter 4 describes the downscaled climate projections (section 4.1), how they were evaluated to generate the climate change maps in this appendix (section 4.2), and how the maps might be interpreted for climate change messages (section 4.3).

Maps in this appendix are organized as follows:

- There are six sections: one for each region showing region-specific maps and another for the Western U.S. showing maps for all regions' results.

- Each section includes 18 maps: 9 for precipitation and 9 for temperature.

- For each variable, the nine maps represent the three future change periods noted above and the following three cases: changes using models in the CMIP3 archive downscaled with BCSD, changes in the CMIP5 archive downscaled with BCSD, and the difference between the CMIP3 and CMIP5 projections.

- By inspecting the maps by column (from top to bottom map), the reader can gain a sense for what the CMIP3 and CMIP5 models express for a given future period (first and second rows) and how they differ (third row).

[1] Data source the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multimodel dataset available online at: 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 available online at: http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/.

Maps are available for use in other reports. Should you wish to use them, simply copy and paste the maps of interest from the following pages. It is suggested that maps be used in three-map sets for a given future period and variable (i.e., a single column of maps from the following pages). Given that case, the following caption may be used:

> Figure #.—Ensemble-median changes in climatological (precipitation or temperature) for (future period) relative to 1970–1999. Maps show changes from BCSD CMIP3 (top), changes from BCSD CMIP5 (middle), and their difference (bottom). Map values are based on BCSC CMIP3 and CMIP5 information available at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html. Development of map values is described in Bureau of Reclamation (2013).

Where Bureau of Reclamation (2013) is the reference for this literature synthesis:

Bureau of Reclamation (Reclamation). 2013. *Literature Synthesis on Climate Change Implications for Water and Environmental Resources, Third Edition*. Technical Memorandum 86-68210-2013-06, prepared by Bureau of Reclamation, U.S. Department of the Interior.

Pacific Northwest Region

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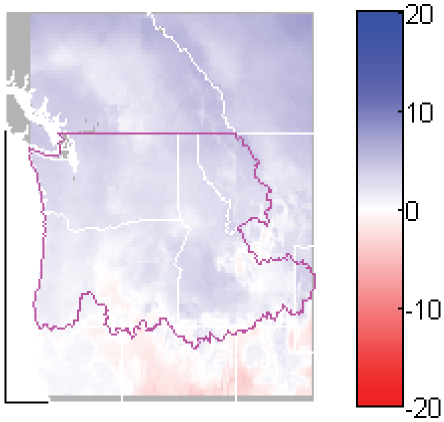
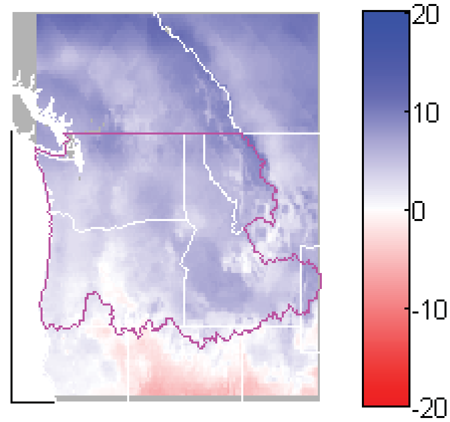
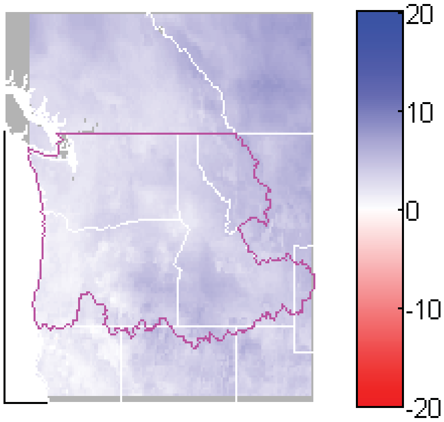
Mean-Annual Precipitation Change, percent
CMIP3,1970-1999 to 2010-2039,50%tile



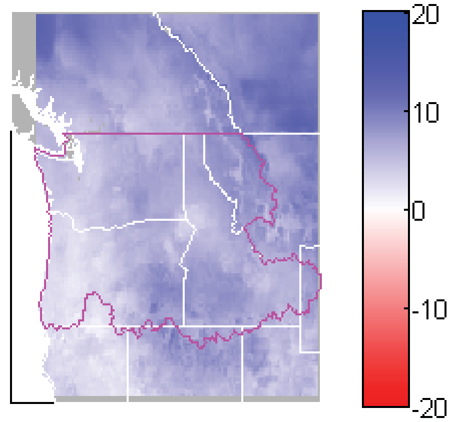
Mean-Annual Precipitation Change, percent
CMIP3,1970-1999 to 2040-2069,50%tile



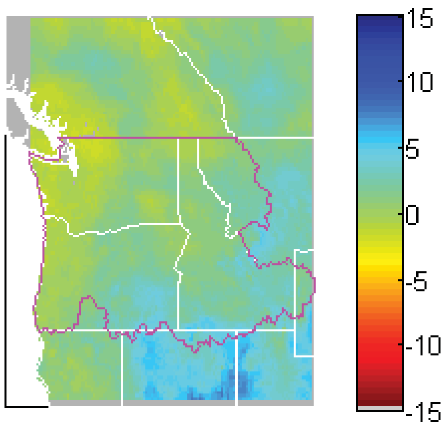
Mean-Annual Precipitation Change, percent
CMIP5,1970-1999 to 2010-2039,50%tile



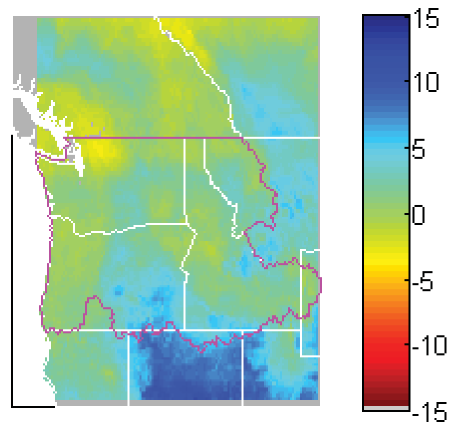
Mean-Annual Precipitation Change, percent
CMIP5,1970-1999 to 2040-2069,50%tile



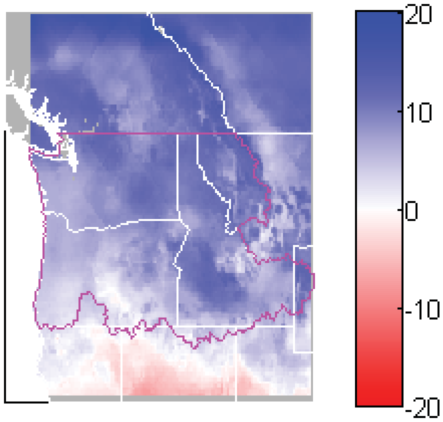
Mean-Annual Precipitation Change, percent
CMIP5-CMIP3,1970-1999 to 2010-2039,50%tile



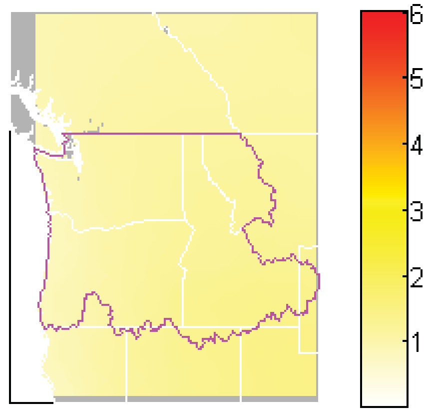
Mean-Annual Precipitation Change, percent
CMIP5-CMIP3,1970-1999 to 2040-2069,50%tile



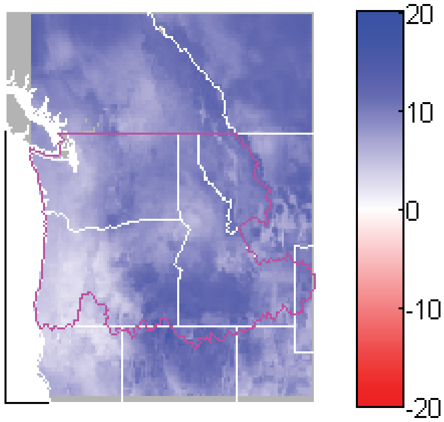
Mean-Annual Precipitation Change, percent
CMIP3,1970-1999 to 2070-2099,50%tile



Mean-Annual Temperature Change,°C
CMIP3,1970-1999 to 2010-2039,50%tile



Mean-Annual Precipitation Change, percent
CMIP5,1970-1999 to 2070-2099,50%tile



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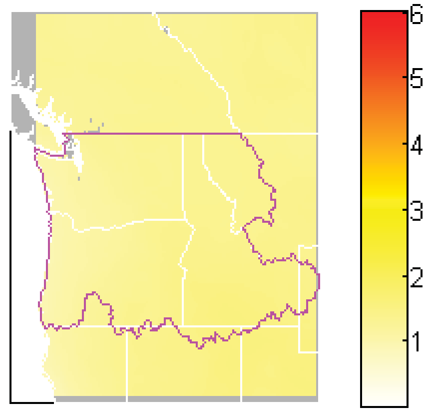
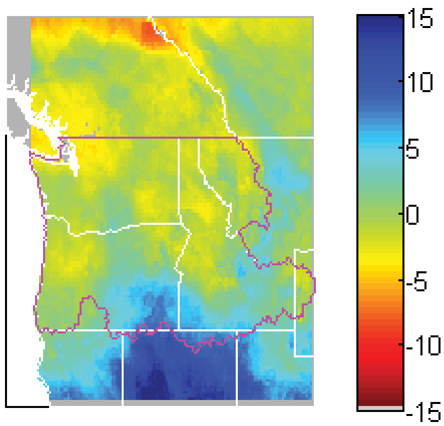
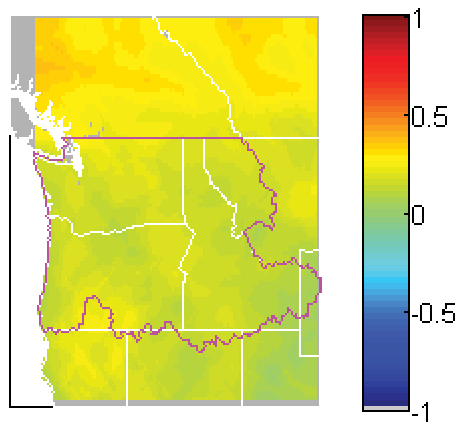
CMIP5,1970-1999 to 2010-2039,50%tile



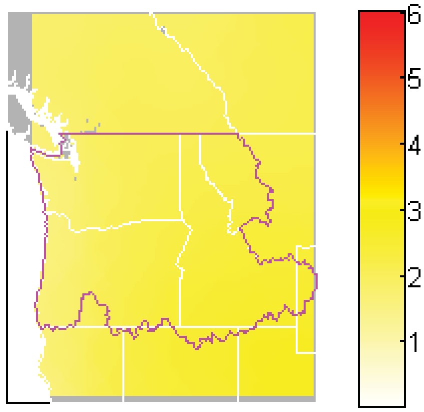
Mean-Annual Precipitation Change, percent
CMIP5-CMIP3,1970-1999 to 2070-2099,50%tile



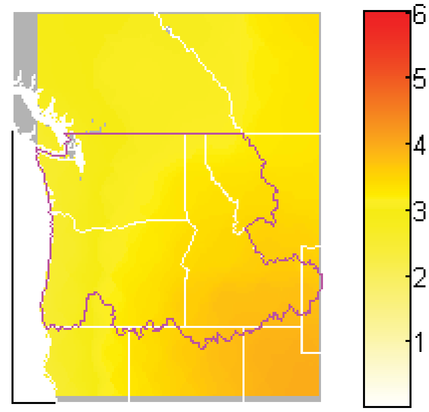
Mean-Annual Temperature Change,°C
CMIP5-CMIP3,1970-1999 to 2010-2039,50%tile



Mean-Annual Temperature Change,°C
CMIP3,1970-1999 to 2040-2069,50%tile



Mean-Annual Temperature Change,°C
CMIP3,1970-1999 to 2070-2099,50%tile



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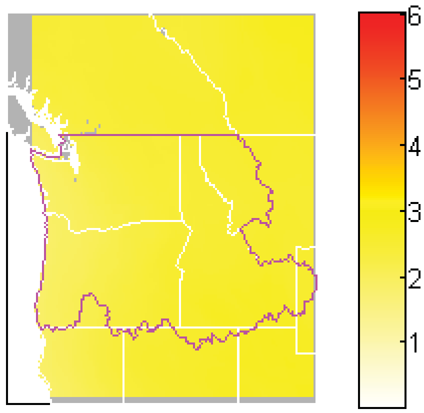

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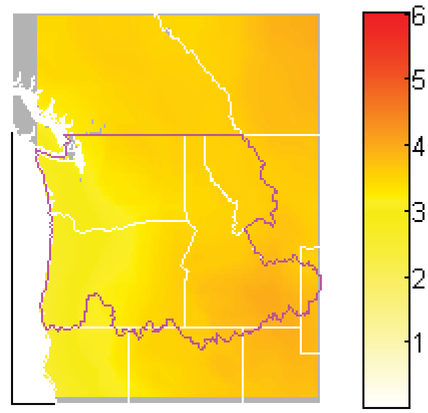
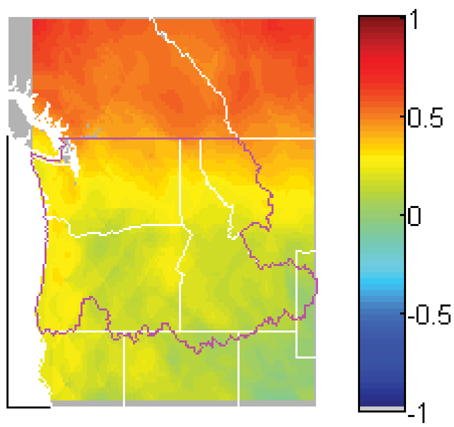
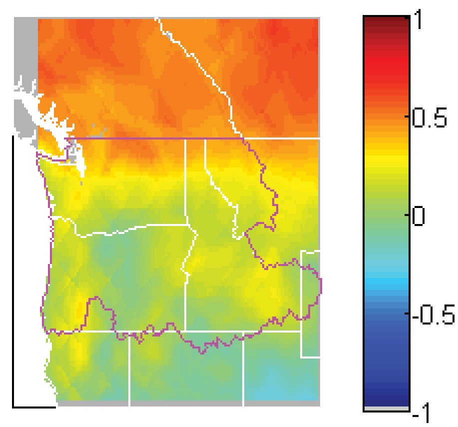


Mean-Annual Temperature Change,°C
CMIP5-CMIP3,1970-1999 to 2040-2069,50%tile



Mean-Annual Temperature Change,°C
CMIP5-CMIP3,1970-1999 to 2070-2099,50%tile



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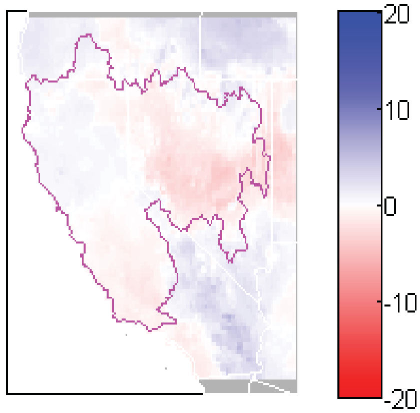
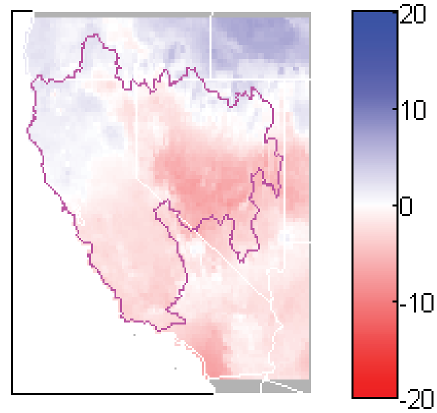
Mid-Pacific Region

Mean-Annual Precipitation Change, percent
CMIP3,1970-1999 to 2010-2039,50%tile



Mean-Annual Precipitation Change, percent
CMIP3,1970-1999 to 2040-2069,50%tile



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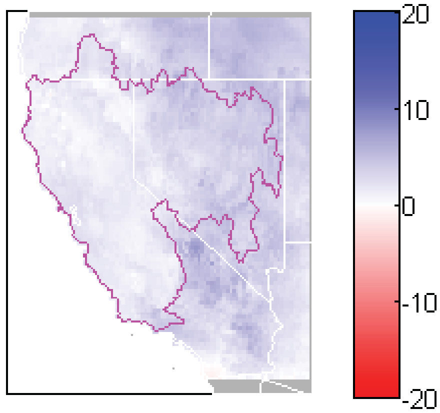

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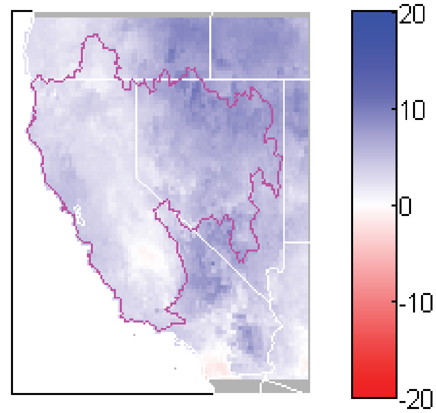

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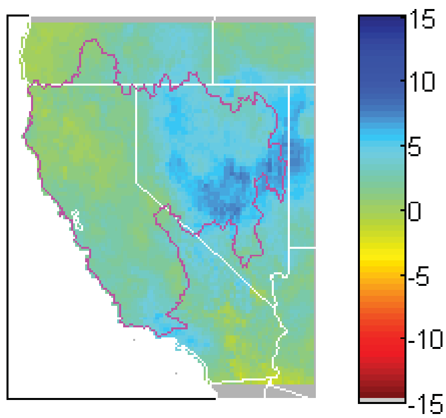
CMIP5-CMIP3,1970-1999 to 2010-2039,50%tile



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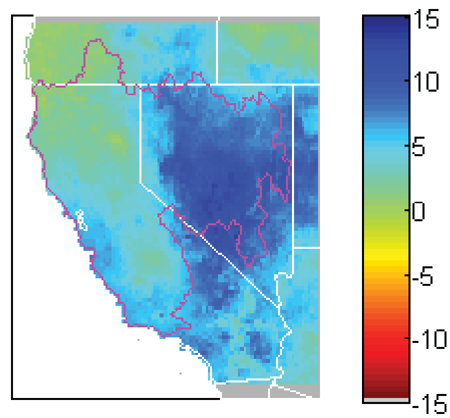
CMIP5-CMIP3,1970-1999 to 2040-2069,50%tile



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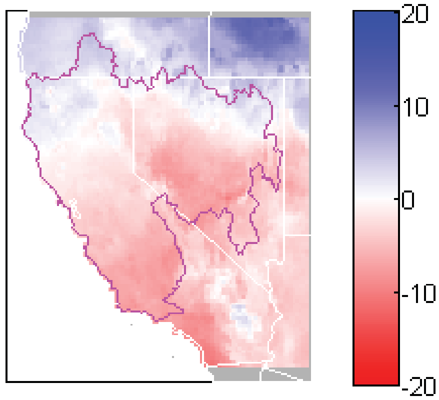
CMIP3,1970-1999 to 2070-2099,50%tile



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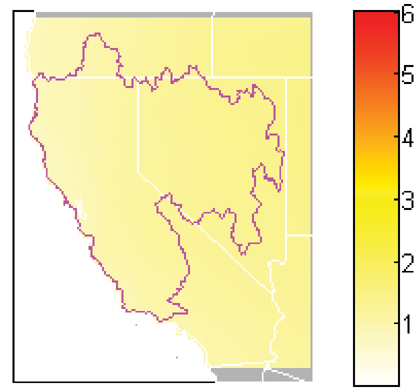

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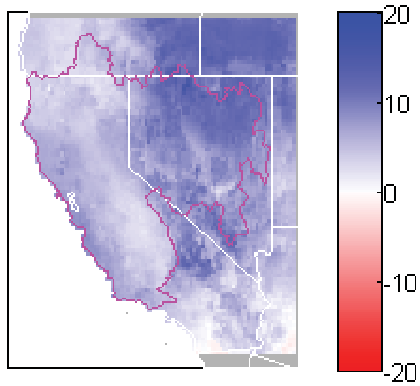

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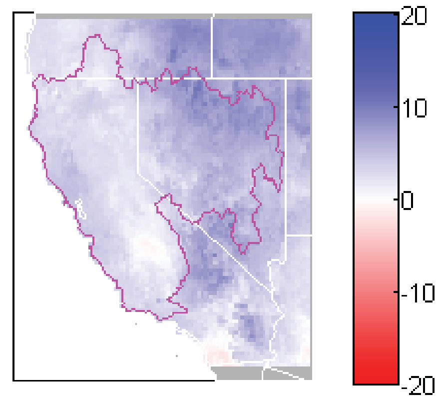

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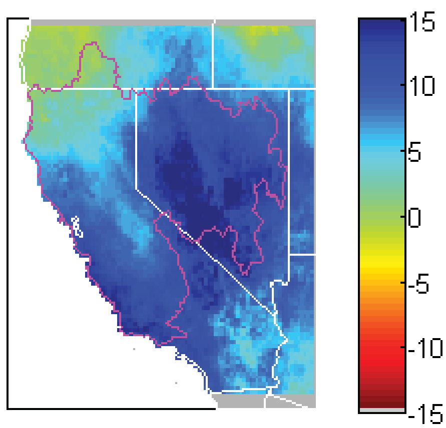

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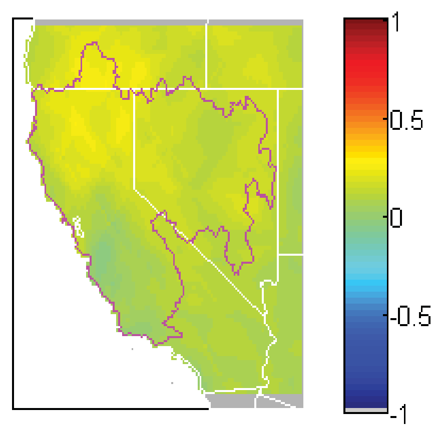

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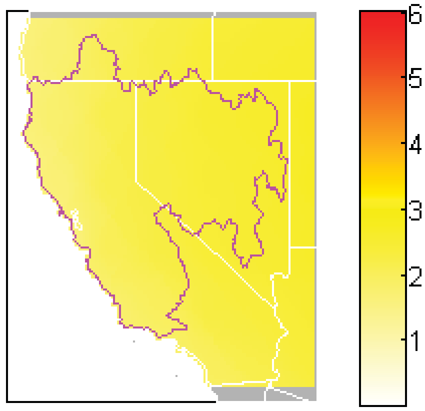

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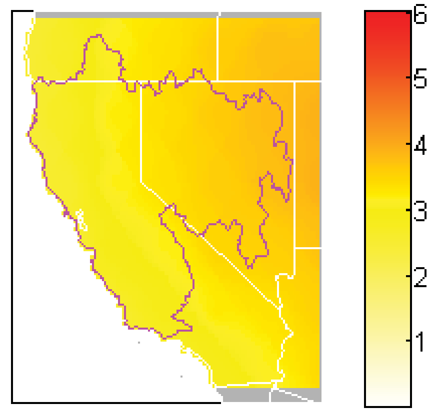

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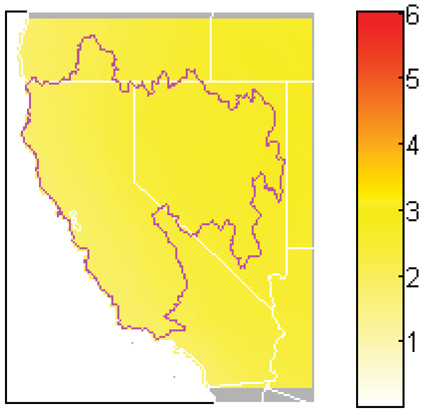

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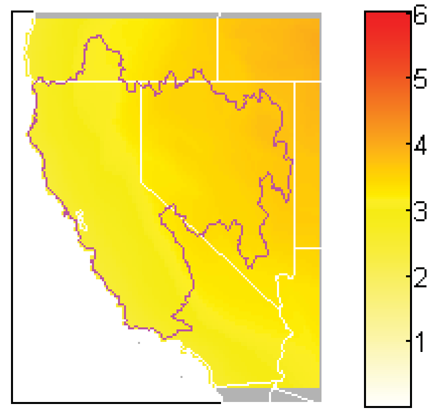

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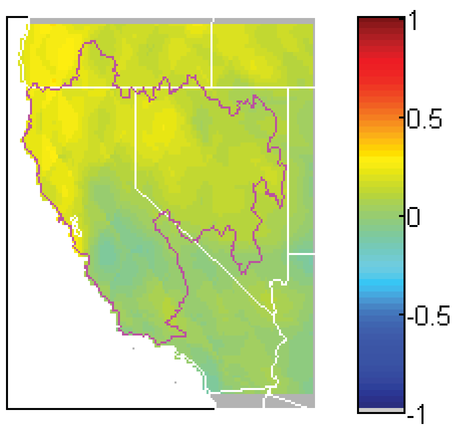
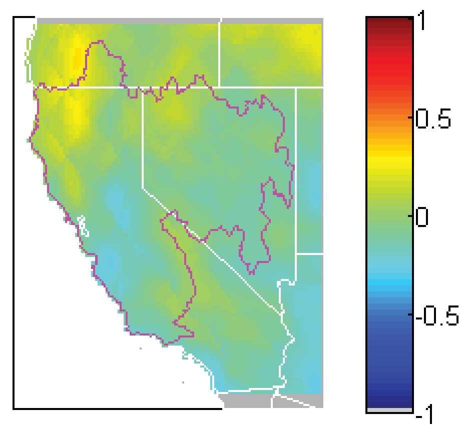


Mean-Annual Temperature Change,°C
CMIP5-CMIP3,1970-1999 to 2070-2099,50%tile



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Lower Colorado Region

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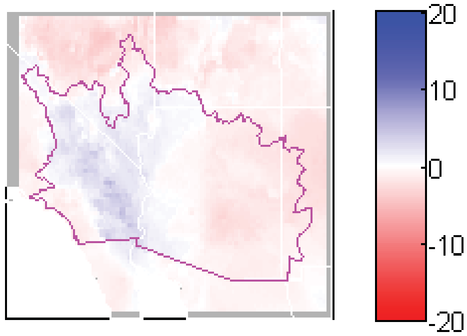
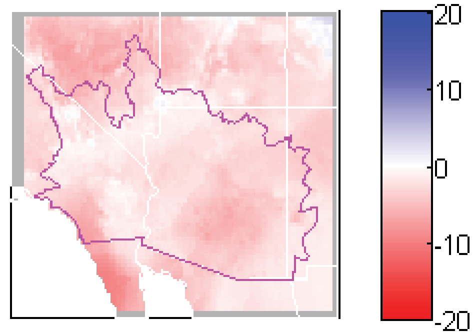
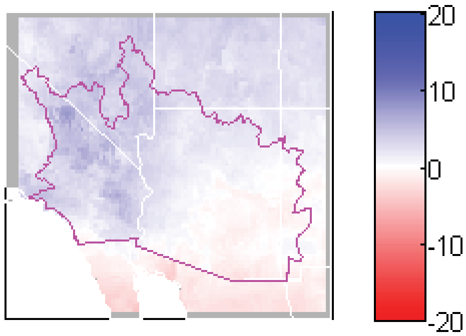
Mean-Annual Precipitation Change, percent
CMIP3,1970-1999 to 2010-2039,50%tile



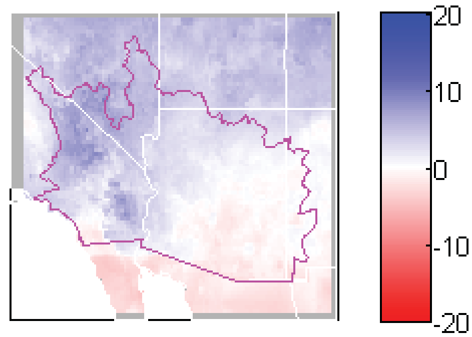
Mean-Annual Precipitation Change, percent
CMIP3,1970-1999 to 2040-2069,50%tile



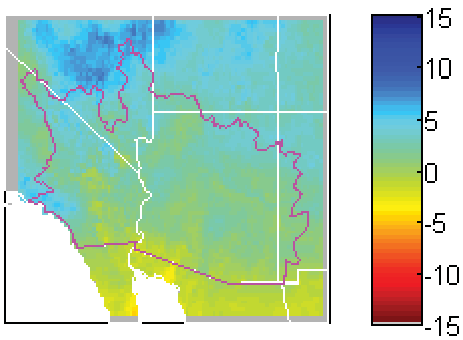
Mean-Annual Precipitation Change, percent
CMIP5,1970-1999 to 2010-2039,50%tile



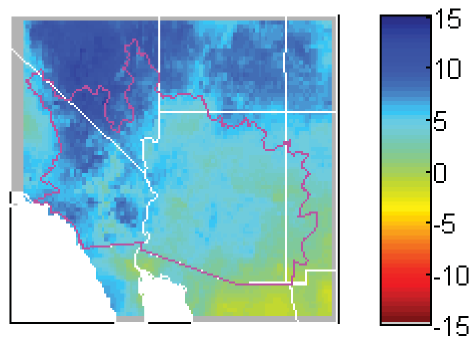
Mean-Annual Precipitation Change, percent
CMIP5,1970-1999 to 2040-2069,50%tile

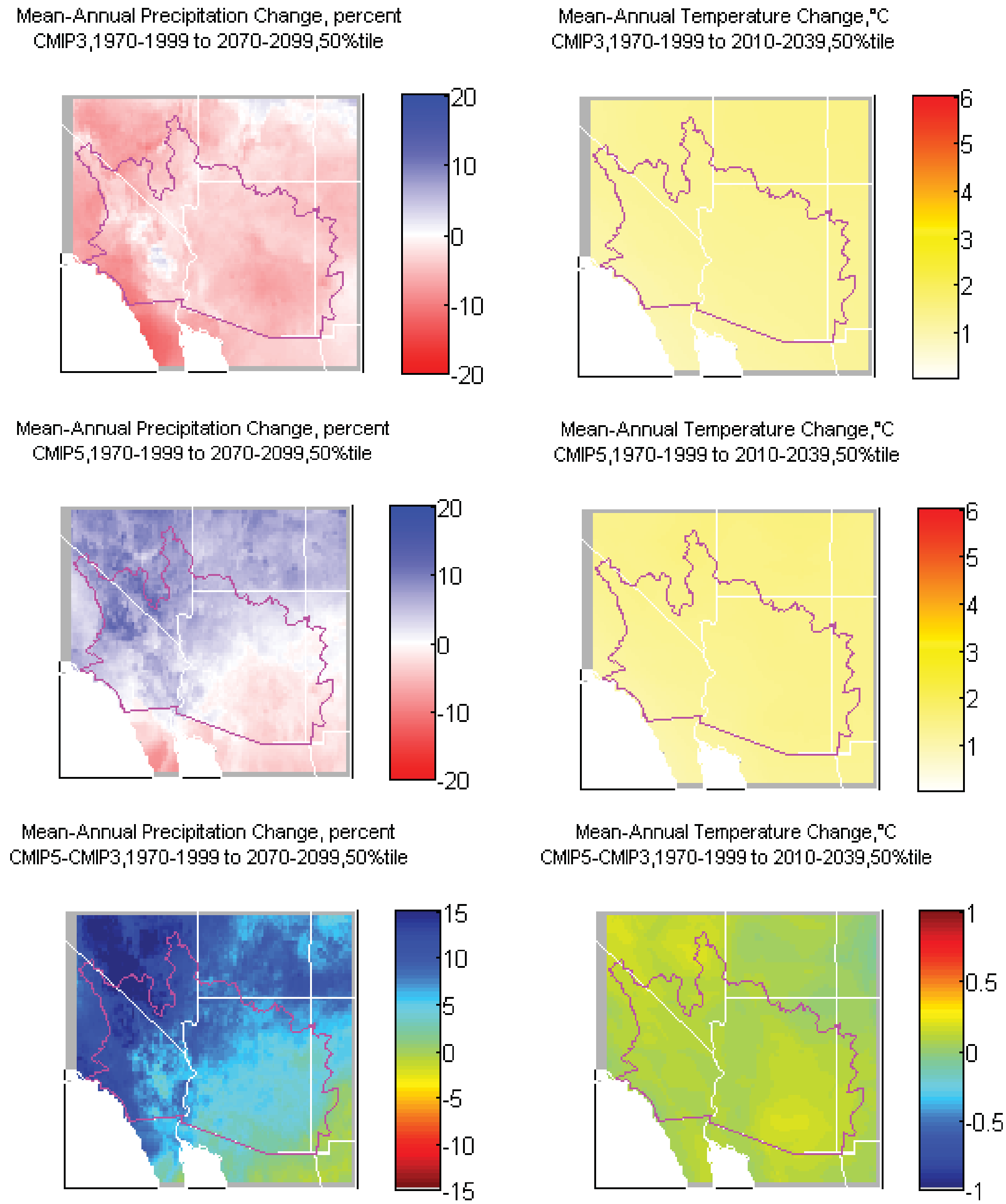


Mean-Annual Precipitation Change, percent
CMIP5-CMIP3,1970-1999 to 2010-2039,50%tile



Mean-Annual Precipitation Change, percent
CMIP5-CMIP3,1970-1999 to 2040-2069,50%tile




Mean-Annual Precipitation Change, percent
CMIP3,1970-1999 to 2070-2099,50%tile
20
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Mean-Annual Temperature Change,°C
CMIP3,1970-1999 to 2010-2039,50%tile
6
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2
1
Mean-Annual Precipitation Change, percent
CMIP5,1970-1999 to 2070-2099,50%tile
20
10
0
-10
-20
Mean-Annual Temperature Change,°C
CMIP5,1970-1999 to 2010-2039,50%tile
6
5
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2
1
Mean-Annual Precipitation Change, percent
CMIP5-CMIP3,1970-1999 to 2070-2099,50%tile
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-5
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Mean-Annual Temperature Change,°C
CMIP5-CMIP3,1970-1999 to 2010-2039,50%tile
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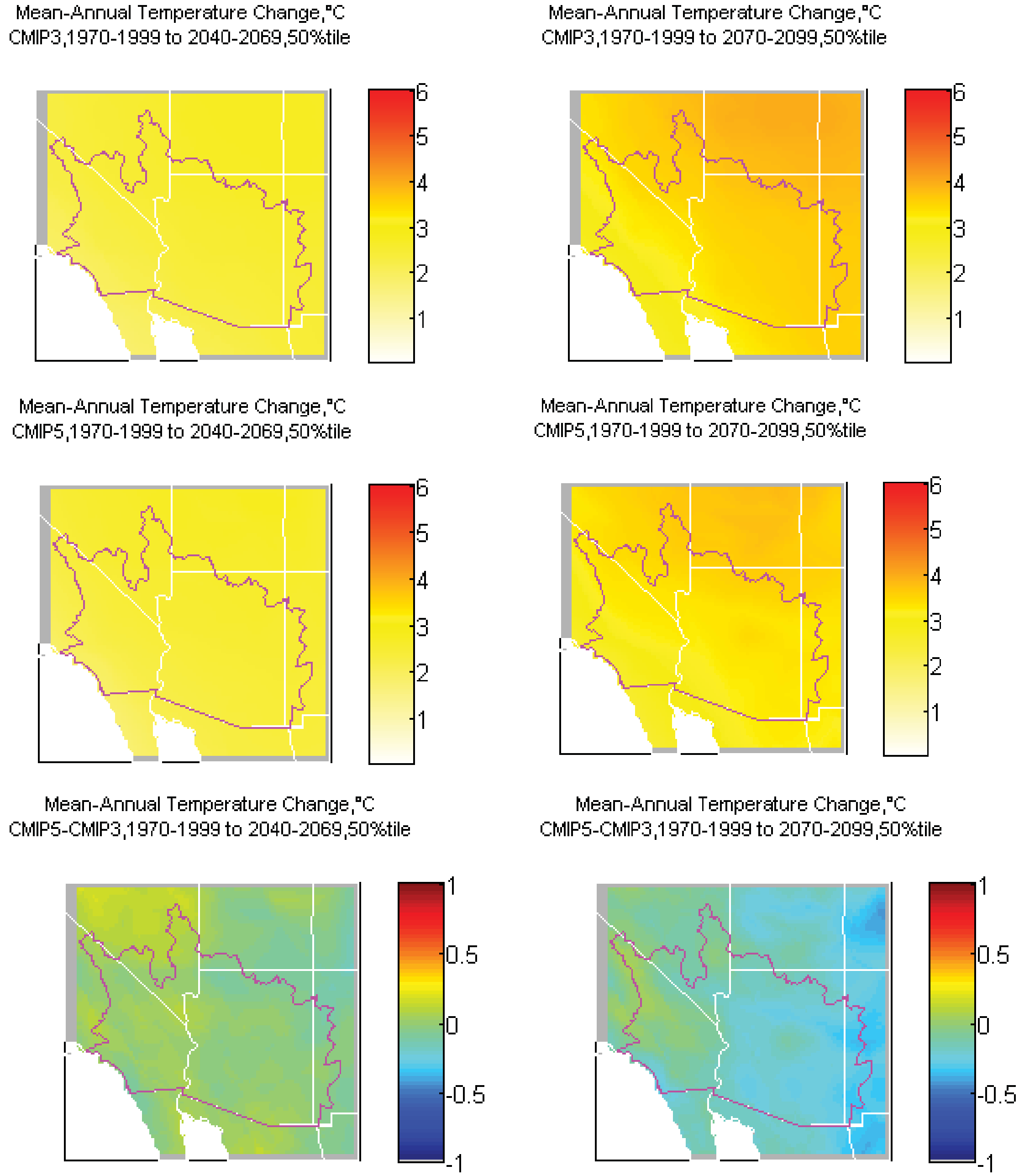
Mean-Annual Temperature Change,°C
CMIP3,1970-1999 to 2040-2069,50%tile
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Mean-Annual Temperature Change,°C
CMIP3,1970-1999 to 2070-2099,50%tile
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Mean-Annual Temperature Change,°C
CMIP5,1970-1999 to 2040-2069,50%tile
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Mean-Annual Temperature Change,°C
CMIP5,1970-1999 to 2070-2099,50%tile
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Mean-Annual Temperature Change,°C
CMIP5-CMIP3,1970-1999 to 2040-2069,50%tile
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Mean-Annual Temperature Change,°C
CMIP5-CMIP3,1970-1999 to 2070-2099,50%tile
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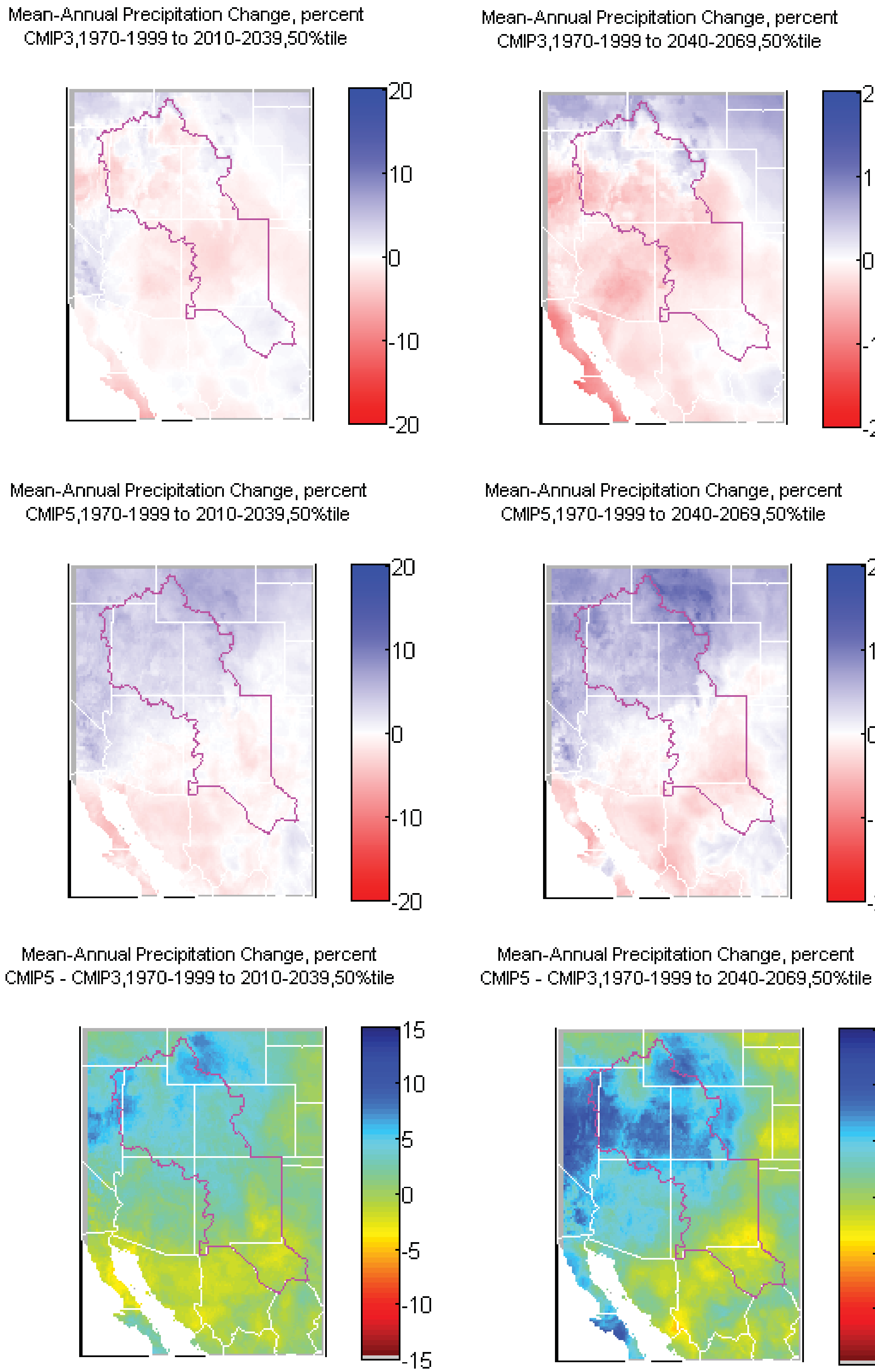
Upper Colorado Region


Mean-Annual Precipitation Change, percent
CMIP3,1970-1999 to 2010-2039,50%tile
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Mean-Annual Precipitation Change, percent
CMIP3,1970-1999 to 2040-2069,50%tile
20
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-20
Mean-Annual Precipitation Change, percent
CMIP5,1970-1999 to 2010-2039,50%tile
20
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-10
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Mean-Annual Precipitation Change, percent
CMIP5,1970-1999 to 2040-2069,50%tile
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Mean-Annual Precipitation Change, percent
CMIP5 - CMIP3,1970-1999 to 2010-2039,50%tile
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-5
-10
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Mean-Annual Precipitation Change, percent
CMIP5 - CMIP3,1970-1999 to 2040-2069,50%tile
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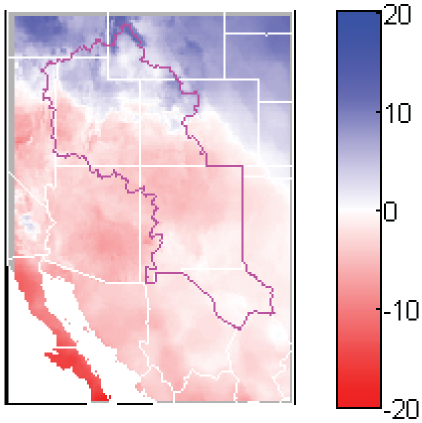
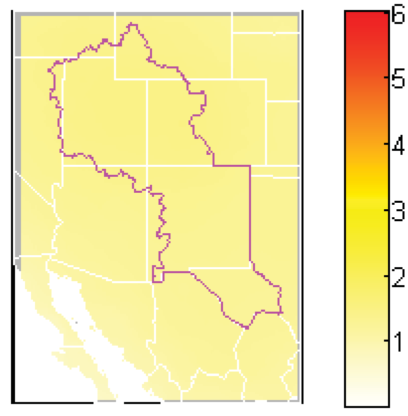
-15

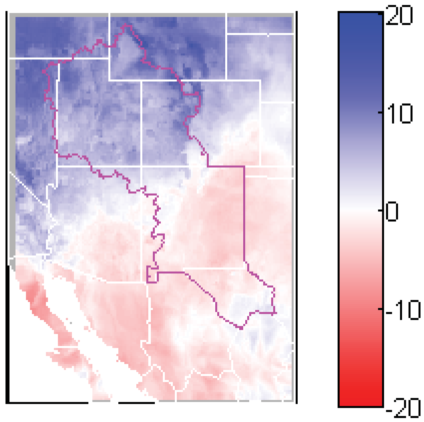
Mean-Annual Precipitation Change, percent
CMIP3,1970-1999 to 2070-2099,50%tile



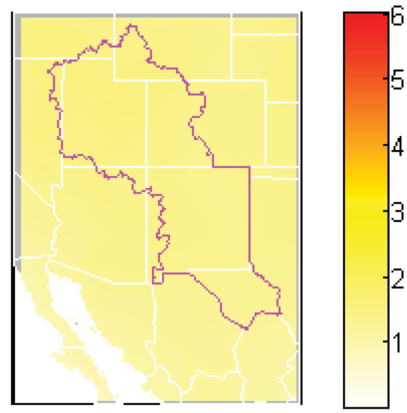
Mean-Annual Temperature Change,°C
CMIP3,1970-1999 to 2010-2039,50%tile



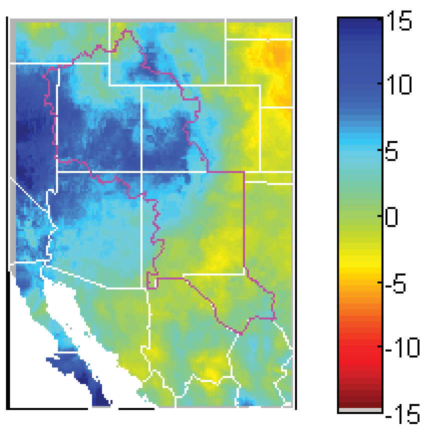
Mean-Annual Precipitation Change, percent
CMIP5,1970-1999 to 2070-2099,50%tile



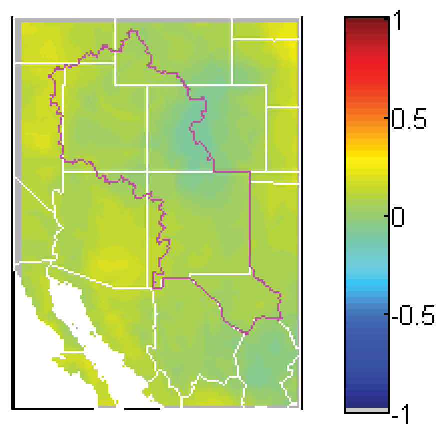
Mean-Annual Temperature Change,°C
CMIP5,1970-1999 to 2010-2039,50%tile

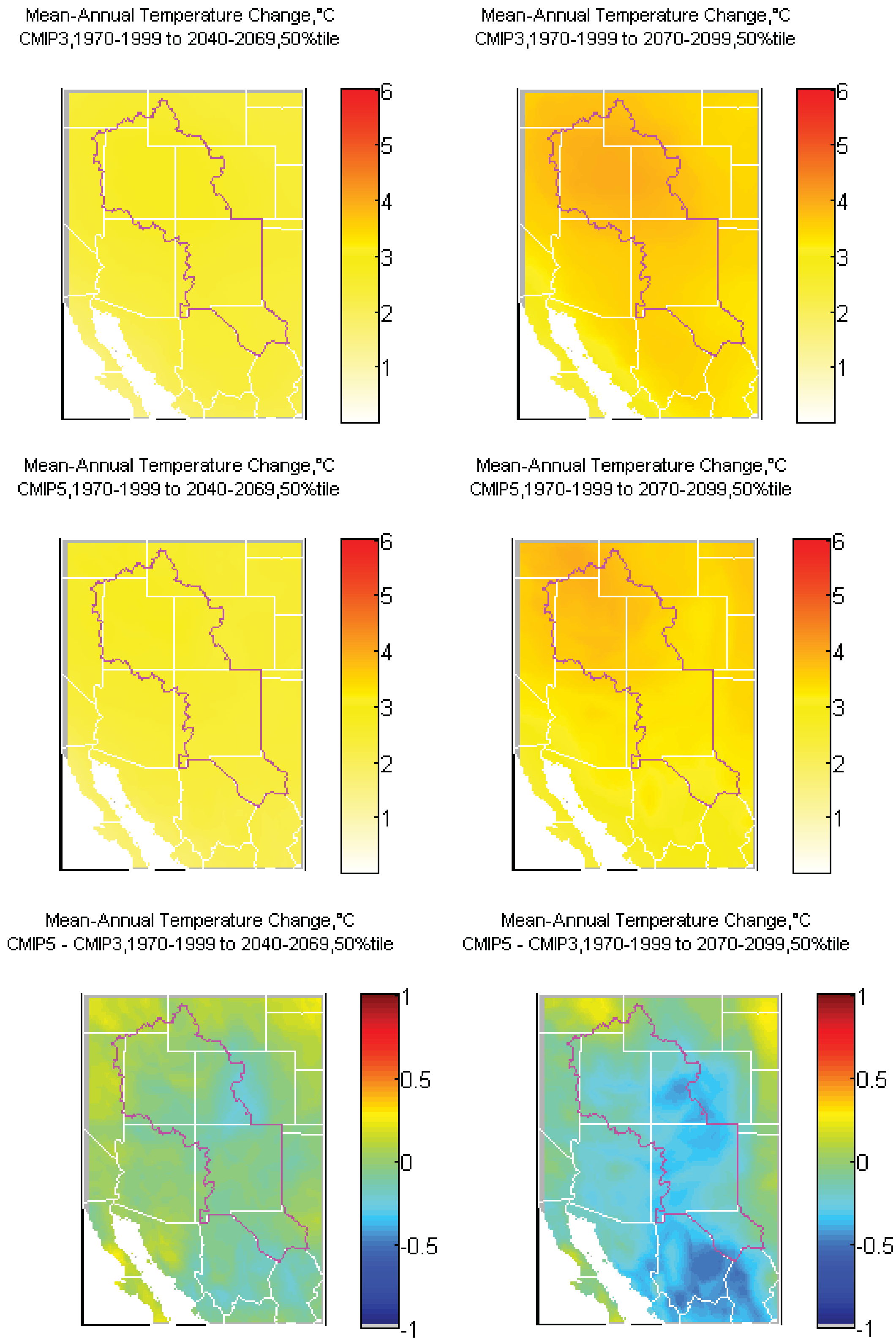


Mean-Annual Precipitation Change, percent
CMIP5 - CMIP3,1970-1999 to 2070-2099,50%tile



Mean-Annual Temperature Change,°C
CMIP5 - CMIP3,1970-1999 to 2010-2039,50%tile




Mean-Annual Temperature Change,°C
CMIP3,1970-1999 to 2040-2069,50%tile
Mean-Annual Temperature Change,°C
CMIP3,1970-1999 to 2070-2099,50%tile
Mean-Annual Temperature Change,°C
CMIP5,1970-1999 to 2040-2069,50%tile
Mean-Annual Temperature Change,°C
CMIP5,1970-1999 to 2070-2099,50%tile
Mean-Annual Temperature Change,°C
CMIP5 - CMIP3,1970-1999 to 2040-2069,50%tile
Mean-Annual Temperature Change,°C
CMIP5 - CMIP3,1970-1999 to 2070-2099,50%tile
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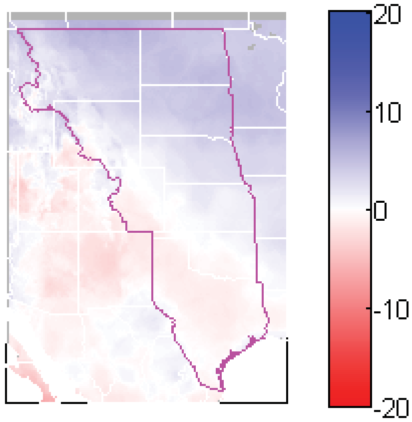
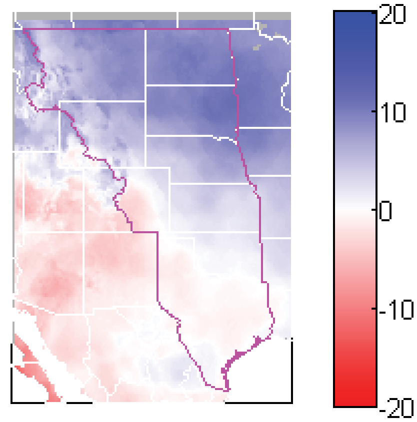
Great Plains Region

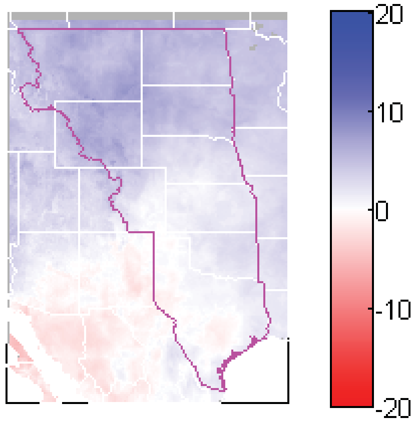
Mean-Annual Precipitation Change, percent
CMIP3,1970-1999 to 2010-2039,50%tile



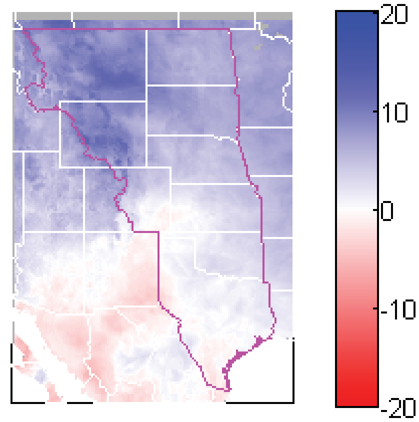
Mean-Annual Precipitation Change, percent
CMIP3,1970-1999 to 2040-2069,50%tile



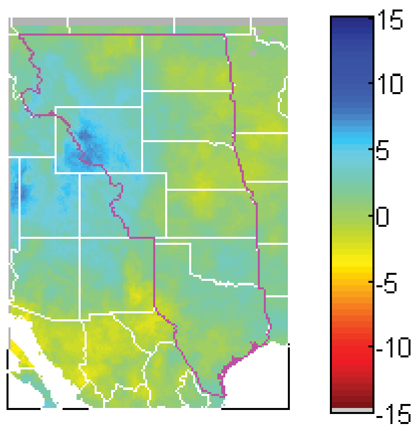
Mean-Annual Precipitation Change, percent
CMIP5,1970-1999 to 2010-2039,50%tile



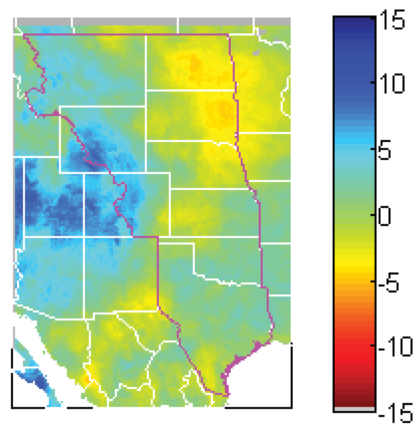
Mean-Annual Precipitation Change, percent
CMIP5,1970-1999 to 2040-2069,50%tile



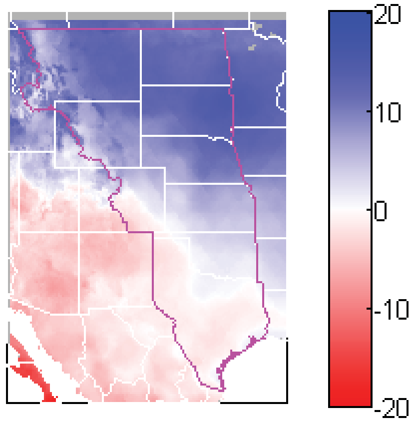
Mean-Annual Precipitation Change, percent
CMIP5-CMIP3,1970-1999 to 2010-2039,50%tile



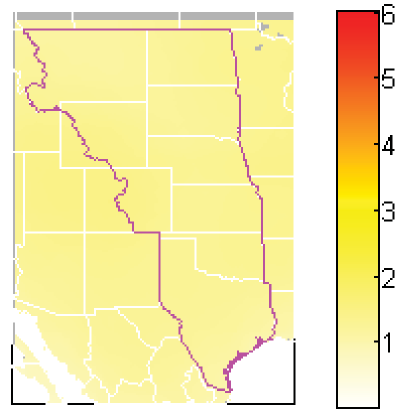
Mean-Annual Precipitation Change, percent
CMIP5-CMIP3,1970-1999 to 2040-2069,50%tile



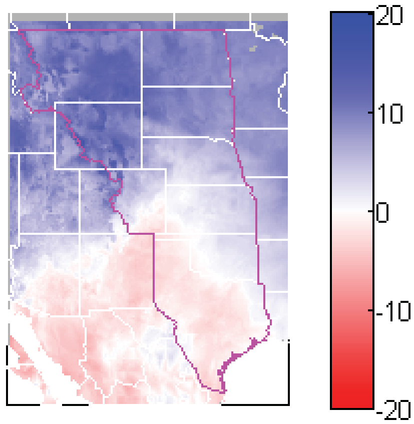
Mean-Annual Precipitation Change, percent
CMIP3,1970-1999 to 2070-2099,50%tile



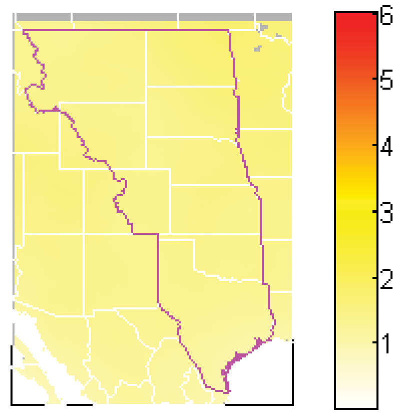
Mean-Annual Temperature Change,°C
CMIP3,1970-1999 to 2010-2039,50%tile



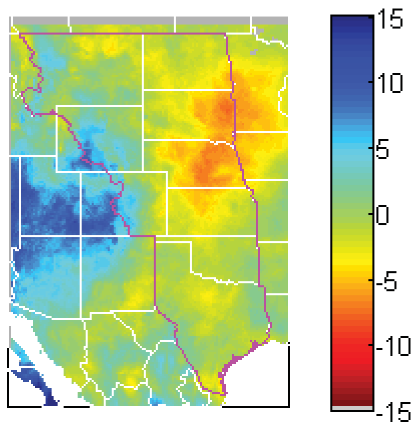
Mean-Annual Precipitation Change, percent
CMIP5,1970-1999 to 2070-2099,50%tile



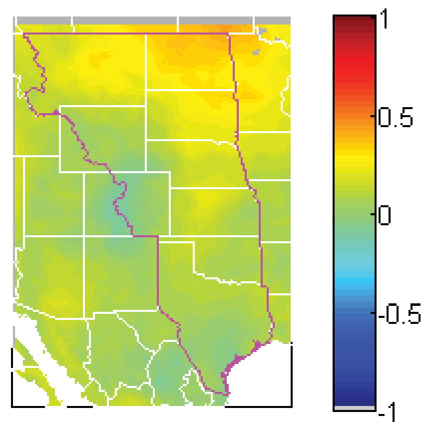
Mean-Annual Temperature Change,°C
CMIP5,1970-1999 to 2010-2039,50%tile

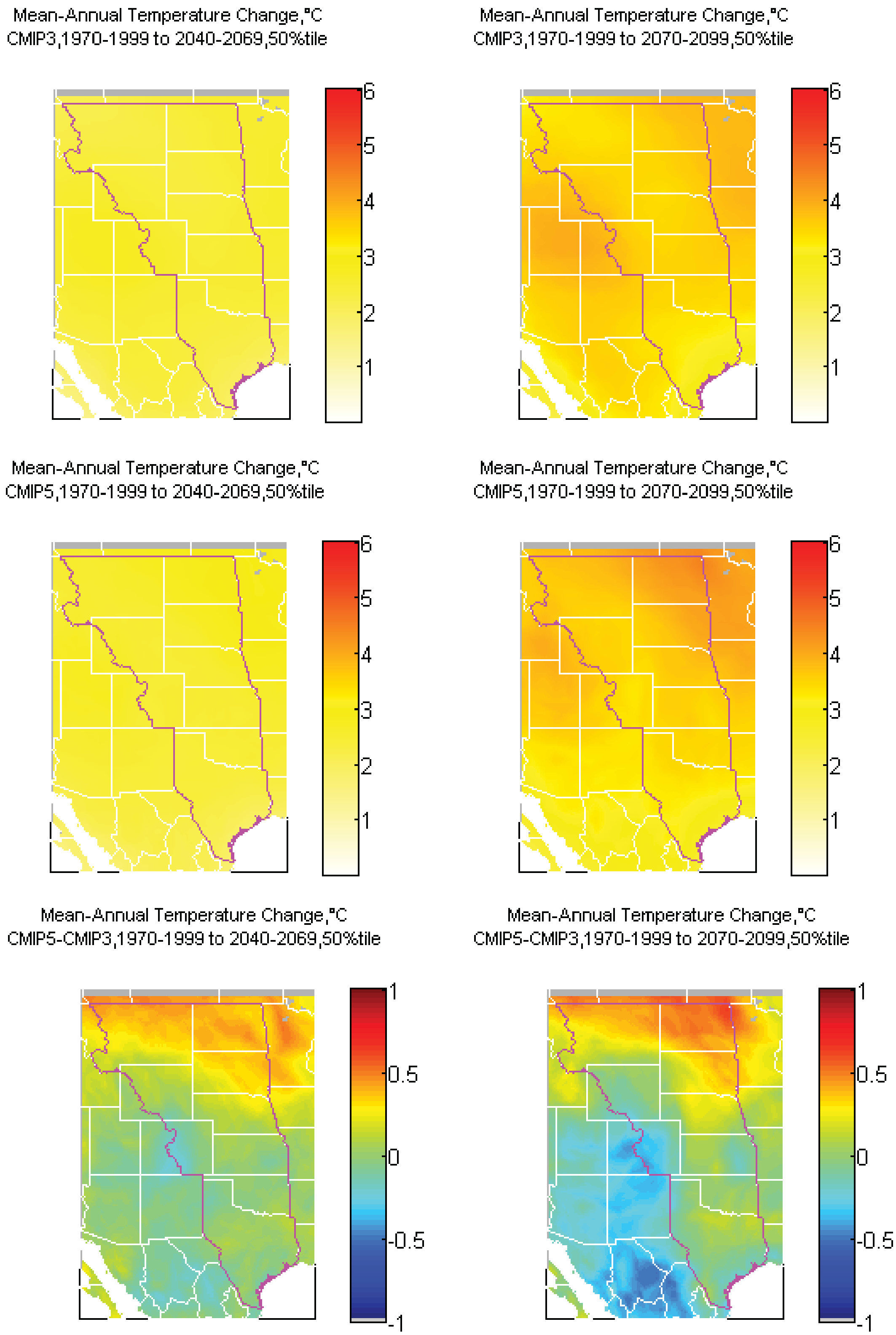


Mean-Annual Precipitation Change, percent
CMIP5-CMIP3,1970-1999 to 2070-2099,50%tile



Mean-Annual Temperature Change,°C
CMIP5-CMIP3,1970-1999 to 2010-2039,50%tile




Mean-Annual Temperature Change,°C
CMIP3,1970-1999 to 2040-2069,50%tile
Mean-Annual Temperature Change,°C
CMIP3,1970-1999 to 2070-2099,50%tile
Mean-Annual Temperature Change,°C
CMIP5,1970-1999 to 2040-2069,50%tile
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CMIP5,1970-1999 to 2070-2099,50%tile
Mean-Annual Temperature Change,°C
CMIP5-CMIP3,1970-1999 to 2040-2069,50%tile
Mean-Annual Temperature Change,°C
CMIP5-CMIP3,1970-1999 to 2070-2099,50%tile
6
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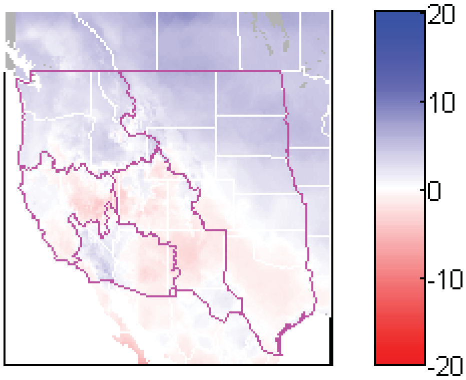
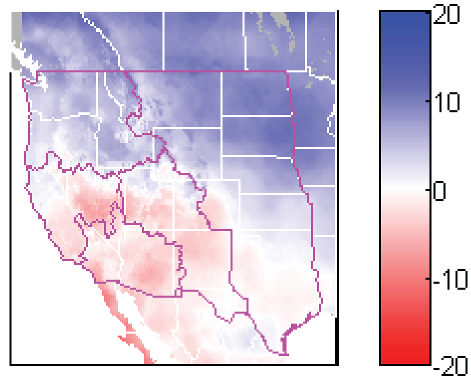
All Reclamation Regions (Western U.S.)

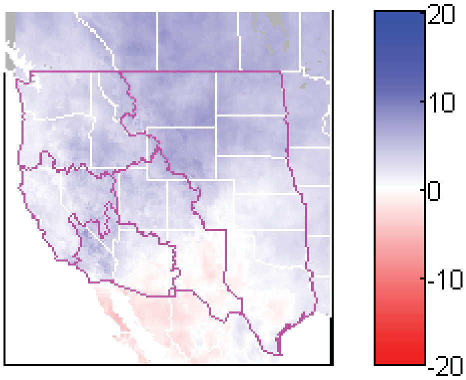
Mean-Annual Precipitation Change, percent
CMIP3,1970-1999 to 2010-2039,50%tile



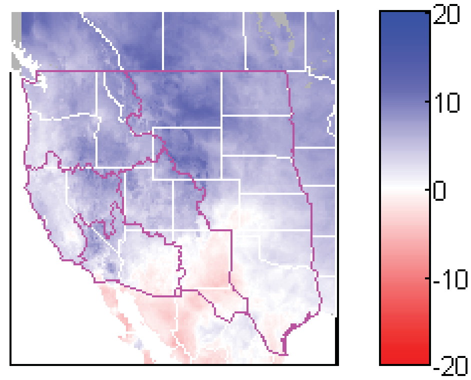
Mean-Annual Precipitation Change, percent
CMIP3,1970-1999 to 2040-2069,50%tile



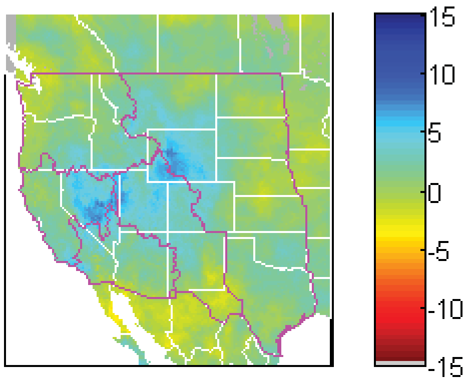
Mean-Annual Precipitation Change, percent
CMIP5,1970-1999 to 2010-2039,50%tile



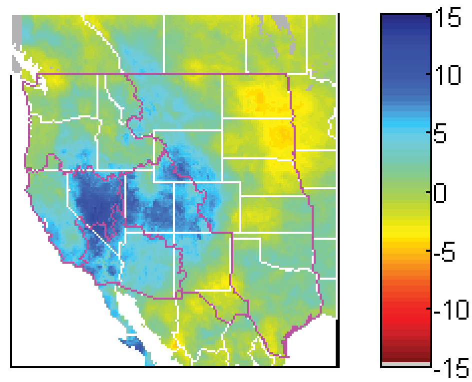
Mean-Annual Precipitation Change, percent
CMIP5,1970-1999 to 2040-2069,50%tile



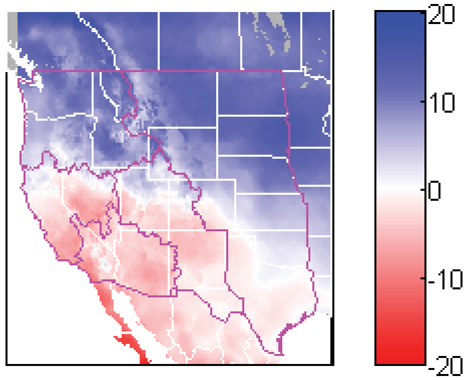
Mean-Annual Precipitation Change, percent
CMIP5 - CMIP3,1970-1999 to 2010-2039,50%tile



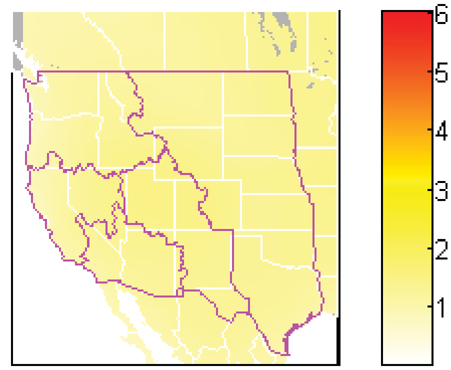
Mean-Annual Precipitation Change, percent
CMIP5 - CMIP3,1970-1999 to 2040-2069,50%tile



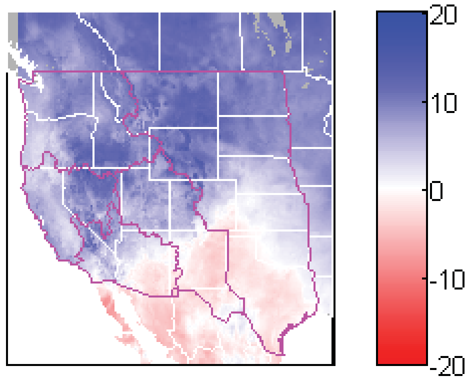
Mean-Annual Precipitation Change, percent
CMIP3,1970-1999 to 2070-2099,50%tile



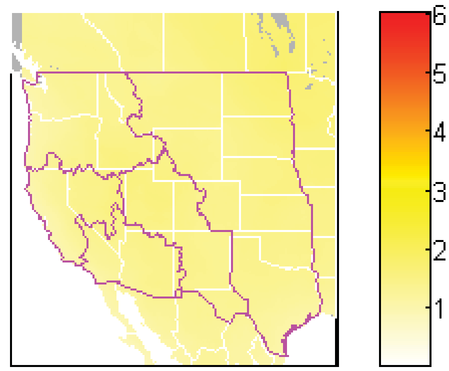
Mean-Annual Temperature Change,°C
CMIP3,1970-1999 to 2010-2039,50%tile



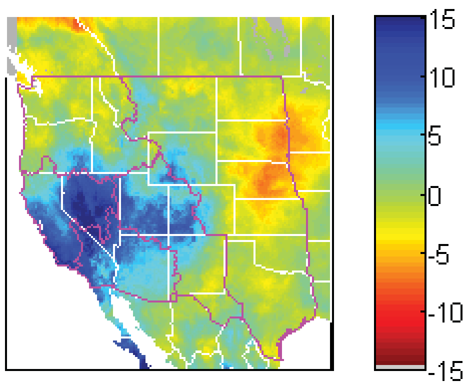
Mean-Annual Precipitation Change, percent
CMIP5,1970-1999 to 2070-2099,50%tile



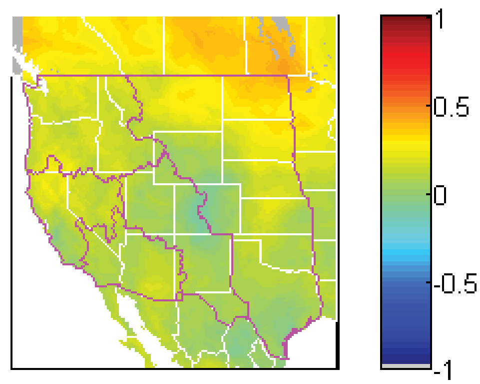
Mean-Annual Temperature Change,°C
CMIP5,1970-1999 to 2010-2039,50%tile

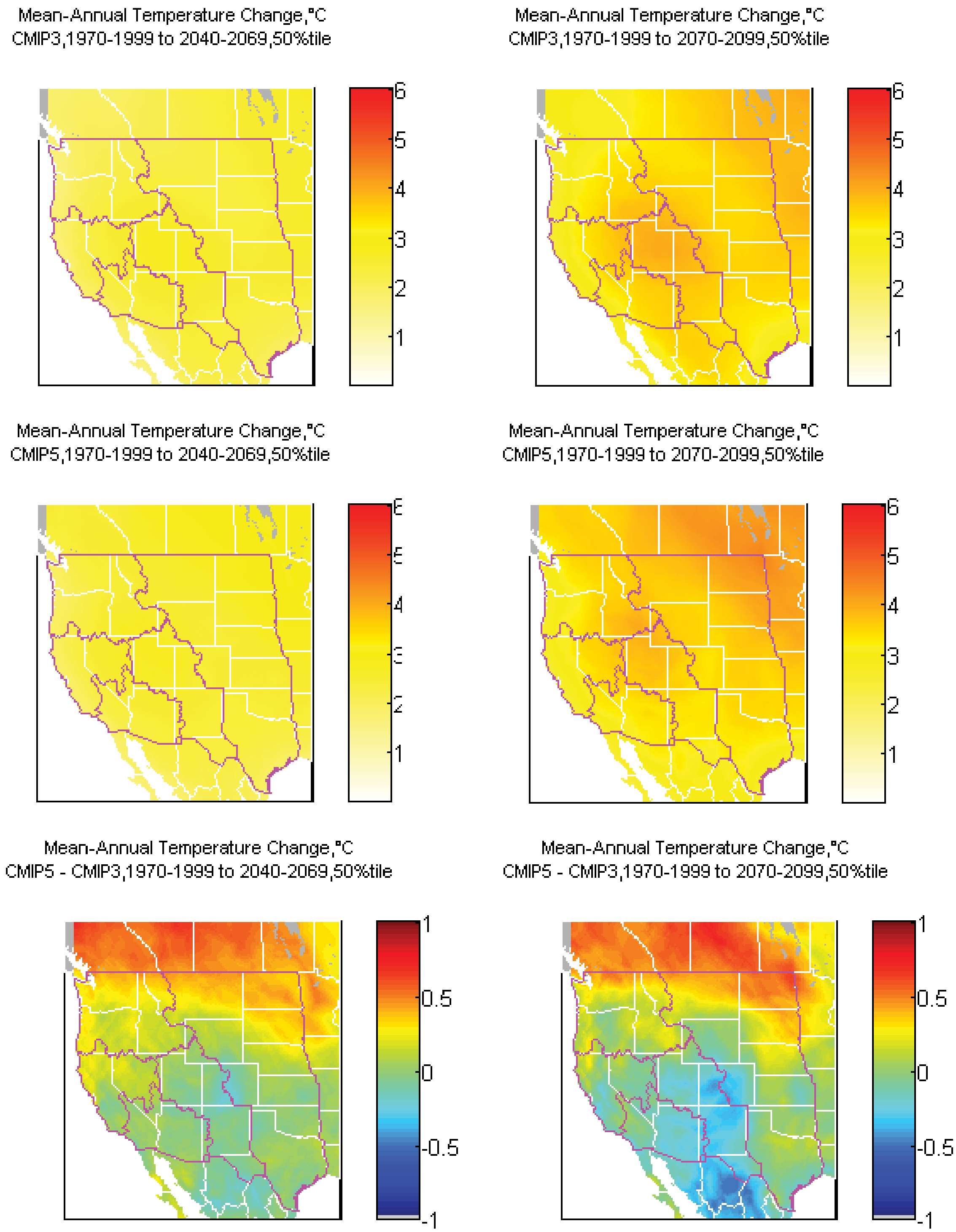


Mean-Annual Precipitation Change, percent
CMIP5 - CMIP3,1970-1999 to 2070-2099,50%tile



Mean-Annual Temperature Change,°C
CMIP5 - CMIP3,1970-1999 to 2010-2039,50%tile




Mean-Annual Temperature Change,°C
CMIP3,1970-1999 to 2040-2069,50%tile
Mean-Annual Temperature Change,°C
CMIP3,1970-1999 to 2070-2099,50%tile
Mean-Annual Temperature Change,°C
CMIP5,1970-1999 to 2040-2069,50%tile
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CMIP5,1970-1999 to 2070-2099,50%tile
Mean-Annual Temperature Change,°C
CMIP5 - CMIP3,1970-1999 to 2040-2069,50%tile
Mean-Annual Temperature Change,°C
CMIP5 - CMIP3,1970-1999 to 2070-2099,50%tile
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Appendix C. Glossary of Terms

Anthropogenic: Resulting from or produced by human beings.

Atmosphere-Ocean General Circulation Model (AOGCM): See Climate Model.

Bias Correction: Simulations or forecasts of climate from dynamical models such as AOGCMs do not precisely correspond to reality (i.e., observations), thus, resulting in "bias." There are statistical methods to correct this, 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 Assessment 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.

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.

Empirical: Relying upon or derived from observation or experiment; based on experimental data, not on a theory.

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).

Greenhouse Gas 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.

Ground Water: 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.

Interpolation: The estimation of unknown intermediate values from known discrete values of a dependent variable.

IPCC Fourth Assessment Report (AR4): The 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.

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.

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 PDO index, and the Interdecadal Pacific Oscillation (IPO) index.

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.

Paleoclimatology: 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.

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.

Special Report on Emissions Scenarios (SRES) (IPCC 2007): SRES scenarios are *GHG emission scenarios* developed by Nakićenović and Swart (2000) and used, among others, as a basis for some of the *climate projections* shown in IPCC 2007. The following terms are relevant for a better understanding of the structure and use of the set of SRES scenarios:

Illustrative Scenario: A scenario that is illustrative for each of the six scenario groups reflected in the Summary for Policymakers of Nakićenović and Swart (2000). They include four revised scenario markers for the scenario groups A1B, A2, B1, B2, and two additional scenarios for the A1FI and A1T groups. All scenario groups are equally sound.

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.

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.

Stochastic Hydrology: The science that pertains to the probabilistic description and modeling of the value of hydrologic phenomena, particularly the dynamic behavior and the statistical analysis of records of such phenomena.

Storage: The retention of water or delay of runoff either by planned operation, as in a reservoir, or by temporary filling of overflow areas, as in the progression of a flood wave through a natural stream channel.

Temporal: Of, relating to, or limited by time (i.e., temporal boundaries).

Variable Infiltration Capacity (VIC) Model: VIC is a macroscale hydrologic model that solves full water and energy balances. VIC is a research model; and in its various forms, it has been applied to many watersheds including the Columbia River, the Ohio River, the Arkansas-Red Rivers, and the Upper Mississippi Rivers as well as being applied globally.

Water Balance (Water Budget): A summation of inputs, outputs, and net changes to a particular water resource system over a fixed period.

Watershed: All the land and water within the confines of a certain water drainage area; the total area drained by a river and its tributaries.

Water Supply: Process or activity by which a given amount of water is provided for some use (e.g., municipal, industrial, and agricultural).

Water Year: A continuous 12-month period selected to present data relative to hydrologic or meteorological phenomena during which a complete annual hydrologic cycle normally occurs. The water year used by the U.S. Geological Survey runs from October 1 through September 30 and is designated by the year in which it ends.