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Projected Effects of Climate Change in California: Ecoregional Summaries Emphasizing Consequences for Wildlife

Version 1.0 • 10 February 2011

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Cover photo: Jenner Headlands at the Russian River mouth, Sonoma County, California, May 2010.

By Ryan DiGaudio, PRBO.

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PRBO CONSERVATION SCIENCE

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PRBO Conservation Science is a non-profit conservation and education organization dedicated to advancing conservation through birds and ecosystem research. Founded in 1965 as Point Reyes Bird Observatory, PRBO Conservation Science partners with hundreds of governmental and non-governmental agencies as well as private interests to ensure that every dollar invested in conservation yields the most for biodiversity—benefiting our environment, our economy, and our communities.

PRBO's mission: PRBO Conservation Science is dedicated to conserving birds, other wildlife and ecosystems through innovative scientific research and outreach.

Introduction

Increasingly, land and water managers are faced with incorporating the projected effects of climate change into their decision-making process. Published information on the effects of climate change is vast and growing rapidly. Unfortunately, there are relatively few resources available that synthesize information about climate change as it relates to wildlife habitat. To address this need for a synthesis, we have created an ecoregional summary of the projected effects on climate change on wildlife habitat in California.

WHY AN ECOREGIONAL APPROACH?

Because California is a large and topographically diverse state, the effects of climate change will vary geographically. Additionally, conservation planning is typically done at, or in the context of, ecologically defined regions. To address this variability and conservation need, we have summarized the projected effects of climate change for the ten terrestrial ecoregions used in the California Bird Species of Special Concern (Figure 1; Shuford and Gardali 2008) and two additional marine ecoregions (Spalding et al. 2007). This organization allows local land and water managers to access information that is relevant to their specific ecoregions. In some cases we refer to one of California's ten hydrologic regions (http://www.waterplan.water.ca.gov/docs/maps/hr.jpg) which are different from the terrestrial ecoregions.

EMISSIONS SCENARIOS AND CLIMATE MODELS

To project future climate, climate modelers use emissions scenarios that describe how forcings will change over time that are then combined with climate models that convert changes in forcings into changes in atmospheric conditions, such as temperature and precipitation.

The IPCC has generated 40 emissions scenarios that are grouped into families representing common themes. The IPCC (Nakićenović and Stewart 2000) presented four families of scenarios (identified as A1, A2, B1, and B2) used to describe future patterns of human population growth, energy-technology development, and landuse patterns. The A1 and B1 scenarios have been used to bracket the most (A1) and least (B1) extreme increases in anthropogenic climate-forcing (Hayhoe et al. 2004). As a tool for decision making, emissions scenarios are important for understanding how particular emissions policies may influence the future climate.

Emissions scenarios are used as inputs for global circulation models (GCM), which are at the core of most climate projections (IPCC 2007). Atmospheric global circulation models (AGCM) describe the dynamics of air pressure, velocity, temperature, and water vapor. Oceanic global circulation models (OGCM) provide a complementary description of sea surface temperatures, ocean currents, and sea ice. Because atmospheric processes and ocean conditions are interdependent, many climate models are coupled atmospheric and oceanic global circulation models (AOGCM).

Application of the results of AOGCMs to many ecological questions may be limited by their relatively coarse spatial resolution: AOGCM grid cells often span hundreds of kilometers.

At this scale, a single grid cell for central California could extend from the coast to the foothills of the Sierra Nevada Mountains. Because this area is climatically diverse, it is unlikely that a climate projection at such a coarse spatial scale will be meaningful for understanding the local ecological effects of climate change. There are two tools available for expressing AOGCM results at a finer spatial scale: statistical downscaling and regional climate models (RCM).

HOW WILL CLIMATE CHANGE AFFECT WILDLIFE HABITAT?

We define habitat as the suite of abiotic (e.g., seasonal temperature regimes) and biotic (e.g., food resources and vegetation structure and composition) conditions that regulate the distribution and abundance of wildlife. For our purposes, we focused on summarizing the projected changes in eight components of terrestrial wildlife habitat: air temperature, precipitation, snowpack, streamflow, water availability, sea level rise, fire, and vegetation change. For marine habitat we focused on ocean acidification, upwelling, storminess, and El Niño events. While there are undoubtedly many other habitat components that will be affected by climate change, we felt that these eight specific areas had a sufficient amount of information available to begin a meaningful synthesis.

ECOREGIONAL SUMMARIES OF REGIONAL CLIMATE MODELS

While our primary goal was to assemble the available literature relative to each ecoregion, we discovered that for some ecoregions, detailed information on future climatic conditions were lacking. Thus, we provide two sources of information: customized ecoregional summaries of temperature and precipitation calculated by PRBO using recent regional climate models produced by Mark Snyder (UC Santa Cruz) and recently applied to birds by Stralberg et al. (2009), as well as other relevant information from the literature that corresponds to the ecoregion of interest.

For customized temperature and precipitation calculations by ecoregion, we summarized the expected changes by comparing current climate to modeled climate projections. Current climate conditions were summarized using 30-year (1971–2000) monthly climate normals interpolated at an 800-m grid resolution by the PRISM Group (Daly et al. 1994). Future climate conditions were summarized using projections from a regional climate model, RegCM3 at a 30-km resolution (Pal et al. 2007), with emissions trajectories taken from the Intergovernmental Panel on Climate Change (IPCC) SRES A2 scenario and boundary conditions based on output from two GCMs. The GCMs used were the National Center for Atmospheric Research (NCAR) Community Climate System Model (CCSM3.0), an atmosphere-ocean global climate model (AOGCM) run from 1870–2099 and the Geophysical Fluid Dynamics Laboratory (GFDL) GCM CM2.1, an AOGCM run from 1860–2099.

For the CCSM boundary conditions, the regional climate model (RCM) was run from 2038-2069, and for the GFDL boundary conditions, the run was 2038-2070. For these time periods monthly temperature and precipitation outputs were averaged across years to obtain one set of monthly values for the current and future time windows. The 30-km resolution GCM results were then statistically downscaled to a 800-m resolution using change values relative to the PRISM grid (Stralberg et al. 2009, Wiens et al. 2009).

ECOREGIONAL SUMMARIES OF VEGETATION CHANGE

As for the climate conditions, we provide two sources of information: customized ecoregional summaries of vegetation generated by PRBO and other relevant information from the literature that corresponds to the ecoregion of interest.

For the customized ecoregional vegetation summaries, we used comparisons of current and future vegetation projections (using 2030-2070 climate to project vegetation change) modeled by Stralberg et al. (2009) based on the California Gap Analysis vegetation layer (Davis 1998). These maps used 12 broad vegetation groupings that were aggregated from the California Wildlife Habitat Relationship types (Mayer and Laudenslayer Jr. 1988). For each ecoregion, we calculated the projected proportional change in the area of a vegetation type as:

(Future area – Current area) / Current area

Again, because these projections were calculated using both sets of global climate model boundary conditions, we present a range of values representing variability associated with the two sets of global conditions. We reported only the changes in the "major" vegetation types that currently comprise more than 10% of the total ecoregional area.

HOW DO WE DEFINE WILDLIFE?

These ecoregional summaries were originally developed as part of an effort to incorporate climate change threats into the California Bird Species of Special Concern (Shuford and Gardali 2008). Thus, our main focus has been on habitat components that are most applicable to terrestrial and marine birds and mammals. While we have attempted to provide information that is broadly applicable, there are some components of wildlife habitat (e.g., stream temperatures for fish) that we do not address in detail.

WHAT THREATS WILL THESE CHANGES POSE TO WILDLIFE?

For each ecoregion we have attempted to interpret the climate change effects in the context of the threats they may pose to wildlife. This summary was based on our opinion of what changes would have the greatest effect on wildlife.

THE PROBLEM OF UNCERTAINTY

One the greatest challenges in dealing with climate change in California is that there are uncertainties associated with projections of future conditions, yet there is the need to make important long-term decisions to accommodate those potential changes (Dettinger 2005). Different global and regional climate models produce differences in the projected future climate conditions. Despite these uncertainties, there are some important generalizations for California: (1) uncertainties associated with future greenhouse-gas emissions are comparable with the differences among climate models, so that neither source of uncertainties should be neglected or underrepresented; (2) over the next 100 years, climate models currently project greater and more consistent changes in temperature than in precipitation; (3) projections of extremely wet futures for California are outliers among current projections; and (4) projections that are warmest tend to yield a moderately drier California, while the cooler projections yield a somewhat wetter future.

In writing the summaries, we have tried to describe whether projected changes are either well-supported by multiple studies, or if there is a lack of consensus across multiple studies about the direction of the projected change. Such syntheses can provide a qualitative assessment of the uncertainty associated with projected changes.

CONFRONTING THE ALPHABET SOUP OF CLIMATE MODELING

Because the acronyms and jargon of climate modeling can be daunting, we have documented all abbreviations used in this document (Table 1). This table provides both the full name and a more detailed description of the abbreviated term(s) (usually either a climate model or an emissions scenario). Then, in each ecoregional summary we provide a separate “Models at a Glance” table. These tables provide the climate model(s) and emissions scenario(s) that were used in each of the studies we discuss for that particular ecoregion. Capturing this information in a table allowed us to focus our ecoregional summaries on the projected effects on wildlife habitat without including overwhelming detail on the models or emissions scenarios. The separate ecoregional tables also provide a means to quickly evaluate the underlying projections in each of the studies.

Map of California Ecoregions

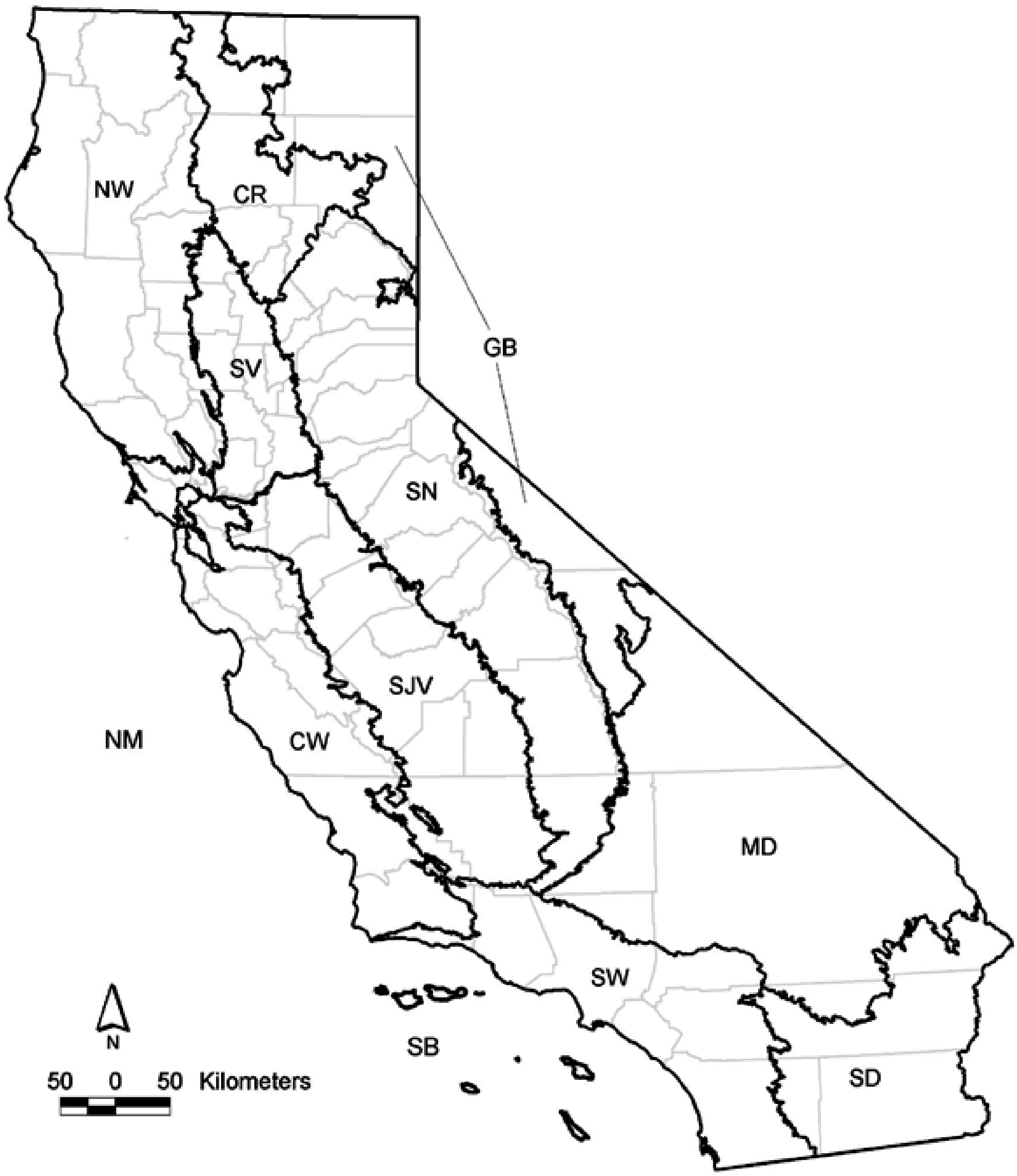

FIGURE 1. California ecoregions adapted from Hickman (1993). NW = Northwestern California, CR = Cascade Range, SN = Sierra Nevada, SV = Sacramento Valley, SJV = San Joaquin Valley, CW = Central Western California, SW = Southwestern California, MD = Mojave Desert, SD = Sonoran (Colorado) Desert, GB = Great Basin, NM = Northern Marine, SB = Southern Bight

Table of Climate Models Abbreviations Used

Table 1. Abbreviations at a glance: Climate models, emissions scenarios, and other abbreviations used in this document.

Abbreviation	Full name	Description
A1B, A2, B1, B2	IPCC/SRES emissions scenarios	The six families of emissions scenarios discussed in the IPCC's Third Assessment Report (TAR) and Fourth Assessment Report (AR4). For more information see: http://www.grida.no/publications/other/ipcc_sr/?src=/climate/ipcc/emission/
AOGCM	Atmospheric and oceanic global circulation models	Coupled models that link atmospheric processes and ocean conditions.
CM2.1	Climate Model Version 2.x	The CM2.x climate models are used for the GFDL's research. They are being applied to decadal-to-centennial time scales, as well as to seasonal-to-interannual problems, such as El Niño research and experimental forecasts. More information available at: http://nomads.gfdl.noaa.gov/CM2.X/
CSM1.3 and CCSM 3.0	Climate System Model Version 1.3	The Community Climate System Model was developed by NCAR in Boulder, Colorado. It is composed of four independent models (ocean, atmosphere, sea ice, and land surface) originally developed in 1994. The name was subsequently changed from CSM to CCSM. More information available at: http://www.ccsm.ucar.edu/
GCM	General Circulation Model or Global Climate Model	A mathematical model of the general circulation of a planetary atmosphere or ocean and based on the Navier-Stokes equations on a rotating sphere with thermodynamic terms for various energy sources (radiation, latent heat).
CT	Center timing	With respect to streamflow, the day when half the annual flow has passed a given point.
GFDL	Geophysical Fluid Dynamics Laboratory	The Geophysical Fluid Dynamics Laboratory (GFDL) develops and uses mathematical models and computer simulations to improve understanding and prediction of the behavior of the atmosphere, the oceans, and climate. More information available at: http://www.gfdl.noaa.gov/

GISS	Goddard Institute for Space Studies	A key objective of GISS research is prediction of atmospheric and climate changes in the 21st century. The research combines analysis of comprehensive global datasets, derived mainly from spacecraft observations, with global models of atmospheric, land surface, and oceanic processes. More information available at: http://www.giss.nasa.gov/
HadCM3, HadCM2	Hadley Centre Coupled Model, version x	A coupled atmosphere-ocean general circulation model (AOGCM) developed at the Hadley Centre in the United Kingdom. It was one of the major models used in the IPCC Third Assessment Report in 2001.
IPCC	Intergovernmental Panel on Climate Change	The Intergovernmental Panel on Climate Change is the leading body for the assessment of climate change. Established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO), they provide the world with a clear scientific view on the current state of climate change and its potential environmental and socio-economic consequences. More information available at: http://www.ipcc.ch/
IS92a to IS92f		Six IS92 emissions scenarios (IS92a to f) were published in the 1992 Supplementary Report to the IPCC Assessment. More information available at: http://sedac.ciesin.columbia.edu/ddc/is92/
PCM	Parallel Climate Model	A coupling of the NCAR Community Climate Model version 3, the LANL Parallel Ocean Program, and a sea ice model from the Naval Postgraduate School combined in a massively parallel computer environment. More information available at: http://www.cgd.ucar.edu/pcm/
PDO	Pacific Decadal Oscillation	A pattern of Pacific climate variability that shifts phases on at least inter-decadal time scale, usually about 20 to 30 years.
RCM	Regional climate model	A mathematical model of planetary atmosphere or ocean conditions for a region of the globe that is driven by conditions derived from global climate models.
RegCM2.5, RegCM3	Regional Climate Model versions 2.5 and 3	A 3-dimensional regional climate model. More information available at: http://users.ictp.it/RegCNET/model.html

SRES	Special Report on Emissions Scenarios	The Special Report on Emissions Scenarios (SRES) was a report prepared by the Intergovernmental Panel on Climate Change (IPCC) for the Third Assessment Report (TAR) in 2001, on future emission scenarios to be used for driving global circulation models to develop climate change scenarios. More information available at: http://www.grida.no/publications/other/ipcc_sr/?src=/climate/ipcc/emission/

Projected Effects of Climate Change in the Northwestern California Ecoregion

TEMPERATURE

Ecoregional summary of California regional climate model. In Northwestern California, regional climate models project mean annual temperature increases of 1.7–1.9°C by 2070. For the same time period mean diurnal temperature range is projected to increase by 0.1–0.2°C based on two RCMs presented in Stralberg et al. 2009.

Other sources of information. Bell et al. (2004) projected that with a doubling of atmospheric CO_2 there will be a significant increase in extreme temperature events on the North Coast. Mean maximum and minimum temperatures were projected to increase by 2.5°C and 2.3°C, respectively. Thus, the daily mean temperature range was projected to increase slightly, by 0.1°C. The frequency of extremely hot days (exceeding long-term 95th percentile) was projected to increase by 27 days per year and days exceeding 32.2°C by 9.5 days per year. Prolonged (7-day) hot spells were projected to increase by about 1.6 events per year and increase in duration by about 3 days. The frost-free growing season on average was projected to begin 25 days earlier and last 38 days longer. These models projected 37 fewer days of extreme cold (below the long-term 95th percentile) and 45 fewer days below 0°C, and prolonged (7-day) cold spells decreased by about 1.3 events per year. As has been demonstrated for Central and Southern California, many of these change will probably be less pronounced along the coast of the ecoregion and more extreme inland and at higher elevations (Cayan et al. 2008b).

Summary. The projected impacts of climate change on thermal conditions in Northwestern California will be warmer winter temperatures, earlier warming in the spring, and increased summer temperatures.

PRECIPITATION

Ecoregional summary of California regional climate model. In Northwestern California, regional climate models project a decrease in mean annual rainfall of 101 to 387 mm by 2070. The range of these changes (-7% to -28%) illustrate the differences between the two regional climate model projections with regard to precipitation, and the sensitivity of the regional results to the variability in the two global climate models used to provide the boundary conditions. This sensitivity indicates substantial uncertainty in precipitation projections.

Other sources of information. Earlier regional climate models (with different GCM inputs) run by Snyder et al. (2004) and Snyder and Sloan (2005) projected modest (3%) increases in precipitation for the North Coast by the end of 21st century. In contrast, more recent climate models project either little change or moderate decreases (10–20%) in precipitation for Northern California (Cayan et al. 2008b). In short, there is still substantial uncertainty about future precipitation in the North Coast.

Bell et al. (2004) projected that with a doubling of atmospheric CO_2 there would be few significant changes in extreme precipitation events in the North Coast region of California. Even for models that projected very little change in annual precipitation, Cayan et al. (2008b) reported a modest tendency for increases in the number and magnitude of large precipitation events in northern California by the end of the 21st century. The frequency of El Niño warm tropical events was projected to remain about the same as in historical simulations, and modeled El Niño events continued to be related to anomalous precipitation patterns over California (Cayan et al. 2008b).

Summary. Currently, there is greater uncertainty about the precipitation projections than for temperature in Northwestern California, but with some evidence for a slightly drier future climate relative to current conditions.

SNOWPACK

Snyder et al. (2004) projected with a doubling of atmospheric CO_2 concentrations that snow accumulation will decrease by 73% in the North Coast region of California. Reductions in monthly median snow heights from January to April ranged from 46 to 111 mm. Cayan et al. (2008b) projected overall snowpack losses for San Joaquin, Sacramento, and parts of the Trinity (relevant to this ecoregion) drainages will range from about 32% to 79% by the end of the century. Most of these changes are projected to occur because warming temperatures cause more precipitation to fall as rain, rather than snow.

STREAMFLOW

There do not appear to be any model projections of future streamflow patterns for Northwestern California. The reduction in snowpack in this region would suggest that snow-fed flows will decrease in duration and magnitude.

Stewart et al. (2005) analyzed the observational record from 1948 to 2002 for streamflow timing in western North America. For non-snowmelt-dominated streams, including those in Northwestern California, there was a trend to later streamflow timing, with the center of mass of annual flow having shifted 5–25 days later, a trend opposite that for the Sierra Nevada.

WATER AVAILABILITY

Environmental water requirements, such as minimum instream flows and required wetland water deliveries, are at risk of reduction, typically by small amounts, under the dry-warm climate scenario (Medellín-Azuara et al. 2008). The costs of environmental flows requirements on the Trinity River and Clear Creek for salmon runs are high and increase substantially with dry climate warming (Medellín-Azuara et al. 2008). Potential increases in the costs of environmental flows for urban, agricultural, and hydropower water supplies could increase controversy in setting environmental flows.

LENTIC SYSTEMS

Lakes, ponds, and other standing water provides important habitat for many wildlife in Northwestern California. Already, many native wildlife in alpine lakes are negatively impacted by introduced fish (Knapp et al. 2001, Pope et al. 2009). Climate change may exacerbate these stresses by further altering invertebrate communities (Porinchu et al. 2010) or changing water levels or water chemistry (Melack et al. 1997, Parker et al. 2008).

SEA LEVEL RISE

A recent analysis of sea level rise for California indicates that by 2035–2064, projected ranges of global sea level rise are ~6–32 cm above 1990 levels, with no discernable inter-scenario differences (Cayan et al. 2008a). By 2070–2100, however, projected ranges of sea level rise diverge across the lower (11–54 cm), middle-upper (14–61 cm), and higher (17–72 cm) emissions scenarios. This recent work suggests larger rises in sea level than earlier projections by Hayhoe et al. (2004): 19.2–40.9 cm by 2070-2099.

The frequency of sea level extremes also may increase if storms become more frequent or severe as a result of climate change (Cayan et al. 2008a). Increases in the duration of high storm-forced sea levels increase the likelihood that they will occur during high tides. The combination of severe winter storms with sea level rise and high tides would result in extreme sea levels that could expose the coast to severe flooding and erosion, damage to coastal structures and real estate, salinity intrusion into delta areas and coastal aquifers, and resulting degradation in the quality and reliability of freshwater supplies. Most coastal damage in California occurs during periods when both extreme sea levels and extreme wave heights occur concurrently. Extreme wave heights and extreme non-tidal fluctuations in sea level tend to increase from south to the north along the California coast, particularly from Point Conception northward. Extreme sea level height fluctuations are also larger to the north, reflecting heightened storm intensities at the more northerly coastal locations.

In Northwestern California, sea level rise may affect coastal and estuarine habitats. Specifically, many tidal marshes may be inundated and lost if sediment supply is not sufficient to keep up with the pace of sea level rise. However, the degree of habitat loss is difficult to quantify. Langley et al. (2009) demonstrated experimentally that elevated levels of the greenhouse gas CO_2 stimulates plant productivity, particularly below ground, thereby boosting marsh surface elevation, which paradoxically may aid some coastal wetlands in counterbalancing rising seas.

FIRE

The effects of climate change on fire regimes in Northwestern California are not well understood. Fried et al. (2004) estimated the impact of climatic change on wildland fire and suppression effectiveness in northern California by linking output from a single general circulation model to local weather and fire records and projecting fire outcomes with an initial-attack suppression model. In the Humboldt ranger unit in Northwestern California, Fried et al. (2004) projected that spread rates will not change forest fuels and will decrease slightly in grass fuels, apparently because projections of slower winds and higher humidity offset the effects of higher temperatures. Projections for redwood forests in northwestern California showed almost no change in escapes or area burned and the small area of grassland there experienced a decrease in burned area and suppression efforts (Fried et al. 2004). More recently, Westerling and Bryant (2008) found the probability of large (>200-ha) fires increases in Northwestern California by the end of the 21st century, particularly under the drier climatic conditions associated with a higher emissions scenarios and the GFDL climate model. Lenihan et al (2008) projected decreases in the area burned along the north coast of Northwestern California, but increases in the area burned along the south coast and inland areas of this ecoregion by the 2070–2099 period.

VEGETATION CHANGE

Ecoregional summary of California vegetation change. Of the five major vegetation groups in this ecoregion, decreases were projected to 2070 in the area of montane hardwood/Douglas-fir (-59 to -77%) and redwood/closed-cone pine (-53 to -57%), increases were projected in the area of ponderosa pine / Klamath mixed conifer (33 to 40%) and blue oak / foothill pine (87 to 119%), and relatively little change in montane hardwood was projected (7 to 8%).

Other sources of information. Although they do not provide summaries of ecoregional change, maps in Lenihan et al. (2008) show Northwestern California vegetation shifting from moist conifer forest to drier mixed evergreen forest and mixed evergreen woodland by the 2070-2099 period. In many coastal regions, the interaction between oceanographic and terrestrial air masses may be ecologically important. Intensifying upwelling along the California coast under climate change may intensify fog development and onshore flows in summer months, leading to decreased temperatures and increased moisture flux over land (Snyder et al. 2003, Lebassi et al. 2009). Coastal terrestrial ecosystems, such as those associated with coastal redwood, could benefit from these changes. However, current trends in fog frequency along the Pacific coast from 1901–2008 have been negative (Johnstone and Dawson 2010), thus the effect of climate change on coastal fog remains uncertain.

THREATS TO WILDLIFE

1. In Northwestern California, the predominant effects of climate change on terrestrial species will likely result from changes in vegetation communities. These changes are likely to include increases in the amount of oak, pine, chaparral, and montane hardwood vegetation, and a loss of conifer dominated vegetation.

2. Some coastal and estuarine habitats may be degraded as a result of sea level rise, but the degree of this loss and degradation is not yet well understood.

3. While high temperature events will become more common, it seems unlikely that temperatures will be high enough to cause direct wildlife mortality, as temperatures in this region are relatively moderate.

4. Snow-fed rivers and streams are likely to have less water, which may diminish the quantity and quality of wildlife habitat.

Models at a Glance: Northwestern California

Citation	**Model**	**Emissions scenario**	**Outputs**
Bell et al. 2004	RegCM2.5	2xCO2	Extreme temperature events
Cayan et al. 2008a	MAGICC	IPCC A1, A2, B1	Sea level rise
Cayan et al. 2008b	PCM, GFDL, and HadCM3 (statistically downscaled)	IPCC A1, A2, B1	Temperature
Fried et al. 2004	GISS	2xCO2	Fire frequency and area burned
Lenihan et al. 2008	GFDL CM2.1 and PCM	IPCC B1 and A2	Percent area burned, vegetation classes
Snyder and Sloan 2005	RegCM2.5	IPCC A1	Temperature and precipitation
Snyder et al. 2004	RegCM2.5	2xCO2	Temperature, precipitation, and snow accumulation
Stralberg et al. 2009	RegCM3 with boundary conditions from GFDL CM2.1 and NCAR CCSM 3.0 (statistically downscaled)	IPCC A2	Temperature, precipitation, and vegetation groups
Westerling and Bryant 2008	GFDL and PCM (statistically downscaled)	IPCC B1 and A2	Probability of large fires

Projected Effects of Climate Change in the Cascade Range Ecoregion

TEMPERATURE

Ecoregional summary of California regional climate model. In the Cascade Range, regional climate models project mean annual temperature increases of 1.8 to 2.2 °C by 2070. For the same time period mean diurnal temperature range is projected to increase by 0.1–0.2°C based on two RCMs presented in Stralberg et al. 2009.

Other sources of information. There is little information on projected changes specific to the Cascade Range of California. Most projected changes are probably consistent with those that are projected to occur in the Sierra Nevada ecoregion (see Sierra Nevada section).

Summary. The projected impacts of climate change on thermal conditions in the Cascade Range will be warmer winter temperatures, earlier warming in the spring, and increased summer temperatures. Few studies have focused exclusively on this ecoregion.

PRECIPITATION

Ecoregional summary of California regional climate model. In the Cascade Range, regional climate models project a decrease in mean annual rainfall of 89 to 360 mm by 2070. The range of these changes (-8% to -32%) illustrate the differences between the two regional climate model projections with regard to precipitation, and the sensitivity of the regional results to the variability in the two global climate models used to provide the boundary conditions. This sensitivity indicates substantial uncertainty in precipitation projections.

Other sources of information. As for temperature, there is little information on projected changes specific to the Cascade Range of California. Most projected changes are probably consistent with those that are projected to occur in the Sierra Nevada ecoregion (see Sierra Nevada section).

Summary. Currently, there is more uncertainty about the precipitation projections than for temperature in the Cascade Range, but with some evidence for a slightly drier future climate relative to current conditions. Few studies have focused exclusively on this ecoregion.

SNOWPACK

Relatively few climate models have focused exclusively on the Cascade Range, instead most lump this area in with the Sierra Nevada. Using a regional climate model, Snyder and Sloan (2005) projected that in some areas of the Sierra Nevada and Cascade Range snow accumulation could decrease by as much as 70%. The snow season was projected to end about one month earlier by the end of the century, with almost all snow melted by May. Temperature increases lead to decreases in snow accumulation, with more precipitation falling as rain. Similarly, Snyder et al. (2004) projected with a doubling of atmospheric CO_2 concentrations that snow accumulation will decrease by 62% in the Sacramento River hydrologic region of California, which encompasses most of the Cascade Range (and Modoc Plateau, west slope northern Sierra, Sacramento Valley). In the Sacramento River hydrologic region, reductions in monthly median snow heights from January to April were projected to range from 55 to 172 mm. See also the snowpack discussion for the Sierra Nevada for results in Mote et al. (2005), as patterns for Cascades of California similar to those for northern Sierra.

STREAMFLOW AND WATER AVAILABILITY

There do not appear to be any model projections of future streamflow patterns for the Cascade Range. The reduction in snowpack in this region could impact the hydrologic budget by shifting spring and summer runoff into the winter months. The reduction in snowpack in this region would suggest that snow-fed flows will decrease in duration and magnitude. There do not appear to be any model projections of future water availability for the Cascade Range.

LENTIC SYSTEMS

Lakes, ponds, and other standing water provides important habitat for many wildlife in the Cascade Range. Already, many wildlife in alpine lakes are impacted by introduced fish (Knapp et al. 2001, Pope et al. 2009). Climate change may exacerbate these stresses by further altering invertebrate communities (Porinchu et al. 2010) or changing water levels or water chemistry (Melack et al. 1997, Parker et al. 2008).

FIRE

On the basis of analyses of wildfire risks in California under four climatic change scenarios, Westerling and Bryant (2008) found the probability of large (>200-ha) fires increases in the Cascade Range by the end of the 21st century, particularly under the drier climatic conditions associated with a higher emissions scenarios and the GFDL climate model. While not summarized quantitatively, maps in Lenihan et al. (2008) show that for much of the Cascade Range, there is little change in the area burned, with the exception of the northern and southeastern portions of the ecoregion, where the area burned is projected to increase by as much as 50%.

VEGETATION CHANGE

Ecoregional summary of California vegetation change. Of the three major vegetation groups in this ecoregion, increases were projected to 2070 in the area of blue oak / foothill pine (94 to 108%), and eastside pine/pinyon pine/juniper (6 to 39%). The third major vegetation type, Sierran mixed conifer/white fir/jeffrey pine, was projected to decrease by 69 to 70%.

Other sources of information. Although they do not provide summaries of ecoregional change, maps in Lenihan et al. (2008) show the Cascade Range vegetation shifting from conifer forest to mixed evergreen forest with more grassland and loss of alpine/subalpine forest by the 2070–2099 period.

THREATS TO WILDLIFE

1. In the Cascade Range, the predominant effects of climate change on wildlife populations will likely result from changes in vegetation communities. These changes will include increases in the amount of oak, pine, chaparral, and montane hardwood vegetation, and a loss of conifer dominated vegetation, especially at higher elevations (e.g., red fir/lodgepole pine/subalpine conifer). This shift may be hastened by changes in fire severity and frequency.

2. While high temperature events will become more common, it seems unlikely that these temperatures will be high enough to cause direct mortality, as temperatures in this region are relatively moderate.

3. Snow-fed rivers and streams will have less water, which may reduce habitat for some wildlife associated with riparian areas and aquatic species.

Models at a Glance: Cascade Range

Citation	**Model**	**Emissions scenario**	**Outputs**
Lenihan et al. 2008	GFDL CM2.1 and PCM	IPCC B1 and A2	Percent area burned, vegetation classes
Pal et al. 2007	RegCM3	IPCC A2	Temperature and precipitation
Snyder and Sloan 2005	RegCM2.5	IPCC A1	Temperature and precipitation
Snyder et al. 2004	RegCM2.5	2xCO2	Temperature, precipitation, and snow accumulation
Stralberg et al. 2009	RegCM3 with boundary conditions from GFDL CM2.1 and NCAR CCSM 3.0 (statistically downscaled)	IPCC A2	Temperature, precipitation, and vegetation groups
Westerling and Bryan 2008	GFDL and PCM (statistically downscaled)	IPCC B1 and A2	Probability of large fires

Projected Effects of Climate Change in the Great Basin Ecoregion

TEMPERATURE

Ecoregional summary of California regional climate model. In the Great Basin, regional climate models project mean annual temperature increases of 1.7-2.4°C by 2070. For the same time period mean diurnal temperature range is projected to increase by 0.1-0.2°C based on two RCMs presented in Stralberg et al. 2009.

Other sources of information. Bell et al. (2004) projected with a doubling of atmospheric CO_2 that there will be a significant increase in extreme temperature events in the North Lahontan (Great Basin) region. Mean maximum and minimum temperatures were projected to increase significantly by 2.7°C and 2.5°C, respectively. Thus, the daily mean temperature range was projected to increase by 0.15°C. The frequency of extremely hot days (exceeding long-term 95th percentile) was projected to increase by 34 days per year, and days exceeding 32.2°C by 0.8 days per year. The frequency of prolonged (7-day) hot spells was projected to increase by about 1.5 events per year and their length was projected to increase by about 7 days. The frost-free growing season was projected to begin 20 days earlier and to last 31 days longer. These models projected 36 fewer days of extreme cold, 47 fewer days below 0°C, and prolonged (7-day) cold spells to decrease by about 1.8 events per year.

Summary. The projected impacts of climate change on thermal conditions in the Great Basin will be warmer winter temperatures, earlier warming in the spring, later cooling in the fall, and increased summer temperatures.

PRECIPITATION

Ecoregional summary of California regional climate model. In the Great Basin, regional climate models project a decrease in mean annual rainfall of 32 to 85 mm by 2070. The range of these changes (-8% to -21%) illustrate the differences between the two regional climate model projections with regard to precipitation, and the sensitivity of the regional results to the variability in the two global climate models used to provide the boundary conditions. This sensitivity indicates substantial uncertainty in precipitation projections.

Other sources of information. Earlier regional climate models (with different GCM inputs) run by Snyder et al. (2004) and Snyder and Sloan (2005) projected 4 to 7% increases in precipitation for the North Lahontan hydrologic region of California by the end of 21st century, but these changes were not statistically significant at either the annual or monthly time scales.

Using a regional climate model, Bell et al. (2004) projected with a doubling of atmospheric CO_2 that there will be some significant changes in precipitation patterns in the North Lahontan region. For annual precipitation, an increase of 0.02 cm in mean rainfall per rain day and of 11 fewer rain days per year were both statistically significant. However, projections of 1.1 cm greater total rainfall per year and 2.8 more days of extremely heavy rainfall (exceeding long-term 95th percentile) were nonsignificant.

Summary. Currently, there is more uncertainty about the precipitation projections than for temperature in the Great Basin, but with some evidence from the most recent investigations for a drier future relative to current conditions.

SNOWPACK

Snyder et al. (2004) projected with a doubling of atmospheric CO_2 concentrations that snow accumulation will decrease significantly by 34% in the North Lahontan hydrologic region of California. Reductions in monthly median snow heights from January to April ranged from 20 to 61 mm.

STREAMFLOW

There do not appear to be any model projections of future streamflow patterns for the Great Basin. The reduction in snowpack in this region would suggest that snow-fed flows will decrease in duration and magnitude.

FIRE

On the basis of analyses of wildfire risks in California under four climatic change scenarios, simulated from GFDL and PCM global climate models and the B1 (2x preindustrial CO_2) and A2 (>3x preindustrial CO_2) emissions scenarios, Westerling and Bryant (2008) projected the probability of large (>200-ha) fires increases in the

Great Basin by the end of the 21st century, more so under the drier, higher emissions (GFDL A2) scenario.

VEGETATION CHANGE

Ecoregional summary of California vegetation change. Of the three major vegetation groups in this ecoregion, increases were projected to 2070 in the area of desert scrub (51 to 63%), and eastside pine/pinyon pine/juniper (45 to 38%). The area of the third major vegetation type, sagebrush/bitterbrush/low sage, was projected to decrease by 56 to 41%.

Other sources of information. Although they do not provide summaries of ecoregional change, maps in Lenihan et al. (2008) show vegetation shifts in the Great Basin that include an increase in the area of conifer forest and grasslands and decreases in the area of shrublands by the 2070-2099 period.

THREATS TO WILDLIFE

1. In the Great Basin, changes in vegetation communities will be important for wildlife. These changes will include projected increases in the amount of pine and juniper forest and desert scrub and grasslands, and a loss of and sagebrush and other shrub habitats. This shift may be hastened by changes in fire severity and frequency.

2. High temperature events will become more common, and may increase by as much as 2.7°C. Given the arid conditions throughout the Great Basin, this increase in temperature may increase heat and water stress for some wildlife.

3. Snow-fed rivers and streams will have less water, especially during the spring and summer, which may reduce habitat for some wildlife associated with riparian areas.

Models at a Glance: Great Basin

Citation	Model	Emissions scenario	Outputs
Lenihan et al. 2008	GFDL CM2.1 and PCM	IPCC B1 and A2	Percent area burned, vegetation classes
Pal et al. 2007	RegCM3	IPCC A2	Temperature and precipitation
Snyder and Sloan 2005	RegCM2.5	IPCC A1	Temperature and precipitation
Snyder et al. 2004	RegCM2.5	2xCO_2	Temperature, precipitation, and snow accumulation
Stralberg et al. 2009	RegCM3 with boundary conditions from GFDL CM2.1 and NCAR CCSM 3.0 (statistically downscaled)	IPCC A2	Temperature, precipitation, and vegetation groups
Westerling and Bryan 2008	GFDL and PCM (statistically downscaled)	IPCC B1 and A2	Probability of large fires

Projected Effects of Climate Change in the Sierra Nevada Ecoregion

TEMPERATURE

Ecoregional summary of California regional climate model. In the Sierra Nevada, regional climate models project mean annual temperature increases of 1.8–2.4°C by 2070. For the same time period mean diurnal temperature range is projected to increase by 0.1–0.2°C based on two RCMs presented in Stralberg et al. 2009.

Other sources of information. By the end of the 21st century, Maurer (2007) projected average annual temperature in the Sierra rises by 3.6–3.8°C and 2.3–2.4°C, respectively, for the higher (A1) and lower (B2) emission scenarios, with the greatest warming in July of 5.0–5.1°C and 3.0–3.1°C. The projected changes were relatively constant from the Northern to Southern Sierra, but varied between lower and higher elevation basins.

The magnitude of warming may vary spatially within the ecoregion. Analysis of temperature variation with elevation and topography in the vicinity of Yosemite National Park indicated that strong westerly winds are associated with relatively warmer temperatures on the east slope and cooler temperatures on the west slope and weaker westerly winds with the opposite pattern (Lundquist and Cayan 2007). Data from 1948 to 2005 indicate weakening westerly winds over this time period, a trend leading to relatively cooler temperatures on the east slope over decadal timescales. This change may have contributed to a trend toward less long-term warming on the east slope than the west slope, which may explain why spring melt timing has advanced more rapidly on the west slope than on the east slope.

Summary. The projected impacts of climate change on thermal conditions in the Sierra Nevada will be warmer winter temperatures, earlier warming in the spring, and increased summer temperatures. The topographic diversity of this ecoregion will likely mean that the magnitude of warming will vary at a very fine spatial resolution.

PRECIPITATION

Ecoregional summary of California regional climate model. In the Sierra Nevada, regional climate models project a decrease in mean annual rainfall of 92 to 339 mm by 2070. The range of these changes (-10% to -5%) illustrate the differences between the two regional climate model projections with regard to precipitation, and the sensitivity of the regional results to the variability in the two global climate models used to provide the boundary conditions. This sensitivity indicates substantial uncertainty in precipitation projections.

Other sources of information. Maurer and Duffy (2005) projected that precipitation would increase an average, across global circulation models, in annual precipitation of 2% and 7% in the Sierra Nevada for years 21–40 and 51–70, respectively, with sharpest increases in winter, at 6% and 13% (Maurer and Duffy 2005).

Maurer (2007) projected annual average precipitation exhibiting small (about 5%) but significant increases in the Sierra Nevada under low emissions in 2011–2040 and comparable decreases for 2041–2070. For all other cases (emission scenarios and time periods), there is no statistically significant change in annual precipitation, though a pattern exists of slight increases in the north declining to slight decreases in the south. On a monthly basis, precipitation increased from December–February and decreased from April–June, both with generally higher magnitudes under the higher than lower emissions scenario, especially by 2071–2100. The spring-summer decline is sharper and the winter increase is smaller in the south than the north. While annual precipitation generally does not differ between emission scenarios, decreases in April–May precipitation are significantly greater for the higher than lower emissions scenario. Overall, the increase in winter precipitation and decrease in spring precipitation shifts the centroid of annual precipitation volume 2–6 days earlier by 2071–2100.

Summary. The projected effects of climate change on total precipitation in the Sierra Nevada remain uncertain. This uncertainty is associated both with the climate models and emissions scenarios and with the complex topography and weather patterns in this region. As a result, it is currently difficult to draw general conclusions about the effects of climate change on precipitation patterns in the Sierra Nevada.

SNOWPACK

Although total precipitation may not change greatly, the results of multiple climate modeling efforts have all projected that by the end of the 21st century, there will be dramatic decreases in end-of-the-year snowpack in the Sierra. However, these decreases will also be highly variable throughout the Sierra depending on the elevation and region. Specifically, the reduction in snowpack will probably be greater in the lower elevation northern Sierra than in the higher elevation southern Sierra.

Using a PCM model, Knowles and Cayan (2002) projected that April snowpack in the Cascades and Sierra Nevada will decline 5% compared to present conditions by 2030, >33% by 2060, and about 50% by 2090. Snowpack loss is projected to be greatest at mid to lower elevations, where it is more sensitive to temperature changes than at higher colder elevations. Thus, snowpack loss is most severe in the lower elevation mountains in the north than in the higher elevation mountains to the south. By 2090, the northern Sierra and Cascades could lose 66% of their April snowpack versus 43% in the southern Sierra.

Knowles and Cayan (2004) projected that by 2060 about one-third of the total April snowpack in the Cascades and Sierra Nevada will be lost. Lost snowpack appears as early runoff. In general, the loss of snowpack results in higher runoff peaks prior to April and reduced snowmelt-driven flows in subsequent months. At elevation zones below 2000 m, more than half of the snowpack is lost. For moderate elevations, significant relative reductions of snowpack occur in zones that have historically accumulated significant snowpack, making these altitudes maximally sensitive to climate change. Thus, the largest losses in snowpack volume would occur at elevations between about 1500 and 2000 m. In the northern Sierra, 85% of the snowpack losses occur between 1300 and 2200 m; in the southern Sierra, 85% of the losses occur between 1800 m and 3300 m. The total projected reduction in April snowpack by 2060 is about 38% in the north, and 23% in the south.

Hayhoe et al. (2004) reported that projections of snowpack loss vary substantially with respect to the time periods, emissions scenarios, and elevation ranges. For all elevations, for low and high emission scenarios, respectively, model simulations indicate decreases in snowpack of 26%–38% and 37%–40% for the period 2020–2049 and decreases of 29%–72% and 73%–89% for the period 2070–2099. At elevations of 1000–2000 m for the respective emissions scenarios, simulations indicate decreases in snowpack of 58%–60% and 56%–66% for the period 2020–2049 and decreases of 65%–87% and 95%–97% for the period 2070–2099. At elevations of 2000–3000 m for the respective emissions scenarios, simulations indicate decreases in snowpack of 24%–34% and 34%–36% for the period 2020–2049 and decreases of 22%–75% and 73%–93% for the period 2070–2099. At elevations of 3000–4000 m for the respective emissions scenarios, simulations indicate deviations in snowpack of -11% to 4% and decreases of 15%–16% for the period 2020–2049 and deviations of -48% to +15% and decreases of 33%–68% for the period 2070–2099.

Dettinger et al. (2004) concluded that the steadily warming business-as-usual climate yields gradual decreases in end-of-winter (1 April) snowpack such that by the end of the 21st century, the average snow water content is reduced to 67%, 51%, and 21% of the historic (1970–1998) totals in the Carson, Merced, and American river basins, respectively. As the year-to-year variability in rainfall fractions progressively increases during the century, the amounts of snowpack formed and then stored for springtime melting also vary widely.

Using regional climate modeling, Snyder et al. (2004) projected that snow accumulation will decrease significantly by 62%, 49%, and 59%, respectively, in the Sacramento River, San Joaquin River, and Tulare Lake hydrologic regions of California, which together contain the main snowpack regions of the west slope of the Sierra Nevada. Monthly reductions in snow height from January to April ranged from 55 to 172 mm, 73 to 109 mm, and 24 to 45 mm for the Sacramento River, San Joaquin River, and Tulare Lake regions, respectively.

Snyder and Sloan (2005) used a regional climate model to examine projected snow accumulations presented for the all of California and for three main subregions: northern (coastal and inland California north of the Los Angeles area), mountain (Sierra Nevada, Cascade Range, and higher-elevation areas in northeastern California), and southern (coastal, inland, and high-desert areas of southern California) for 2080-2099. Statistically significant decreases in snow accumulation of over 100 mm (50%) occur in some months (February–April), with a significant decrease of variable magnitude in all months December–June. Decreases are concentrated in the Sierra Nevada and southern Cascade Range. The snow season ends about one month earlier by the end of the century, with almost all snow melted by May. Temperature increases led to decreases in snow accumulation, with more precipitation falling as rain, which impacts the hydrologic budget by shifting spring and summer runoff into the winter months, reinforcing results of other studies that used different models and driving conditions.

Maurer (2007) projected that by 2071–2100 there will be 36%–80% reductions of end-of-winter snowpack for all basins of the Sierra. There is less snow loss in the southern, higher elevation, basins than for the northern, lower elevation, basins, as rising temperatures are less likely to bring temperatures above freezing at higher elevations. Greater losses under the higher than lower emissions scenarios have high confidence for the lower elevation basins only, indicating changing sensitivity to emissions level with elevation. Maurer et al. (2007) projected that increases in average winter temperature of 1°C, 3°C, and 5°C, result in a loss of 26%, 62%, and 82% of the Sierra's end-of-winter snowpack. Even under a 5°C warming, the highest-elevation regions in the southern Sierra remain snow-dominated, though these represent only a small area and a small volume of stored water.

Cayan et al. (2008b) projected overall snowpack losses for San Joaquin, Sacramento, and (parts of) the Trinity drainages will range from about 32% to 79% by the end of the century. Projections of snowpack loss are about twice as great for the more sensitive GFDL than the less sensitive PCM model; the former model has greater temperature sensitivity to increased greenhouse gas concentrations. Most of the difference reflects the projected warming, the remainder mostly to declining precipitation totals in the more sensitive model. For both models, snowpack losses are greatest in the warmer, medium-high emissions scenario. In terms of water storage, snowpack losses have greatest impact in the relatively warm elevations of 1000–2000 m, with losses of 60% to 93%, and elevations of 2000–3000 m, with losses of 25% to 79%. In the Sierra Nevada, snowpack losses are highest in the northern and central regions because elevations there are lower than to the south. Projections of snowpack loss vary substantially among model scenarios, time period, and elevations. For all elevations for the periods 2005–2034, 2035–2064, and 2070–2099, projected changes in snowpack are -29% to +6%, -12% to -42%, and -32% to -79%, respectively. For the respective time periods, projected reductions in snowpack are -13% to -48% , -26% to -68%, and -60% to -93% for elevations from 1000–2000 m, -33% to +12%, -8% to -36%, and -25% to -79% for elevations from 2000–3000 m, and -13% to +19%, -2% to -16%, and -2% to -55% for elevations from 3000–4000 m.

Howat and Tulaczyk (2005) analyzed the effects of various factors on snowpack in the Sierra Nevada during the latter half of the 20th century. They concluded that warming over the latter half century had little effect on total summer water discharge. Hence, the region's snowpack may be less sensitive to temperature change than predicted by numerical models. Using 53 years of 1 April snowpack data from the Sierra Nevada, a spatially distributed covariance model of snowpack sensitivity to temperature and precipitation indicated that snowpack volume has a greater covariance to precipitation than to temperature. Increasing precipitation and temperature from 1950 to 2002 has led to an increase in snowpack at high elevations and a loss at low elevations, resulting in little or no overall change in snowpack volume. The covariance model predicts a 6%–10% decrease in total snowpack volume per 1°C. Sensitivity, however, is highly dependent on concurrent change in precipitation and is spatially variable, with the lower-elevation watersheds in the north being the most sensitive to warming. Howat and Tulaczyk (2005) cautioned that existing model estimates of changes in precipitation under greenhouse warming scenarios have a high uncertainty and low spatial resolution (Snyder et al. 2002, Maurer and Duffy 2005) and, hence, predictions of potential changes in snow water volume based on these forecasts should also carry a high uncertainty.

STREAMFLOW AND WATER AVAILABILITY

Summary. As a result of warming temperatures, there is a general consensus that declining snowpack and changes in the timing of snowmelt will result in earlier runoff and reduced spring and summer streamflows in the Sierra Nevada.

On the basis of a PCM model, with business-as-usual emissions, Knowles and Cayan (2002) predicted that the loss of snowpack in the Sierra and Cascades results in higher runoff peaks in April and reduced snowmelt-driven flows in subsequent months. The April–July fraction of total annual flow in the northern headwaters is reduced from 0.30 in 2030 to 0.26 in 2060. Combined with the smaller reduction in the south, this represents over 3 km^3 of runoff shifting from after 1 April to before 1 April. By 2090, there is a loss of 1.2 km^3 and 4.4 km^3 of April–July runoff in the south and north, respectively; the total loss of 5.6 km^3 represents about 20% of historic annual flow volume.

Knowles and Cayan (2004) projected that by 2060 both the northern (Sacramento) and the southern (San Joaquin) headwaters show the effect of reduced snowpack, with the largest streamflow impacts in the north. The April–July fraction of total annual flow in the northern headwaters is reduced from 0.36 in 2030 to 0.26 in 2060. Combined with a smaller reduction in the south, this represents over 3 km^3 (~2.5 maf) of runoff shifting from April–July to pre-April 1 flows.

Hayhoe et al. (2004) reported that warmer temperatures and more precipitation falling as rain rather than as snow also causes snowmelt runoff to shift earlier under all model simulations. The magnitude of shift is higher in southern Sierran basins and under the high emissions scenario. Before midcentury, stream inflows to reservoirs decline because of diminished snowpack and increased evaporation. Greater reductions in inflows under high emissions are driven both by higher temperatures and lower average precipitation as compared to under low emissions. Earlier runoff may also increase the risk of flooding.

Declining snowpack, earlier runoff, and reduced spring and summer streamflows will likely affect surface water supplies and shift reliance to groundwater resources often already overdrafted (Hayhoe et al. 2004). Under all scenarios, except PCM low emissions, the projected length, frequency, and severity of extreme droughts in the Sacramento River system by the end of the century will substantially exceed what has been experienced in the 20th century. The proportion of years projected to be dry or critical increases from 32% in the historical period to 50%–64% by the end of the century (except under the PCM low emissions scenario where it decreases 8%).

For the entire Sierra, model simulations indicate deviations in total annual flow of -18% to +5% and decreases of 10%–22% for the period 2020–2049 and deviations of -24% to +12% and decreases of 29%–30% for 2070–2099, for the low and high emission scenarios, respectively (Hayhoe et al. 2004). For the northern Sierra, simulations indicate deviations in annual inflow of -19% to +3% and decreases of 9%–22% for the period 2020–2049 and deviations of -20% to +9% and decreases of 24%–29% for 2070–2099, for the low and high emission scenarios, respectively. For the southern Sierra, simulations indicate deviations in annual inflow of -16% to +10% and decreases of 14%–23% for the period 2020–2049 and deviations in inflow of -33% to +17% and decreases of 30%–43% for 2070–2099, for the low and high emission scenarios, respectively.

For total April–June inflow for the Sierra, simulations indicate deviations in inflow of -11% to -20% and decreases of 19%–24% for the period 2020–2049 and decreases in inflow of 1%–41% and 46%–54% for 2070–2099, for the low and high emission scenarios, respectively (Hayhoe et al. 2004). For April–June inflow for the northern Sierra, simulations indicate decreases in inflow of 16%–21% and 19%–24% for the period 2020–2049 and deviations in inflow of 6%–34% and 45%–47% for 2070–2099, for the low and high emission scenarios, respectively. For total April–June inflow for the southern Sierra, simulations indicate decreases in inflow of 2%–18% and 19%–24% for the period 2020–2049 and deviations in inflow of -52% to +5% and decreases of 47%–65% for 2070–2099, for the low and high emission scenarios, respectively.

For the entire Sierra, simulations indicate deviations from the centroid of total water year flow of -15 to 0 and -7 to +2 days for the period 2020–2049 and negative deviations of 7–23 and 14–32 days for 2070–2099, for the low and high emission scenarios, respectively (Hayhoe et al. 2004). For the northern Sierra, simulations indicate deviations from the centroid of -16 to 0 and -5 to +3 days for the period 2020–2049 and negative deviations of 3–18 and 11–24 days for 2070–2099, for the low and high emission scenarios, respectively. For the southern Sierra, simulations indicate negative deviations from the centroid of 10–19 and 7–12 days for the period 2020–2049 and simulations indicate negative deviations of 22–34 and 34–43 days for 2070–2099, for the low and high emission scenarios, respectively.

Under a business-as-usual scenario (similar to the IS92a scenario), Dettinger et al. (2004) projected there is no significant trend in average streamflow for the American, Carson, and Merced rivers over the 21st century. This is partly because temperature changes by themselves yield relatively small annual-flow changes in these rivers and partly because projected changes in California precipitation are relatively small. Timing of streamflow, however, changes markedly. In the business-as-usual scenario, snowmelt and streamflow occur about one month earlier by 2100 in response to increased proportions of rain to snow and earlier snowmelt episodes. These timing changes are accompanied by increased frequency of winter flooding and, later in the year, result in lower low flows, less summertime soil moisture, increased stresses on basin vegetation and ecosystems, and presumably increased wildfire risks. Over the 21st century, the April–July fraction of annual flow in the three rivers is projected to decrease by 7%–14% and the April–July total flow by 5%–29%. Under the business-as-usual scenario, projected spring fractions of annual flow are projected to become more variable both from year to year and decade to decade. This presumably reflects increased variability of precipitation form (rain versus snow), as winter and spring temperatures increasingly approach or surpass freezing levels in larger parts of the basins.

Patterns of streamflow vary with elevation (Dettinger et al. 2004). The high-elevation Merced and Carson Rivers, characterized by large streamflow peaks in May, respond to projected warming by progressive reductions in peak spring flows and corresponding increases in winter flow. Increased winter flows reflect a greater preponderance of rain than snow in winter, earlier snowmelt, and more winter floods. Flows from the lower altitude American River basin are dominated by wintertime rainfall runoff and winter-to-early-spring snowmelt so that flows peak in winter and early spring. Progressively even more streamflow occurs in the American River in early winter under future scenarios. Thus, flows increase from January to March and decrease in the preceding as well as the following months, so that overall the centroids of flow timing do not change much.

Because snowmelt and runoff occur earlier in the year in response to the warming climate, less water is left in the basins when the warm seasons arrive (Dettinger et al. 2004). Although there is a potential for increased evapotranspiration with the warming climate, this reduction in summertime moisture availability ensures that the actual amounts of summer evapotranspiration decline along with summertime streamflow rates. Remnant snowpack, soil moisture, and shallow ground-water reservoirs are more depleted by summertime in response to earlier runoff. As a result, simulated late summer and autumn flows are much reduced under business-as-usual scenarios.

April–July flows are critical to water-supply management in California because, with a Mediterranean climate (wet winters, dry summers), flows during these months can typically be captured in reservoirs with little risk of floods generated by large storms (Dettinger et al. 2004). By contrast, during the earlier winter and early spring months, storms are common, and reservoirs often have to release water to maintain space for flood control.

By resampling of an 18-member ensemble of climate-change projections (each under three emissions scenarios), Dettinger (2005) estimated projection distribution functions to clarify the implications of the ensemble projections for California. Patterns in annual streamflow changes for the North Fork of the American River in the central Sierra Nevada are similar to those for precipitation change in northern California, reflecting the strong control that precipitation patterns exert on total streamflow amount, as well as the nearly complete buffering of streamflow amounts against responses to temperature changes. By the end of the 21st century, streamflow amounts are biased towards a drier mean and mode. The corresponding projections of streamflow timing mostly reflect the warmer temperatures projected by all the models, although concurrent precipitation changes in the realizations couple nonlinearly with the temperature effects to yield much broader and more multimodal timing distributions. Some of the multimodal character of timing patterns presumably derives from the bimodal character of the joint temperature-precipitation distributions. By 2025, years with earlier than normal median-flow dates are all but eliminated. By the end of the 21st century, the most common median-flow date projections are over a month earlier than 1951–1980 norms.

Maurer and Duffy (2005) assessed the uncertainty in projected impacts on streamflow in California attributable to differing sensitivities of various GCMs; simulations included a control period (unchanging CO_2 and other forcing) and perturbed period (1%/yr CO_2 increase; at 70 yrs doubles CO_2). Hydrologic models using downscaled temperature and precipitation data projected streamflows at strategic points on seven major rivers on the west slope of the Sierra Nevada (three in north in Sacramento River drainage, four in south in San Joaquin River drainage). Although the individual models predicted significantly different regional climate responses to increasing atmospheric CO_2, projected hydrological responses were robust across models. Key patterns were decreases in summer low flows and increases in winter flows and a shift of flow to earlier in the year. Summer flow decreases became consistent across models at lower levels of greenhouse gases than did increases in winter flows.

The changes in flow are driven by an average increase, across models, in annual precipitation of 2%

and 7% for perturbed years 21–40 and 51–70, respectively, with sharpest increases in winter, at 6% and 13% (Maurer and Duffy 2005). The accompanying average temperature rises 1.1 and 2.2°C for the earlier and later perturbed periods, respectively, with summer temperature rising slightly more than in winter, at 1.3 and 2.7°C. These basin-wide changes are nearly identical in the northern and southern Sierra.

In the northern Sierra, by years 21–40 the decrease in late spring and early summer flows is significant, and by years 51–70, the increase in winter and decrease in summer flows are both significant (Maurer and Duffy 2005). In the southern Sierra, the increase in March–April flows is more highly significant than in the north, and reaches significance levels over 90% earlier (by years 21–40), showing the greater influence in the higher altitude (hence more snow-dominated) south of projected temperature changes. At 51–70 years into the perturbed run, the annual hydrograph will shift 11 days earlier in the north and 18 days earlier in the south, the pattern being very robust across models.

Intermodel variation in projected precipitation accounts for most of the uncertainty in increases in winter and spring flow in both the northern and southern Sierra, with a greater influence in the north (Maurer and Duffy 2005). Thus, streamflow impacts in the higher elevation, more snow-dominated south (earlier snowmelt and the shifting of the annual hydrograph to earlier in the year) tend to be more temperature driven, and hence less uncertainty. The influence of intermodel variability in precipitation on late summer streamflow decreases in later years, as higher temperatures dominate the hydrologic response, and melting snowpack has less influence. Conversely, the contribution of variability in precipitation to early summer streamflow uncertainty increases later in the perturbed period.

From model projections of changes in Sierra streamflow under higher and lower emission scenarios, Maurer (2007) reported there is high confidence of increasing winter streamflow, from temperature-driven effects of an increased proportion of rain versus snow and increased snowmelt, and, secondarily, increasing winter precipitation. Also, there is a high confidence of decreasing streamflow in late spring and summer. The increases in winter flows are markedly greater for the higher than lower emissions scenario, particularly for 2071–2100. Differences in patterns exist between the northern, lower elevation, basins, and the southern, higher elevation, basins. Winter flows increase from December–March, extending to April in the south (i.e., at higher elevation increases in precipitation can be stored as snow, later augmenting flow). Correspondingly, flows decrease mainly from April–September to the north and from May–October in the south. Increases in winter and decreases in summer flows are of greater magnitude under the higher than lower emissions scenario. The highest confidence in differing responses to streamflow is for May–August declines, with decreases being sharper for the higher than lower emissions scenario. Under higher emissions, in the north the increases in winter flow more than offset the declines in summer, producing a small (low confidence) increase in annual flow; in the south, the winter increase is offset by the late season decrease, with little change in annual volume. Under lower emissions, both the north and south show slight declines in annual flow. The combined effect of changes in precipitation, temperature, and snowpack produce an earlier arrival of annual flow volume by as much as 36 days by 2071–2100. This shift is significantly less for lower than higher emissions by the end of the century.

Maurer et al. (2007) projected the effects of climate warming on streamflow timing in the Sierra Nevada. Areas with average winter temperatures of -2°C to -4°C (i.e., below but near freezing), which store the greatest amount of end-of-winter snow, are the most likely to exhibit significant shifts in "center timing" (CT) of streamflow (day when half annual flow has passed a given point). Hence, areas with (snow-dominated) elevations from 2000–2800 m are the most sensitive to temperature increases. At these elevations, a warming of 5°C is projected to shift CT in excess of 45 days earlier in the year than in the period 1961–1990; average shifts in timing will exceed 40 and 45 days earlier in the north and south, respectively. At elevations of 1600–2400 m, even low levels of temperature increases (1°–2°C) are projected to shift CT 10–15 days earlier. With levels of warming above 3°C (projected under mid-to-high emissions scenarios), CT shifts exceed 30 days for elevations of 2000–2800 m; almost all zones below 2000 m become rain-dominated, essentially eliminating the influence of snow on streamflow timing in the northern Sierra Nevada.

TWENTIETH-CENTURY STREAMFLOW PATTERNS

Stewart et al. (2005) analyzed observational records from 1948 to 2002 and found trends for the Sierra

Nevada toward earlier onsets of the snowmelt spring pulse and central timing of streamflow by 10-30 days and a decreasing fraction of annual flow from April–July (increasing in March); mean annual flows have remained constant or marginally increased. These timing changes have resulted in increasing fractions of annual flow occurring earlier in the water year by 1–4 weeks. Central timing of streamflow and precipitation are positively correlated in rivers throughout the Sierra Nevada, but notably no substantial precipitation trends were evident in that area; positive correlations indicate that snowmelt and snowmelt-fed streamflow tend to occur later with increasing winter precipitation. Greater winter snow-water equivalent is strongly associated with later snowmelt and the date of central timing of snowmelt for most gauges in the Sierra Nevada, even very early in the snowmelt season (1 February; even stronger for 1 April). El Niño–Southern Oscillation conditions are associated with higher-than-average winter precipitation, leading to a delay in snowmelt and negative correlations with center timing of streamflow.

The primary cause for the regionally coherent trends toward earlier snowmelt and streamflow timing is a broad-scale increase of winter and spring temperatures by about 1–3°C over the past 50 years (Stewart et al. 2005). Interestingly, changes due to temperature increases have overwhelmed opposing precipitation-driven changes over much of the western United States during the same period. Although these temperature changes are partly controlled by the effects of the Pacific Decadal Oscillation (PDO), a separate and significant part of the variance is associated with a springtime warming trend, consistent with observed changes in regional and global temperatures, that spans the PDO phases.

If observed trends in streamflow timing persist, they will affect western water resources in several important ways (Stewart et al. 2005). In western North America, springtime snowmelt has been relied upon to supply 50%–80% of the annual flow volume. Progressively earlier snowmelt and snow-fed streamflow will increasingly challenge many water resource management systems by modifying assumptions about the predictability and seasonal deliveries of snowmelt and runoff. The most impacted will likely be rivers where associated flood risks may increase, or where cool-season storage cannot accommodate lost snowpack reserves. Earlier streamflow may impinge on the flood protection stages of reservoir operations so that less streamflow can be captured safely in key reservoirs. Almost everywhere in western North America, a 10–50% decrease in the spring-summer streamflow fractions will accentuate the typical seasonal summer drought with important consequences for warm-season supplies, ecosystems, and wildfire risks.

In the Sierra Nevada, the spring pulse (first major surge in snowmelt discharge) exhibits a statistically stronger and spatially more extensive early melt pattern than the center of mass, with the linear trend in spring pulse for a number of river basins in the central Sierra being significantly earlier by >20 days at the end than the middle of the 20th century (Peterson et al. 2008). In general, the timing of peak flow is earlier, and the magnitude is increasing over the end of the century.

LENTIC SYSTEMS

Lakes, ponds, and other standing water provides important habitat for many wildlife in the Sierra Nevada. Already, many wildlife in alpine lakes are impacted by introduced fish (Knapp et al. 2001, Pope et al. 2009). Climate change may exacerbate these stresses by further altering invertebrate communities (Porinchu et al. 2010) or changing water levels or water chemistry (Melack et al. 1997, Parker et al. 2008). If ponds are fed by snowmelt and/or streams, they may dry out or be more ephemeral during the non-winter months.

Summary. As a result of warming temperatures, there is a general consensus that declining snowpack and changes in the timing of snowmelt will result in earlier runoff and reduced spring and summer streamflows in the Sierra Nevada. Projected declines in water availability, which are already well underway, will have profound consequences for water use in a region already contending with the clash between rising demands and increasing allocations of water for endangered fish and wildlife.

FIRE

There is general consensus that increasing CO_2 levels will result in conditions that favor larger and more intense fires in a number of vegetation types in the Sierra Nevada. However, over long term, these conditions may lead to vegetation shifts that support less severe wildfire regimes.

Fried et al. (2004) estimated the impact of climatic change on wildland fire and suppression effectiveness in northern California by linking output from a single GCM to local weather and fire records and projecting fire outcomes with an initial-attack suppression model. This analysis suggests warmer, windier and somewhat drier conditions in the Sierra foothills and an increased impact of fires. The climate change scenario increased the number of fast-burning fires and reduced the number of slow-burning fires. Considering impacts by vegetation type, there were substantial increases in the projected frequency of fast-spreading fires in grass and moderate increases in brush. By influencing fuel moisture and wind speed, climate change caused fires to burn with greater intensity which triggered more intensive suppression efforts. Higher intensity fires are also more likely to overwhelm suppression efforts and lead to greater damage to both natural resources and property. Most fires under both present climate and doubling-of-CO_2 scenarios have moderate fire intensity and rates of spread and are unlikely to become large, damaging fires. In the Sierra foothills, the few fires with extreme behavior that are most likely to become large and damaging will grow in number several fold under climate change. Despite enhancement of fire suppression efforts, the number of escaped fires increased 125% and the area burned by contained fires increased 41% in the Sierra Nevada. The expected annual number of escaped fires rose 143% in grass and 121% in brush. The area burned by contained fires increased in all four vegetation fuel types: the area burned for brush more than doubled and increased by 65% in oak woodland.

On the basis of analyses of wildfire risks in California under four climatic change scenarios, Westerling and Bryant (2008) projected that the probability of large (>200-ha) fires increases in the Sierra Nevada by the end of the 21st century, more so under the drier, higher emissions scenario and particularly on the west slope and in the foothills.

While not summarized quantitatively, maps in Lenihan et al (2008) show between current conditions and the 2070–2099 period that in the eastern Sierra Nevada the area burned is projected to increase by as much as 50%, while on the west slope there is little change projected in the mean annual area burned.

While there is consistent evidence toward shifts in conditions that lead to more frequent and severe fires, over longer time periods, changing climatic conditions may result in shifts in vegetation with reduced fuel loads leading to less frequent and intense wildfires (Parisien and Moritz 2009).

Summary. There is general consensus that increasing CO_2 levels will result in larger and more intense fires in a number of vegetation types in the Sierra Nevada. However, over the longer term, these conditions may lead to vegetation shifts that support less severe wildfire regimes.

VEGETATION CHANGE

Ecoregional summary of California vegetation change. Of the three major vegetation groups in this ecoregion, decreases were projected to 2070 in the area of sierra mixed conifer/white fir/Jeffrey pine (-12 to -32%), and increases were projected in the amount of area of ponderosa pine / Klamath mixed conifer (55 to 94%) and blue oak / foothill pine (23 to 97%).

Other sources of information. Although they do not provide summaries of ecoregional change, maps in Lenihan et al. (2008) show Sierra Nevada vegetation with decreasing area of conifer forest and alpine/subalpine forest and increasing area of grassland and mixed evergreen forest by the 2070–2099 period.

THREATS TO WILDLIFE

1. A predominant effect of climate change on wildlife populations in the Sierra Nevada region will likely result from changes in vegetation communities. These changes will include increases in the amount of grassland and oak/pine vegetation, and a loss of conifer dominated vegetation, especially at higher elevations (e.g., red fir/lodgepole pine/subalpine conifer). This shift may be hastened by changes in fire severity and frequency.

2. While high temperature events will become more common, it seems unlikely that these temperatures will be high enough to cause direct mortality, as temperatures in much of this region are relatively moderate. However, thermal stress may be possible at the lowest elevations and/or for species with very narrow temperature tolerance levels.

3. Snow-fed rivers and streams will have less water, which may reduce and degrade habitat for some wildlife associated with riparian areas.

4. Importantly, there will be severe changes in the timing of peak streamflows, with these flows occurring earlier in the spring. These changes may have important consequences for species sensitive to changes in seasonal phonologies and those dependent on a specific environmental trigger that is disrupted by changes in streamflow timing.

Models at a Glance: Sierra Nevada

Citation	Model	Emissions scenario	Outputs
Cayan et al. 2008	PCM, GFDL, and HadCM3 (statistically downscaled)	IPCC A1, A2, B1	Temperature
Dettinger et al. 2004	PCM (statistically downscaled)	"business as usual"	Snowpack, snowmelt, and Merced, Carson, and American River streamflows
Dettinger et al. 2005	18 GCMs (statistically downscaled)	A2, B2, and IS92a	Streamflow
Fried et al. 2004	GISS	2xCO2	Fire frequency and area burned
Hayhoe et al. 2004	HadCM3 and PCM (statistically downscaled)	IPCC A1 and B1	Temperature, precipitation, streamflow, and sea level rise
Knowles and Cayan 2002, 2004	PCM (statistically downscaled)	"business as usual" greenhouse gas buildups	Snowpack, Sacramento/San Joaquin outflow
Lenihan et al. 2008	GFDL CM2.1 and PCM	IPCC B1 and A2	Percent area burned, vegetation classes
Maurer and Duffy 2005	10 GCMs (statistically downscaled)	2xCO2 by 2070	Temperature, precipitation, and streamflow
Maurer et al. 2007	11 GCMs (statistically downscaled)	A2 and B1	Temperature, precipitation, and streamflow
Pal et al. 2007	RegCM3	IPCC A2	Temperature and precipitation
Snyder and Sloan 2005	RegCM2.5	IPCC A1	Temperature and precipitation
Snyder et al. 2004	RegCM2.5	2xCO2	Temperature, precipitation, and snow accumulation
Stralberg et al. 2009	RegCM3 with boundary conditions from GFDL CM2.1 and NCAR CCSM 3.0 (statistically downscaled)	IPCC A2	Temperature, precipitation, and vegetation groups
Westerling and Bryant 2008	GFDL and PCM (statistically downscaled)	IPCC B1 and A2	Probability of large fires

Projected Effects of Climate Change in the Sacramento Valley Ecoregion (including the Delta)

TEMPERATURE

Ecoregional summary of California regional climate model. In the Sacramento Valley, regional climate models project mean annual temperature increases of 1.7–2.0°C by 2070. For the same time period mean diurnal temperature range is projected to increase by 0.1–0.2°C based on two RCMs presented in Stralberg et al. 2009.

Other sources of information. Snyder and Sloan (2005) projected mean annual temperature in the Sacramento Valley would increase by 2.4°C and mean diurnal temperature range to narrow by -0.4°C by the end of the 21st century.

Summary. The projected impacts of climate change on thermal conditions in the Sacramento Valley will be warmer winter temperatures. Local land-use and land-cover may interact with climate change to exacerbate changes in local temperatures.

PRECIPITATION

Ecoregional summary of California regional climate model. For the Sacramento Valley, regional climate models project a decrease in mean annual rainfall of 47 to 175 mm by 2070. The range of these changes (-9% to -32%) illustrate the differences between the two regional climate model projections with regard to precipitation, and the sensitivity of the regional results to the variability in the two global climate models used to provide the boundary conditions. This sensitivity indicates substantial uncertainty in precipitation projections.

Other sources of information. Snyder and Sloan (2005) projected mean annual precipitation to increase by 1.5 cm (2.8%) by the end of the 21st century.

Summary. Currently, there is more uncertainty about the precipitation projections for temperature in the Sacramento Valley, but with some evidence for a slightly drier future climate relative to current conditions.

STREAMFLOW AND WATER AVAILABILITY

Historically, flows on the Sacramento River and many of its tributaries were primarily driven by patterns of Sierra Nevada snowmelt, thus changes in snow pack and timing of runoff impacted river flows. Medellín-Azuara et al. (2008) modeled streamflows in California toward the end of the 21st century on the basis of a single climate model run under a relatively high emissions scenario. Projections included a decrease in total annual streamflows and earlier snowmelt, with streamflows increasing slightly in January and February but decreasing in all other months. Annual streamflows statewide are projected to decrease by 27%, with inflows from surrounding mountains to the Sacramento Valley projected to decrease by 22%.

Today, the flow of the Sacramento River is heavily managed through a series of dams and diversions. As a result, it is likely that flows on the Sacramento River will be more influenced by management decisions than by climate change effects.

However, even though the timing of flows may be mediated by hydrological infrastructure, the ability to deal with extreme flow events will likely remain limited. Accidental levee breaks in the Sacramento–San Joaquin River system have occurred in 25% of years during the 20th century. The threshold of river discharge above which levee breaks occurs corresponds to small floods occurring about every 2–3 years (Florsheim and Dettinger 2007). Levee breaks and peak river discharges cycle broadly on a 12–15 year time scale, in concert with warm-wet storm patterns, but less often and more frequently than the El Niño Southern Oscillation (~3–6 yrs) and Pacific Decadal Oscillation (~20–30 yrs) climate phenomena, respectively. These variations and thresholds have persisted through the 20th century suggesting that historical flood control efforts have not reduced the occurrence or frequency of levee breaks. Current climate-change projections suggest that storm patterns and fluvial responses are expected to aggravate future risks of levee breaks.

Brekke et al. (2004) simulated regional climate projections for the years 2010–2039 and 2050–2079 using two global climate models (HadCM2 and PCM) under a scenario of a 1%-per-year increase in global CO_2 levels relative to those in the late 20th century for the entire Central Valley. The HadCM2 model projected faster warming than PCM, and the HadCM2 and PCM models projected wetter and drier conditions, respectively, relative to present climate. The HadCM2 model projected increased reservoir inflows, increased storage limited by existing capacity, increased river flows, increased west side deliveries, and little impact to Delta water quality. The PCM model projected similar minimal impacts to Delta water quality. The PCM model, however, projected decreased reservoir inflows, decreased storage, decreased river flows, and severe reductions in west side deliveries. The finding of minimal impact on Delta water quality conditions relative to reductions in west side delivery levels is predicated on the current allocation priorities assumed for the simulations.

The Brekke et al. (2004) assessment is limited by a number of factors. First, it represents only a small portion of the climate change possibilities, e.g., just one CO_2 increase scenario. Also, it does not include adjustments for valley floor interactions between ground water and surface water, water consumption among urban and agricultural users, water allocation contracts, and reservoir operations regulations.

VERNAL POOL HYDROLOGY

Pyke (2005) explored the potential impacts of projected changes in climate and land-use for five fairy shrimp species endemic to vernal pools in California's Central Valley. Scenarios describing habitat extent and climate were developed for 2040 and 2100 and compared to a 1990s baseline. Potential changes in climate relevant to vernal pool hydrology were evaluated for four scenarios: two for cooler, low precipitation conditions—year 2040, -0.4°C and -4% precipitation, and year 2100, -1°C and -10% precipitation—two for warmer, higher precipitation conditions—year 2040, +1.2°C and +12%, and year 2100, +3°C and +30% precipitation.

Hydrologic conditions in vernal pools were found to be sensitive to projected climate changes, and, in the absence of habitat loss, warmer temperatures and greater winter precipitation would drive vernal pools toward longer, more frequent periods of inundation (Pyke 2005). Overall, changes in precipitation consistently over-rode changes in evapotranspiration resulting from temperature change and dominated vernal pool water balance. Consequently, a shift toward warmer, higher precipitation conditions during the winter would push pools toward longer, more frequent periods of inundation. These hydrologic changes were not evenly distributed, with the greatest sensitivity occurring in the middle of the Central Valley. For baseline vernal pool habitat in the mid-1990s, the +3°C and +30% precipitation scenario yielded an average of 20 additional days of inundation per year (+22%) with inundations greater than 30 days occurring in 8% more years (+11%) by 2100. Conversely, cooler, lower precipitation conditions shifted the pattern toward shorter, less frequent inundation. This resulted in an average net loss of 6 flooded days per year (-6%) with 30-day flooding events occurring in 3% fewer years (-4%) under the -1°C and -10% precipitation scenarios.

WATER TEMPERATURES

Salmon runs in the Sacramento River are sensitive to water temperatures, and increasing air temperatures may cause increases in water temperature that threaten these populations (Yates et al. 2008)

SEA LEVEL RISE

See discussion of sea level patterns and effects described for the Sacramento–San Joaquin River Delta in the Central Western California Ecoregion narrative.

FIRE

On the basis of analyses of wildfire risks in California under four climatic change scenarios, simulated from GFDL and PCM global climate models and the B1 (2x preindustrial CO2) and A2 (>3x preindustrial CO2) emissions scenarios, Westerling and Bryant (2008) projected the probability of large (>200-ha) fires will increase slightly in the Sacramento Valley by the end of the 21st century, more so under the drier, higher emissions scenario.

VEGETATION CHANGE

Ecoregional summary of California vegetation change. Because much of the Sacramento Valley ecoregion is in agriculture or other managed habitat, changes in land management and land use will be more important than shifts in natural vegetation. However, in this ecoregion, grasslands are projected to decrease by 1 to 20% by 2070. Riparian habitat is an important feature of the Sacramento Valley and it is not known how it will be affected by climate change.

THREATS TO WILDLIFE

1. In the Sacramento Valley, the predominant effects of climate change on wildlife populations will likely result from changes in water availability. Water availability will be directly affected by climate change, and also indirectly affected by management decisions designed to capture and store water for human consumption. Some wildlife species have come to rely on some types of agriculture. Hence, if water management causes severe

changes in the amount of grain crops, some row crops, and pasturelands, some wildlife taxa may be impacted. Species sensitive to the timing, amount and reliability of water supplies could be severely impacted. Several fish species, for example, are especially sensitive to the timing of spring runoff and average flow. Additionally, if water for managed wetlands is not available, the habitat will be degraded and many species could be severely impacted.

2. Estuarine habitats in the Delta may be degraded as a result of sea level rise and increasing salinity, but the degree of this loss is not yet well understood. Aquatic species sensitive to changes in salinity are likely to be at-risk.

3. High temperature events will become more common, and may result in thermal stress for species with narrow temperature tolerance levels at one or more life stages.

4. Because much of the Sacramento Valley is used for agriculture, the effects of climate change on vegetation communities will probably be of limited importance for most birds. Additionally managed wetlands comprise a substantial amount of habitat in the Sacramento Valley which could be compromised by water availability (see above).

Models at a glance: Sacramento Valley (including the Delta)

Citation	Model	Emissions scenario	Outputs
Medellín-Azuara et al. 2008	GFDL	IPCC A2	Streamflow
Pal et al. 2007	RegCM3	IPCC A2	Temperature and precipitation
Snyder and Sloan 2005	RegCM2.5	IPCC A1	Temperature and precipitation
Snyder et al. 2004	RegCM2.5	2xCO2	Temperature, precipitation, and snow accumulation
Stralberg et al. 2009	RegCM3 with boundary conditions from GFDL CM2.1 and NCAR CCSM 3.0 (statistically downscaled)	IPCC A2	Temperature, precipitation, and vegetation groups
Westerling and Bryan 2008	GFDL and PCM (statistically downscaled)	IPCC B1 and A2	Probability of large fires

Projected Effects of Climate Change in the San Joaquin Valley Ecoregion (including the Delta)

TEMPERATURE

Ecoregional summary of California regional climate model. In the San Joaquin Valley, regional climate models project mean annual temperature increases of 1.4–2.0°C by 2070. For the same time period mean diurnal temperature range is projected to increase by 0.1–0.2°C.

Other sources of information. The mean annual temperature in the San Joaquin Valley is projected to increase by 2.5°C and mean diurnal temperature range to narrow by -0.3°C by the end of the 21st century (Snyder and Sloan 2005).

Already there is evidence that temperatures in the San Joaquin Valley are changing. However, the relative contribution of land-use change and climate change to these patterns remains uncertain. For the period 1910–2003, minimum temperatures in the San Joaquin Valley have warmed at a highly significant rate in all seasons, particularly in summer and fall (~3°C) (Christy et al. 2006). These authors suggested that the warming trends in the San Joaquin Valley, and smaller cooling trends (for minimum temperatures in summer) in the adjacent southern Sierra Nevada, are related to the altered surface environment from the growth of irrigated agriculture, essentially changing a high-albedo desert into a darker, moister, vegetated plain. The darker surface allows for more absorption of solar energy while the additional water mass in plant material and wet ground increases the heat capacity, providing a daytime repository of energy to be lost via sensible heat flux at night.

In response to the paper by Christy et al. (2006), Bonfils et al. (2007) examined four high-quality observational datasets to compare trends in summer nighttime temperature among the Central Valley, the adjacent Sierra Nevada, and other parts of California. Similar to Christy et al. (2006), they found all datasets (but one) showed summer nighttime (daily minimum) temperatures are rising in the Central Valley but none showed a nighttime cooling signal in the Sierra. Rather, daily temperature minima were rising in the mountains at a rate similar or faster than in the valley. In fact, all datasets consistently showed a rise in daily minima across the entire state, from the western coast to the eastern mountains, and across all elevations. If nighttime warming was a consequence of irrigation, as posited by Christy et al. (2006), it should be warming more rapidly in the valley than in other regions, which was not the case. That the rise in minimum temperatures has occurred across the entire state, affected all elevations, and accelerated during the second half of the 20th century suggests a large-scale influence on California climate. It is possible that various human-induced factors (greenhouse warming and urbanization) act in concert to raise the temperature of summer nights in the Central Valley, while irrigation mitigates greenhouse warming during the day.

Summary. The projected impacts of climate change on thermal conditions in the San Joaquin Valley will be warmer winter temperatures, earlier warming in the spring, and increased summer temperatures. Local land-use and land-cover may interact with climate change to exacerbate changes in local temperatures.

PRECIPITATION

Ecoregional summary of California regional climate model. In the San Joaquin Valley, regional climate models project a decrease in mean annual rainfall of 23 to 81 mm by 2070. The range of these changes (-9% to -30%) illustrate the differences between the two regional climate model projections with regard to precipitation, and the sensitivity of the regional results to the variability in the two global climate models used to provide the boundary conditions. This sensitivity indicates substantial uncertainty in precipitation projections.

Other sources of information. Snyder and Sloan (2005) projected mean annual precipitation in the San Joaquin Valley to decrease by -0.5 cm (–1.8%) by the end of the 21st century.

Summary. Currently, there is more uncertainty about the projections for precipitation than there is for temperature in the San Joaquin Valley, but with some evidence for a slightly drier future climate relative to current conditions.

STREAMFLOW AND WATER AVAILABILITY

Brekke et al. (2004) simulated regional climate projections for the periods 2010–2039 and 2050–2079 using two global climate models (HadCM2 and PCM) under a scenario of a 1%-per-year increase in global

CO_2 levels relative to those in the late 20th century for the entire Central Valley. The HadCM2 model projected faster warming than PCM, and the HadCM2 and PCM models projected wetter and drier conditions, respectively, relative to present climate. The HadCM2 model projected increased reservoir inflows, increased storage limited by existing capacity, increased river flows, increased west side deliveries, and little impact to Delta water quality. The PCM model projected similar minimal impacts to Delta water quality. The PCM model, however, projected decreased reservoir inflows, decreased storage, decreased river flows, and severe reductions in west side deliveries. The finding of minimal impact on Delta water quality conditions relative to reductions in west side delivery levels is predicated on the current allocation priorities assumed for the simulations.

The Brekke et al. (2004) assessment is limited by a number of factors. First, it represents only a small portion of the climate change possibilities, e.g., just one CO_2 increase scenario. Also, it does not include adjustments for valley floor interactions between ground water and surface water, water consumption among urban and agricultural users, water allocation contracts, and reservoir operations regulations.

VERNAL POOL HYDROLOGY

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Hydrologic conditions in vernal pools were found to be sensitive to projected climate changes, and, in the absence of habitat loss, warmer temperatures and greater winter precipitation would drive vernal pools toward longer, more frequent periods of inundation (Pyke 2005). Overall, changes in precipitation consistently over-rode changes in evapotranspiration resulting from temperature change and dominated vernal pool water balance. Consequently, a shift toward warmer, higher precipitation conditions during the winter would push pools toward longer, more frequent periods of inundation. These hydrologic changes were not evenly distributed, with the greatest sensitivity occurring in the middle of the Central Valley. For baseline vernal pool habitat in the mid-1990s, the +3°C and +30% precipitation scenario yielded an average of 20 additional days of inundation per year (+22%) with inundations greater than 30 days occurring in 8% more years (+11%) by 2100. Conversely, cooler, lower precipitation conditions shifted the pattern toward shorter, less frequent inundation. This resulted in an average net loss of 6 flooded days per year (-6%) with 30-day flooding events occurring in 3% fewer years (-4%) under the -1°C and –10% precipitation scenarios.

SEA LEVEL RISE

A recent analysis of sea level rise for California indicates that by 2035–2064, projected ranges of global sea level rise are ~6–32 cm above 1990 levels, with no discernable inter-scenario differences (Cayan et al. 2008a). By 2070–2100, however, projected ranges of sea level rise diverge across the lower (11–54 cm), middle-upper (14–61 cm), and higher (17–72 cm) emissions scenarios. This recent work suggests larger rises in sea level than did early projections by Hayhoe et al. (2004): 8.7–12.7 cm by 2020–2049 and 19.2–40.9 cm by 2070–2099.

Sea level rise, coupled with ongoing subsidence of islands, will magnify the instability of the levee network of the Sacramento–San Joaquin River Delta, leading to increased potential for island flooding and a high probability of sudden landscape change occurring within the Delta during the next 50 years (Mount and Twiss 2005). Specifically, there is a two-in-three chance that levee failures from an extreme 100-year flood event or earthquake will cause catastrophic regional flooding by 2050. Failure of the levees and the flooding of subsided islands, particularly during the spring and summer months, has the potential to significantly degrade water quality by drawing brackish water into the Delta during rapid flooding of islands and by changing the dynamics of the tidal prism in the west Delta. Also, subsided islands and deeply flooded islands provide poor quality habitat for native aquatic plant and animal communities.

In the Delta, sea level rise may affect coastal and estuarine habitats. Specifically, many tidal marshes may be inundated and lost. However, the degree of habitat loss is difficult to quantify. Langley et al. (2009) conducted experiments showing that elevated levels of the greenhouse gas CO2 stimulates plant productivity, particularly below ground, thereby boosting marsh surface elevation, which paradoxically may aid some coastal wetlands in counterbalancing rising seas.

FIRE

Westerling and Bryant (2008) projected the probability of large (>200-ha) fires decreases slightly in the San Joaquin Valley by the end of the 21st century under all four scenarios (two GCMs and 2 emissions scenarios).

VEGETATION CHANGE

Ecoregional summary of California vegetation change. Like the Sacramento Valley ecoregion, much of the San Joaquin Valley is in agriculture or other managed habitat, changes in land management and land use will be more important than natural shifts in vegetation. However, in this ecoregion, the amount of area covered by grasslands is projected to decrease by 6 to 11% by 2070. Riparian habitat is an important feature of the Sacramento Valley and it is not known how it will be affected by climate change.

THREATS TO WILDLIFE

1. In the San Joaquin Valley, the predominant effects of climate change on wildlife populations will likely result from changes in water availability. Water availability will be directly affected by climate change, and also indirectly affected by management decisions designed to capture and store water for human consumption. Some wildlife species have come to rely on some types of agriculture. Hence, if water management causes severe changes in the amount of grain crops, some row crops, and pasturelands, some wildlife taxa may be impacted. Species sensitive to the timing, amount and reliability of water supplies could be severely impacted. Several fish species, for example, are especially sensitive to the timing of spring runoff and average flow. Additionally, if water for managed wetlands is not available, the habitat will be degraded and many species could be severely impacted.

2. Estuarine habitats in the Delta are likely to be degraded as a result of sea level rise and increasing salinity, but the degree of this loss is not yet well understood. Aquatic species sensitive to changes in salinity are likely to be at-risk.

3. High temperature events will become more common, and may result in thermal stress for species with narrow temperature tolerance levels at one or more life stages.

4. Because much of the San Joaquin Valley is used for agriculture, the effects of climate change on vegetation communities will probably be of limited importance for most birds. Managed wetlands comprise a substantial amount of habitat in the San Joaquin Valley which could be compromised by water availability (see above).

Models at a Glance: San Joaquin Valley (including the Delta)

Citation	**Model**	**Emissions scenario**	**Outputs**
Brekke et al. 2004	HadCM2 and PCM	1% per year CO2 increase	Streamflow
Pal et al. 2007	RegCM3	IPCC A2	Temperature and precipitation
Snyder and Sloan 2005	RegCM2.5	IPCC A1	Temperature and precipitation
Snyder et al. 2004	RegCM2.5	2xCO2	Temperature, precipitation, and snow accumulation
Stralberg et al. 2009	RegCM3 with boundary conditions from GFDL CM2.1 and NCAR CCSM 3.0 (statistically downscaled)	IPCC A2	Temperature, precipitation, and vegetation groups
Vicuna et al. 2007	PCM and HadCM3	A1FI and B1	Inflows to California reservoirs
Westerling and Bryan 2008	GFDL and PCM (statistically downscaled)	IPCC B1 and A2	Probability of large fires

Projected Effects of Climate Change in the Central Western California Ecoregion

TEMPERATURE

Ecoregional summary of California regional climate model. In Central Western California, regional climate models project mean annual temperature increases of 1.6–1.9°C by 2070. For the same time period mean diurnal temperature range is projected to increase by 0.1–0.2°C based on two RCMs presented in Stralberg et al. 2009.

Other sources of information. Snyder et al. (2004) projected with a doubling of atmospheric CO2 concentrations that median annual temperatures will increase by about 2.3°C in the Central Coast hydrologic region of California. Temperature increases are >2°C in all months except January, July, and October through December. Similarly, Snyder and Sloan (2005) projected mean annual temperature in Central Western California will increase by 2.3°C and mean diurnal temperature range will narrow by -0.4°C by the end of the 21st century.

Using a regional climate model, Bell et al. (2004) projected that there will be a significant increase in some extreme temperature events on the Central Coast. Mean maximum and minimum temperatures are projected to increase significantly by 1.99°C and 1.93°C, respectively, but the slight increase in the daily mean temperature range of 0.06°C is non-significant. The frequency of extremely hot days (exceeding long-term 95th percentile) was projected to increase 15 days per year and days exceeding 32.2°C by 12 days per year. Prolonged (7-day) hot spells were projected to increase by about 1.0 event per year, but changes in the duration (0.7 days longer) or mean temperature (increase of 0.8°C) of such events are nonsignificant. The frost-free growing season on average was projected to begin 34 days earlier and last 47 days longer. The models projected 57 fewer days of extreme cold and 8 fewer days below 0°C. Prolonged (7-day) cold spells were projected to decrease by about 2.8 events per year, the duration of cold spells was projected to decrease 2.7 days, and the mean temperature was projected to increase by 0.2°C.

Summary. The projected impacts of climate change on thermal conditions in Central Western California will be warmer winter temperatures, earlier warming in the spring, and increased summer temperatures.

PRECIPITATION

Ecoregional summary of California regional climate model. In Central Western California, regional climate models project a decrease in mean annual rainfall of 61 to 188 mm by 2070. The range of these changes (-11% to -32%) illustrate the differences between the two regional climate model projections with regard to precipitation, and the sensitivity of the regional results to the variability in the two global climate models used to provide the boundary conditions. This sensitivity indicates substantial uncertainty in precipitation projections.

Other sources of information. Most models suggest that changes in precipitation in the Central Western Ecoregion will be relatively modest. Bell et al. (2004) projected that with a doubling of atmospheric CO2 there will be no significant changes in precipitation patterns on the Central Coast. Projections of a decrease of 0.02 cm in mean rainfall per rain day, 5.1 fewer rain days per year, 3.4 cm less total rainfall, and 2.4 fewer days of extremely heavy rainfall (exceeding long-term 95th percentile) were all non-significant.

Snyder et al. (2004) projected with a doubling of atmospheric CO2 concentrations that median annual precipitation will decrease by about 12.3% in the Central Coast hydrologic region of California, but changes in precipitation were not significant at either the annual or monthly time scales. Similarly, Snyder and Sloan (2005) projected mean annual precipitation in Central Western California would decrease by -1.6 cm (-2.8%) by the end of the 21st century.

STREAMFLOW, STORAGE, AND ESTUARINE DYNAMICS

Under business-as-usual emissions, projected rising temperatures resulting in diminished snowpack and earlier runoff that is currently used to recharge reservoirs could bring adverse impacts to estuarine and watershed ecosystems in Central Western California (Knowles and Cayan 2002, 2004). Among the potential hazards are increased winter flooding and contamination of freshwater supplies by summer saline intrusion. High salinities would likely be exacerbated by sea level rise. The increased possibility of levee failures, which would result from higher wet-season flows and increased sea level, could have additional negative impacts.

On the basis of simulations of estuarine dynamics in the San Francisco Bay estuary, Knowles and Cayan (2002) estimated in dry years salinity change between present and 2090 conditions would be on the order of 1–3 practical salinity units. However, the approach used by Knowles and Cayan (2002) to project salinity changes does not take into account the likelihood that reservoir operators would attempt to mitigate the effects of warming by releasing more water into the Delta. Also, the projected rise in temperatures of about 2°C used in the study is at the low end of the range of 1–6°C warming estimates from the various climate models. Hence, an increase less than 2°C would reduce the impact on snowpack, streamflow, and salinity, whereas a greater increases in temperature would magnify these impacts.

On the basis of PCM climate model inputs to hydrologic and estuarine models, Knowles and Cayan (2004) projected the mean annual cycle of daily inflows to the San Francisco Bay estuary will change substantially by 2060. Estuarine inflows from the Sacramento–San Joaquin watershed are projected to increase an average of about 20% from October through February and decrease by about 20% from March through September. On the whole, total annual flow is very nearly conserved, with winter gains approximately balancing spring-summer losses.

Higher winter inflows result in slight increases in the amount of watershed runoff present in the estuary during winter months relative to historic levels, but it is the reduced inflows in the spring and summer that have the largest projected impact on the estuary's waters, reducing the amount of watershed runoff in the estuary by a maximum of 8% by late June (Knowles and Cayan 2004). The disparate response to inflow changes is due to the low rate of flushing of estuarine waters in the spring and summer relative to winter. The high flows of the winter months do not allow the effects of winter inflow anomalies to persist and accumulate in the estuary, whereas the lower spring-summer inflows allow the inflow reductions to have a cumulative impact on the composition of the estuary's waters. Since the lost freshwater is replaced by seawater, these changes translate into higher spring-summer salinities in the estuary. The average May–August salt content of the estuary of about 100 million metric tons increases by nearly 5.7 million metric tons. This change would manifest more strongly in the northern reach of the estuary given its proximity to the watershed outflow. Average May–August salinity in the northern reach is projected to increase by 2.2 psu. These impacts can vary quite strongly depending on the character of the water year (Knowles and Cayan 2004).

The projected changes presented do not account for any attempts at mitigation (e.g., releasing more water from reservoirs), but they do indicate the effects that such attempts must be designed to counter and which specific regions and elevation ranges will likely be involved (Knowles and Cayan 2004). Other factors that will also have to be considered include changes in municipal and agricultural freshwater demands, which will also have a large impact on estuarine inflows. Another critical influence on estuarine conditions will be sea level rise, which is projected to proceed at a rate of 50 cm over the next 100 years, an acceleration of the recent historical rate of 23 cm per century. This effect is likely to add to salinity increases projected from changing runoff patterns, and the increased possibility of levee failure that would result from higher wet-season flows and increased sea level could have additional impacts (and see below). Changing runoff patterns could also alter streamflow temperatures, potentially affecting downstream ecosystems including fish populations.

In addition to assessing possible impacts and guiding mitigation planning, understanding which elevations are most sensitive to climate warming delineates the mountain and riparian ecosystems most likely to be altered by hydrologic changes such as significant loss of snow cover (Knowles and Cayan 2004). Changes in the water balance will likely have profound effects on the ecology of mid-elevation mountain zones, and changes in vegetation and land cover could produce a secondary effect that further alters the hydrologic balance.

SEA LEVEL RISE

A recent analysis of sea level rise for California indicates that by 2035–2064, projected ranges of global sea level rise are ~6–32 cm above 1990 levels, with no discernable inter-scenario differences (Cayan et al. 2008a). By 2070–2100, however, projected ranges of sea level rise diverge across the lower (11–54 cm), middle-upper (14–61 cm), and higher (17–72 cm) emissions scenarios. This recent work suggests larger rises in sea level than did early projections by Hayhoe et al. (2004): 8.7–12.7 cm by 2020–2049 and 19.2–40.9 cm by 2070–2099.

The frequency of sea level extremes also may increase if storms become more frequent or severe as a result of climate change (Cayan et al. 2008a). Increases in the duration of high storm-forced sea levels increases the likelihood that storms will occur during high tides. The combination of severe winter storms with sea level rise and high tides could result in extreme sea levels that could expose the coast to severe flooding and erosion, damage to coastal structures and real estate, salinity intrusion into delta areas and coastal aquifers, and degradation in the quality and reliability of freshwater supplies. Most coastal damage in California is projected to occur during periods when both extreme sea levels and extreme wave heights occur concurrently. Extreme wave heights and extreme non-tidal fluctuations in sea level tend to increase from south to the north along the California coast, particularly from Point Conception northward. Extreme sea level height fluctuations are also larger to the north, reflecting heightened storm intensities at the more northerly coastal locations.

In Central Western California, sea level rise may affect coastal and estuarine habitats. Specifically, many tidal marshes may be inundated and lost. However, the degree of habitat loss is difficult to quantify. Langley et al. (2009) conducted experiments showing that elevated levels of the greenhouse gas CO2 stimulates plant productivity, particularly below ground, thereby boosting marsh surface elevation, which paradoxically may aid some coastal wetlands in counterbalancing rising seas.

Sea level rise, coupled with ongoing subsidence of islands, will magnify the instability of the levee network of the Sacramento–San Joaquin River Delta, leading to increased potential for island flooding and a high probability of sudden landscape change occurring within the Delta during the next 50 years (Mount and Twiss 2005). Specifically, there is a two-in-three chance that levee failures from an extreme 100-year flood event or earthquake will cause catastrophic regional flooding by 2050. Failure of the levees and the flooding of subsided islands, particularly during the spring and summer months, has the potential to significantly degrade water quality by drawing brackish water into the Delta during rapid flooding of islands and by changing the dynamics of the tidal prism in the west Delta. Also, subsided islands and deeply flooded islands provide poor quality habitat for native aquatic plant and animal communities.

FIRE

There is a general consensus that climate change will result in more and larger fires in Central Western California. Fried et al. (2004) estimated the impact of climatic change on wildland fire and suppression effectiveness in northern California by linking output from a single general circulation model to local weather and fire records and projecting fire outcomes with an initial-attack suppression model. Climate output applied to the fire models were used to project warmer, windier and somewhat drier conditions in the inner Coast Ranges of central California and increased fire spread rates and impacts. Considering impacts by vegetation type, there were substantial increases in the frequency of fast-spreading fires in grass and moderate increases in brush. By influencing fuel moisture and wind speed, climatic change caused fires to burn with greater intensity which triggered more intensive suppression efforts. Higher intensity fires are also more likely to overwhelm suppression efforts and to lead to greater damage to both natural resources and property. Most fires under both present climate and doubling-of-CO2 scenarios have moderate fire intensity and rates of spread and are unlikely to become large, damaging fires. In the interior Coast Ranges, the few fires with extreme behavior that are most likely to become large and damaging will grow in number several fold under climate change.

Despite enhancement of fire suppression efforts, the number of escaped fires increased 51% and the area burned by contained fires increased 41% in the Coast Ranges (Fried et al. 2004). In forests, fires moved much more slowly and impacts would be slight. Response in chaparral and oak woodlands was intermediate between that in grass and forest. In the Coast Ranges, contained fires in grass and brush were projected to burn 41% and 34% more area, respectively, under climate change than under the present climate. The greater impact of climate change in grass is not surprising given the greater influence of wind speed in rate-of-spread calculations for such fuels and the elevated wind speed predictions during fire season under changed climate.

Westerling and Bryant (2008) projected the probability of large (>200-ha) fires increases in Central Western California by the end of the 21st century. While not summarized quantitatively, maps in Lenihan et al. (2008) show that for much of the Central Western California, the area burned is projected to increase from 10–50% by the 2070–2099 period.

VEGETATION CHANGE

Ecoregional summary of California vegetation change. Of the three major vegetation groups in this ecoregion, decreases were projected to 2070 in the area of chaparral / coastal scrub (-19 to -43%) and blue oak woodland / foothill pine (-44 to -55%), and an increase was projected in area of grassland (85 to 140%).

Other sources of information. Although they do not provide summaries of ecoregional change, maps in Lenihan et al. (2008) project decreases in the area of conifer forest and shrublands, and increases in the area of grassland by the 2070–2099 period in Central Western California.

THREATS TO WILDLIFE

1. A predominant effect of climate change on wildlife populations in the Central Western ecoregion will likely result from changes in vegetation communities. These changes will include substantial increases in the amount of grassland and decreases in most other major vegetation communities. This shift may be hastened by changes in fire severity and frequency.

2. Sea level rise will likely affect many taxa in this region especially in the Delta but also in important coastal estuaries and the coastal strand. Aquatic species sensitive to changes in salinity are likely to be at-risk.

3. While high temperature events will become more common, it seems unlikely that these temperatures will be high enough to cause direct mortality, as temperatures in much of this region are relatively moderate. However, thermal stress may be possible for species with very narrow temperature tolerance levels.

4. The effects of increasing fires in this region are likely to impact species directly through increased mortality and indirectly by modifying vegetation structure and composition.

Models at a Glance: Central Western California

Citation	Model	Emissions scenario	Outputs
Bell et al. 2004	RegCM2.5	2xCO2	Extreme temperature events
Cayan et al. 2008a	MAGICC	IPCC A1, A2, B1	Sea level rise
Fried et al. 2004	GISS	2xCO2	Fire frequency and area burned
Hayhoe et al. 2004	HadCM3 and PCM (statistically downscaled)	IPCC A1 and B1	Temperature, precipitation, streamflow, sea level rise
Knowles and Cayan 2002, 2004	PCM	"business as usual" greenhouse gas buildups	Snowpack, Sacramento/San Joaquin outflow, San Francisco Bay estuary salinity
Pal et al. 2007	RegCM3	IPCC A2	Temperature and precipitation
Snyder and Sloan 2005	RegCM2.5	IPCC A1	Temperature and precipitation
Snyder et al. 2004	RegCM2.5	2xCO2	Temperature, precipitation, and snow accumulation
Stralberg et al. 2009	RegCM3 with boundary conditions from GFDL CM2.1 and NCAR CCSM 3.0 (statistically downscaled)	IPCC A2	Temperature, precipitation, and vegetation groups
Westerling and Bryant 2008	GFDL and PCM (statistically downscaled)	IPCC B1 and A2	Probability of large fires

Projected Effects of Climate Change in the Southwestern California Ecoregion

TEMPERATURE

Ecoregional summary of California regional climate model. In Southwestern California, regional climate models project mean annual temperature increases of 1.7 to 2.2 °C by 2070. For the same time period mean diurnal temperature range is projected to increase by 0.1–0.2°C based on two RCMs presented in Stralberg et al. 2009.

Other sources of information. There is a general consensus across multiple models that temperatures in Southwestern California will increase in most months by about 2°C over the next 100 years. Snyder et al. (2004) projected with a doubling of atmospheric CO2 concentrations that median temperatures will increase by about 2.5°C in the South Coast hydrologic region of California. Temperature increases were >2°C in all months except January and October through December. In a subsequent study, regional climate modeling by Snyder and Sloan (2005) projected mean annual temperature in Southwestern California is to increase by 2.5°C and mean diurnal temperature range to narrow–0.4°C by the end of the 21st century.

Using regional climate models, Bell et al. (2004) projected a significant increase in extreme temperature events on the South Coast. Mean maximum and minimum temperatures were projected to increase by 2.08°C and 1.99°C, respectively, as was the daily mean temperature range by 0.09°C. The frequency of extremely hot days (exceeds long-term 95th percentile) and the number of days exceeding 32.2°C per year was projected to increase by about 11 days. Prolonged (7-day) hot spells per year were projected to increase by about 0.8 events per year, but changes in the duration (0.1 days longer) or mean temperature (increase of 0.6°C) of such events was not significantly different. The frost-free growing season on average was projected to begin 35 days earlier and to last 62 days longer. The models projected 48 fewer days of extreme cold and 15 fewer days below 0°C. Prolonged (7-day) cold spells per year were projected to decrease by about 2.5 events per, the duration of cold spells was projected to decrease by 2.8 days, and the mean temperature of cold spells was projected to increase, nonsignificantly, by 0.1°C.

Summary. There is a general consensus across multiple models that over the next 100 years temperatures in Southwestern California will increase in most months by about 2°C.

PRECIPITATION

Ecoregional summary of California regional climate model. In Southwestern California, regional climate models project a decrease in mean annual rainfall of 51 to 184 mm by 2070. The range of these changes (-10% to -37%) illustrate the differences between the two regional climate model projections with regard to precipitation, and the sensitivity of the regional results to the variability in the two global climate models used to provide the boundary conditions. This sensitivity indicates substantial uncertainty in precipitation projections.

Other sources of information. There is relatively little consensus about the projected effects of climate change on precipitation patterns in Southwestern California. Some projections suggest almost no change, whereas others project decreases of up to 37%. Bell et al. (2004) projected few significant changes in precipitation patterns on the South Coast. For annual precipitation, the Bell study projected a decrease of 0.02 cm in mean rainfall per rain day, 4.6 fewer rain days per year, and 3.0 cm more total rainfall per year (but all projected changes were not statistically significant). The projection for 3.2 fewer days of extremely heavy rainfall (exceeding long-term 95th percentile) was significant.

Using a regional climate model Snyder et al. (2004) projected with a doubling of atmospheric CO2 concentrations that median annual precipitation will decrease by about 17.1% in the South Coast hydrologic region of California. Changes in precipitation were not significant at either the annual or monthly time scales. In a subsequent study with regional climate modeling, Snyder and Sloan (2005) projected mean annual precipitation in Southwestern California to decrease by -2.0 cm (-4.0%) by the end of the 21st century.

Summary. There is relatively little consensus about the projected effects of climate change on precipitation patterns in Southwestern California: some projections suggest almost no change, others project decreases of up to 37%.

STREAMFLOW

There is no published information on the projected effects of climate change on streamflow in Southwestern California at this time.

SNOWPACK

Snyder et al. (2004) projected snow accumulation will decrease by 90% in the South Coast hydrologic region of California. Reductions in monthly median snow heights were 0.0 and -0.1 mm in January and February, respectively. Neither the annual or monthly changes were statistically significant.

SEA LEVEL RISE

A recent analysis of sea level rise for California indicates that by 2035–2064, projected ranges of global sea level rise are ~6–32 cm above 1990 levels, with no discernable inter-scenario differences (Cayan et al. 2008a). By 2070–2100, however, projected ranges of sea level rise diverge across the lower (11–54 cm), middle-upper (14–61 cm), and higher (17–72 cm) emissions scenarios. This recent work suggests larger rises in sea level than did early projections by Hayhoe et al. (2004): 8.7–12.7 cm by 2020–2049 and 19.2–40.9 cm by 2070–2099.

The frequency of sea level extremes may be increased if storms become more frequent or severe as a result of climate change (Cayan et al. 2008a). Increases in the duration of high storm-forced sea levels increase the likelihood that they will occur during high tides. The combination of severe winter storms with sea level rise and high tides would result in extreme sea levels that could expose the coast to severe flooding and erosion, damage to coastal structures and real estate, salinity intrusion into delta areas and coastal aquifers, and the degradation of the quality and reliability of freshwater supplies. Most coastal damage in California is projected to occur during periods when extreme sea levels and extreme wave heights occur concurrently. Extreme wave heights and extreme non-tidal fluctuations in sea level tend to increase from south to the north along the California coast, particularly from Point Conception northward.

In Southwestern California, sea level rise may affect coastal and estuarine habitats. Specifically, many tidal marshes may be inundated and lost. However, the degree of habitat loss is difficult to quantify. Langley et al. (2009) conducted experiments showing that elevated levels of the greenhouse gas CO2 stimulates plant productivity, particularly below ground, thereby boosting marsh surface elevation, which paradoxically may aid some coastal wetlands in counterbalancing rising seas.

FIRE

Wildfires periodically burn large areas of chaparral and adjacent woodlands in autumn and winter in southern California (Westerling et al. 2004). These fires often occur in conjunction with Santa Ana weather events, which combine high winds and low humidity, and tend to follow a wet winter rainy season. There is currently no consensus on how climate change will influence Santa Ana events or fire in Southwestern California.

On the basis of analyses of wildfire risks in California, Westerling and Bryant (2008) projected the probability of large (>200-ha) fires in southern California ranged from a decrease of -29% to an increase of +28%. This variability is primarily driven by the climate model used to make forecasts. Drier conditions projected by one model led to reduced fire risks in large parts of southern California, with some exceptions (e.g., fire risks are increased in parts of the San Bernardino Mountains). Under the wetter climate model, the probability of large fires in southern California increased, particularly in low-elevation ecosystems dominated by grass and low-density shrub vegetation types.

While not summarized quantitatively, maps in Lenihan et al. (2008) also show that projected changes in wildfire vary across climate models. With the GFDL model, the area of Southwestern California that is burned annually was projected to decrease, but with the PCM model much of the area burned was projected to increase by the 2070–2099 period.

The effects of climate change on Santa Anna winds remain uncertain. Miller and Schlegel (2006) modeled Santa Ana wind patterns with respect to their influence on southern California wildfires. Initial analysis showed consistent shifts in Santa Ana wind events from earlier (September–October) to later (November–December) in the season. These authors suggested that by the end of the 21st century, climate change may increase the extent of California coastal areas burned by wildfires because Santa Ana winds occur more frequently during critical dry periods. However, model projections indicate a reduction in Santa Ana wind events, and a corresponding reduction in their mean intensity, in the mid 21st compared with the late-20th century, which appears at least partially caused by a change in the climate from anthropogenic forcing (Hughes et al. 2009, Hughes and Hall 2010). Given the role Santa Ana winds play in spreading wildfire in the region, the effects of climate change on Santa Ana wind timing and intensity will be important.

Summary. For Southwestern California, uncertainty associated with climate models makes it difficult to make definitive conclusions about the effects of increasing green house gas concentrations on fire regimes.

VEGETATION CHANGE

Ecoregional summary of California vegetation change. In Southwestern California, the area of chaparral / coastal scrub was projected to decreases 38–44% by 2070, and area of grassland, while currently only 3% of the ecoregion, was projected to increase by 345–390%.

Other sources of information. Although they do not provide summaries of ecoregional change, maps in Lenihan et al. (2008) project decreases in amount of shrublands and increases in the amount grassland by the 2070–2099 period in Southwestern California.

THREATS TO WILDLIFE

1. In Southwestern California, the predominant effects of climate change on wildlife populations will likely result from changes in vegetation communities. These changes will include increases in the amount of grassland and a loss of coastal scrub habitats. This shift may be hastened by changes in fire severity and frequency.

2. Some coastal an estuarine habitats as well as coastal strand habitats may be degraded due to sea level rise, but the degree of this loss and degradation is not yet well understood. Aquatic species sensitive to changes in salinity are likely to be at-risk.

3. High temperature events will become more common and species with very narrow temperature tolerance levels may experience thermal stress. Additionally, an increase in extreme high temperature events may cause direct mortality to some species and halt or diminish reproduction.

4. Snow-fed rivers and streams will have less water, which may reduce riparian habitat and affect species associated with riparian areas.

5. The effects of fires in this region are likely to impact species directly through increased mortality and indirectly by modifying vegetation structure and composition. However, there is substantial uncertainty about how fire regimes, including Santa Ana events, will change.

Models at a Glance: Southwestern California

Citation	Model	Emissions scenario	Outputs
Bell et al. 2004	RegCM2.5	2xCO2	Extreme temperature events
Cayan et al. 2008	MAGICC	IPCC A1, A2, B1	Sea level rise
Hayhoe et al. 2004	HadCM3 and PCM (statistically downscaled)	IPCC A1 and B1	Temperature, precipitation, streamflow, sea level rise
Knowles and Cayan 2002, 2004	PCM (statistically downscaled)	"business as usual" greenhouse gas buildups	Snowpack, Sacramento/San Joaquin outflow, San Francisco Bay estuary salinity
Lenihan et al. 2008	GFDL CM2.1 and PCM	IPCC B1 and A2	Percent area burned, vegetation classes
Miller and Schlegel (2006)	GFDLv2 and PCM	IPCC A2 and B1	Frequency of Santa Anna wind occurrence
Pal et al. 2007	RegCM3	IPCC A2	Temperature and precipitation
Snyder and Sloan 2005	RegCM2.5	IPCC A1	Temperature and precipitation
Snyder et al. 2004	RegCM2.5	2xCO2	Temperature, precipitation, and snow accumulation
Stralberg et al. 2009	RegCM3 with boundary conditions from GFDL CM2.1 and NCAR CCSM 3.0 (statistically downscaled)	IPCC A2	Temperature, precipitation, and vegetation groups
Westerling and Bryant 2008	GFDL and PCM (statistically downscaled)	IPCC B1 and A2	Probability of large fires

Projected Effects of Climate Change in the Mojave Desert Ecoregion

TEMPERATURE

Ecoregional summary of California regional climate model. In the Mojave Desert, regional climate models project mean annual temperature increases of 1.9 to 2.6 °C by 2070. For the same time period mean diurnal temperature range is projected to increase by 0–0.2°C based on two RCMs presented in Stralberg et al. 2009.

Other sources of information. Using a regional climate model, Snyder et al. (2004) projected with a doubling of atmospheric CO2 concentrations that median temperatures will increase by about 2.2°C in the South Lahontan hydrologic region of California. Temperature increases are >2°C in all months except October and November. Similarly, Snyder and Sloan (2005) projected mean annual temperature in the Mojave Desert of California to increase by 2.8°C and mean diurnal temperature range to narrow by -0.3°C by the end of the 21st century.

Based on regional climate modeling, Bell et al. (2004) projected with a doubling of atmospheric CO2 that there would be a significant increase in extreme temperature events in the South Lahontan region. Mean maximum and minimum temperatures were projected to increase significantly by 2.6°C and 2.4°C, respectively, as was the daily mean temperature range by 0.18°C. The number of extremely hot days (exceeds long-term 95th percentile) and the number of days exceeding 32.2°C was projected to increase 31 days and 27 days per year, respectively. Prolonged (7-day) hot spells were projected to increase significantly (1.1 events per year), as was the duration (10 days longer) and mean temperature (increase of 0.6°C) of such events. The frost-free growing season on average was projected to begin 22 days earlier and to last 31 days longer. The models project 43 fewer days of extreme cold and 38 fewer days below 0°C. Prolonged (7-day) cold spells will decrease significantly (1.9 events per year) as will the duration of cold spells (3.8 fewer days); the mean temperature of such events will increase significantly by 0.4°C.

Summary. There is a general consensus across multiple models that over the next 100 years temperatures in the Mojave Desert will increase in most months by more than 2 °C.

PRECIPITATION

Ecoregional summary of California regional climate model. In the Mojave Desert, regional climate models project a decrease in mean annual rainfall of 7 to 65 mm by 2070. The range of these changes (-5% to -42%) illustrate the differences between the two regional climate model projections with regard to precipitation, and the sensitivity of the regional results to the variability in the two global climate models used to provide the boundary conditions. This sensitivity indicates substantial uncertainty in precipitation projections.

Other sources of information. Projections for the effects of increased greenhouse gas concentrations on precipitation in the Mojave Desert ecoregion are inconsistent. However, all but one study predicted a decrease in rainfall. Using a regional climate model, Bell et al. (2004) projected few statistically significant changes in precipitation patterns in the South Lahontan region. For annual precipitation, a decrease of 0.02 cm in mean rainfall per rain day, 0.9 more rain days per year, and 1.4 cm less total rainfall per year were all non-significant. A decrease of 2.6 fewer days of extremely heavy rainfall (exceeding long-term 95th percentile), however, was significant.

Similarly, regional climate modeling by Snyder et al. (2004) projected with a doubling of atmospheric CO2 concentrations that median annual precipitation will decrease by about 10.3% in the South Lahontan hydrologic region of California, but changes in precipitation were not significant at either the annual or monthly time scales. In contrast, regional climate model by Snyder and Sloan (2005) projected mean annual precipitation in the Mojave Desert of California would increase by 1.2 cm (7.7%) by the end of the 21st century.

Summary: Presumably Snyder and Sloan 2005 could be replaced with 2009 RCM runs and 2009 RCMs show a decrease in precip. So although there is variation in magnitude, there is concensus that precipitation decreases.

STREAMFLOW

The Colorado River, flowing along the eastern edge of the California portion of the Mojave Desert, has a vast watershed in the West, much of which is beyond the Mojave Desert. The current projections for Colorado

River flows are for a relatively modest decrease (single digit percentages) (Christensen and Lettenmaier 2007). However, even relatively modest changes could result in water supply decreasing below the current demands (Christensen and Lettenmaier 2007).

Other rivers in the Mojave Desert of California include the Mojave River, originating in the San Bernardino Mountains, and the Armargosa River, flowing (mostly underground) from its source in a high desert region northwest of Las Vegas, Nevada. Future streamflow patterns of these two rivers will be affected by precipitation and snowmelt patterns projected for Southwestern California and for the Mojave Desert of Nevada.

FIRE

Fire in the Mojave Desert varies with both climate conditions and vegetation, especially exotic annual grasses, and the relative importance of these factors varies across elevational gradients (Brooks and Matchett 2006). On the basis of wildfire risks in California under four climatic change scenarios, simulated from GFDL and PCM global climate models and the B1 and A2 emissions scenarios, Westerling and Bryant (2008) projected the probability of large (>200-ha) fires in the Mojave Desert at the end of the 21st century is uncertain, with varying outcomes largely driven by differences in precipitation among the different climate models rather than differences resulting from the emissions scenarios. The probability of large fires generally increases under the wetter climate models and decreases under the drier models.

VEGETATION CHANGE

Ecoregional summary of California vegetation change. In the Mojave Desert, preliminary analyses indicate that changes in vegetation are projected to be relatively modest (Stralberg et al. 2009). However, Stralberg et al. (2009) grouped most desert vegetation into a “desert scrub” category, so analyses of more refined vegetation categories may reveal more differences. Based on current analyses, most (89%) of this ecoregion is desert scrub, and this vegetation type is projected to increase only moderately (4–6%).

Other sources of information. Although they do not provide summaries of ecoregional change, maps in Lenihan et al. (2008) show relatively modest changes in vegetation by the 2070–2099 period in the Mojave Desert. While large-scale changes in vegetation types may be relatively modest, there is evidence that within current vegetation types, climate change may influence plant community composition (Collins et al. 2010).

THREATS TO WILDLIFE

1. High temperature events will become more common, and may increase by as much as 2.6°C. Given the already high temperatures throughout the Mojave Desert, this increase in temperature and number of extreme temperature events may exceed the thermal tolerance or impose severe water stress for some wildlife, as has been demonstrated in other arid systems for birds and lizards (McKechnie and Wolf 2010, Sinervo et al. 2010).

2. Some rivers and streams will have less water, which may reduce habitat for some wildlife associated with riparian areas. While the current projections suggest that changes in precipitation may be relatively modest, given the extreme aridity of this region, even relatively modest changes may have large ecological consequences.

Models at a Glance: Mojave Desert

Citation	Model	Emissions scenario	Outputs
Bell et al. 2004	RegCM2.5	2xCO2	Extreme temperature events
Christensen and Lettenmaier 2007	11 GCMs (statistically downscaled)	IPCC B1 and A2	Temperature, precipitation, runoff
Lenihan et al. 2008	GFDL CM2.1 and PCM	IPCC B1 and A2	Percent area burned, vegetation classes
Pal et al. 2007	RegCM3	IPCC A2	Temperature and precipitation
Snyder and Sloan 2005	RegCM2.5	IPCC A1	Temperature and precipitation
Snyder et al. 2004	RegCM2.5	2xCO2	Temperature, precipitation, and snow accumulation
Stralberg et al. 2009	RegCM3 with boundary conditions from GFDL CM2.1 and NCAR CCSM 3.0 (statistically downscaled)	IPCC A2	Temperature, precipitation, and vegetation groups
Westerling and Bryant 2008	GFDL and PCM (statistically downscaled)	IPCC B1 and A2	Probability of large fires

Projected Effects of Climate Change in the Sonoran (Colorado) Desert Ecoregion

TEMPERATURE

Ecoregional summary of California regional climate model. In the Sonoran Desert, regional climate models project mean annual temperature increases of 1.8–2.4°C by 2070. For the same time period mean diurnal temperature range is projected to increase by 0–0.2°C based on two RCMs presented in Stralberg et al. 2009.

Other sources of information. There is a general consensus that increasing greenhouse gas concentrations will result in higher temperatures in the Sonoran Desert ecoregion. Using a regional climate model, Snyder et al. (2004) projected that median annual temperatures would increase by about 2.1°C in the Colorado River hydrologic region of California. Projected temperature increases were >2°C in all months except January, July, and October through December. Similarly, Snyder and Sloan (2005) projected mean annual temperature in the Sonoran (Colorado) Desert of California to increase by 2.7°C and mean diurnal temperature range to narrow by -0.1°C by the end of the 21st century.

Using a regional climate model, Bell et al. (2004) projected that with a doubling of atmospheric CO2 that there would be a significant increase in extreme temperature events in the Colorado River region. Mean maximum and minimum temperatures were projected to increase significantly by 2.3°C and 2.2°C, respectively; a projected increase in the daily mean temperature range of 0.07°C was non-significant. The number of extremely hot days (exceeding long-term 95th percentile) and the number of days exceeding 32.2°C were projected to increase by 22 days and 20 days per year, respectively. Prolonged (7-day) hot spells were projected to increase significantly (1.0 event per year), as were the duration (6 days longer) and mean temperature (increase of 0.8°C) of such events. The frost-free growing season on average was projected to begin 22 days earlier and last 30 days longer. The models project 44 fewer days of extreme cold and 10 fewer days below 0°C. Prolonged (7-day) cold spells were projected to decrease significantly (1.3 fewer events per year) as was the duration of cold spells (4.3 fewer days); the mean temperature of such events was projected to increase, non-significantly, by 0.2°C.

Summary. There is a general consensus across multiple models that over the next 100 years temperatures in the Sonoran Desert will increase in most months by more than 2 °C.

PRECIPITATION

Ecoregional summary of California regional climate model. In the Sonoran Desert, regional climate models project a change in mean annual rainfall that ranges from an increase of 3 mm to a decrease of 55 mm by 2070. The range of these changes (+3% to -45%) illustrates the differences between the two regional climate model projections with regard to precipitation, and the sensitivity of the regional results to the variability in the two global climate models used to provide the boundary conditions. This sensitivity indicates substantial uncertainty in precipitation projections.

Other sources of information. Using a regional climate model, Bell et al. (2004) projected with a doubling of atmospheric CO2 that there would be no significant changes in precipitation patterns in the Colorado River region. For annual precipitation, there were neither significant projected changes in mean rainfall per rain day (3.2 fewer rain days per year) nor total rainfall per year (0.4 cm less). The projection of 3.2 fewer days of extremely heavy rainfall (exceeding long-term 95th percentile) was also non-significant.

Regional climate modeling by Snyder et al. (2004) projected with a doubling of atmospheric CO2 concentrations that median annual precipitation will decrease by about 11.8% in the Colorado River hydrologic region of California, but changes in precipitation are not significant at either the annual or monthly time scales. In contrast, regional climate modeling by Snyder and Sloan (2005) projected mean annual precipitation in the Sonoran (Colorado) Desert of California is projected to increase by 0.8 cm (6.2%) by the end of the 21st century.

Summary. The effect that increasing greenhouse gas concentrations will have on precipitation patterns in the Sonoran Desert ecoregion is currently uncertain.

STREAMFLOW

The Colorado River, flowing along the eastern edge of the California portion of the Sonoran (Colorado) Desert, has a vast watershed in the West, much of it beyond the Sonoran Desert. The current projections for Colorado River flows are for a relatively modest decrease (single digit percentages) (Christensen and Lettenmaier 2007). However, even this relatively modest change could result in water supply decreasing below the current demands (Christensen and Lettenmaier 2007). Because of extensive water diversions for agriculture and municipal use in southern California, patterns of future streamflow in the Colorado River may have substantial impacts in the Imperial Valley, Salton Sea, and coastal areas of Southwestern California.

In addition to the Colorado River, many small intermittent streams will be affected by precipitation and snowmelt patterns projected for Southwestern California and the Sonoran Desert.

FIRE

As in the Mojave Desert (Brooks and Matchett 2006), both climate conditions and vegetation, especially exotic annual grasses, are likely important for determining fire behavior in the Sonoran Desert. Westerling and Bryant (2008) found that the probability of large (>200-ha) fires in the Sonoran Desert at the end of the 21st century is uncertain, with varying outcomes largely driven by differences in precipitation among climate models. The probability of large fires generally increases under the wetter climate models and decreases under the drier models.

VEGETATION CHANGE

Ecoregional summary of California vegetation change. In the Sonoran Desert, changes in vegetation are projected to be relatively modest. Currently, most (69%) of this ecoregion is desert scrub, and this vegetation type was projected to increase only moderately (2–3%). However, Stralberg et al. (2009) grouped most desert vegetation into a “desert scrub” category, so analyses of more refined vegetation categories may reveal more differences.

Other sources of information. Although they do not provide summaries of ecoregional change, maps in Lenihan et al. (2008) show relatively modest changes in vegetation by the 2070–2099 period in the Sonoran Desert. While large-scale changes in vegetation types may be relatively modest, there is evidence that within current vegetation types, climate change may influence plant community composition (Kimball et al. 2010).

THREATS TO WILDLIFE

1. High temperature events will become more common, and may increase by as much as 2.4°C. Given the already high temperatures throughout the Sonoran Desert, this increase in temperature may exceed the thermal tolerance or impose severe water stress for some wildlife, as has been demonstrated in other arid systems for birds and lizards (McKechnie and Wolf 2010, Sinervo et al. 2010).

2. Some rivers and streams will have less water, which may reduce habitat for some wildlife associated with riparian areas. While the current projections suggest that changes in precipitation may be relatively modest, given the extreme aridity of this region, even relatively small changes may have large ecological consequences.

Models at a Glance: Sonoran Desert

Citation	Model	Emissions scenario	Outputs
Snyder et al. 2004	RegCM2.5	2xCO_2	Temperature, precipitation, and snow accumulation
Snyder and Sloan 2005	RegCM2.5	IPCC A1	Temperature and precipitation
Pal et al. 2007	RegCM3	IPCC A2	Temperature and precipitation
Bell et al. 2004	RegCM2.5	2xCO_2	Extreme temperature events
Christensen and Lettenmaier 2007	11 GCMs (statistically downscaled)	IPCC B1 and A2	Temperature, precipitation, runoff
Westerling and Bryant 2008	GFDL and PCM (statistically downscaled)	IPCC B1 and A2	Probability of large fires
Lenihan et al. 2008	GFDL CM2.1 and PCM	IPCC B1 and A2	Percent area burned, vegetation classes
Stralberg et al. 2009	RegCM3 with boundary conditions from GFDL CM2.1 and NCAR CCSM 3.0 (statistically downscaled)	IPCC A2	Temperature, precipitation, and vegetation groups

Projected Effects of Climate Change in the Northern Marine Ecoregion

OCEAN ACIDIFICATION

Over the last 250 years, uptake of anthropogenic CO_2 by the oceans has lowered the pH of seawater by about 0.1, a process termed "ocean acidification" (Feely et al. 2004, Feely et al. 2008). Estimated future increases in atmospheric CO_2 could result in a decrease in surface-water pH of ~0.4 by the end of the century and a corresponding 50% decrease in carbonate ion concentration.

The depth horizon below which calcium carbonate is undersaturated is shallow in the northeastern Pacific Ocean and has risen with increasing CO_2 sequestration in seawater. Although seasonal upwelling of the undersaturated waters onto the continental shelf is a natural phenomenon in this region, the ocean uptake of anthropogenic CO_2 has increased the extent of the affected area. In some parts of northern California, the entire water column shoreward of the 50-m bottom contour has seasonally become undersaturated with respect to aragonite.

The reaction of CO_2 with seawater reduces the availability of carbonate ions needed to form the calcium carbonate used in skeleton and shell formation of marine organisms, such as plankton and shellfish. Water undersaturated with carbonate ions is corrosive, leading to dissolution of pure aragonite and unprotected aragonite shells.

In coming decades, ocean acidification could affect some of the most fundamental biological and geochemical process of the sea and seriously alter the basic structure of pelagic and benthic ecosystems. Presently, little is known about how intermittent exposure to corrosive undersaturated water might affect the development of larval, juvenile, and adult stages of aragonitic calcifying organisms or finfish that populate neritic and benthic environments in the region. Some experiments suggest that changes in saturation state may cause significant changes in overall calcification rates for many species of marine calcifiers. Other research suggests that many species of juvenile fish and shellfish are highly sensitive to above-normal CO_2 concentrations, i.e., higher mortality rates are directly correlated with higher CO_2 concentrations (Fabry et al. 2008).

CHANGES TO UPWELLING

CO_2-induced land-cover feedback. On the basis of a doubling of atmospheric CO_2 levels, models predict that biophysical land cover–atmosphere feedbacks induced by radiative forcing enhance the radiative effects of CO_2 on land-sea thermal contrast, resulting in changes in total seasonal upwelling and upwelling seasonality in the California Current (Diffenbaugh et al. 2004). These effects vary between the two major subregions of this current. In Northern California, feedbacks between land-cover and vegetation further intensify peak- and late-season upwelling, increasing total seasonal upwelling by adding to the effect of CO_2 radiative forcing.

Other models predict that a doubling of atmospheric CO_2 over preindustrial levels will create warmer and drier conditions on land in eastern boundary current regions. Such a change in climate likely would increase heat and water stress for existing vegetation, creating more sparse vegetation cover, decreasing soil moisture and evapotranspiration, increasing surface-sensible heat flux, and further increasing temperatures on land. CO_2-induced changes in land cover could also alter surface reflectivity (albedo), which in turn could alter surface energy balance. If such feedbacks were to enhance the radiative effects of CO_2 by further warming the land and enhancing land-sea temperature contrast, they would increase the severity of effects on upwelling regimes (Diffenbaugh et al. 2004).

Effects of submarine gas eruptions. On a global scale, projections indicate a progressive intensification of upwelling in response to greenhouse gas buildup. A 15% increase in characteristic magnitudes of upwelling-favorable winds, expected to occur over the next few decades, may cause a regime shift to a degraded marine ecosystem with widespread hypoxia and massive eruptions of noxious gases (methane, hydrogen sulfide) (Bakun and Weeks 2004). Hydrogen sulfide, in particular, is highly toxic to marine organisms and also strips dissolved oxygen from the water column as it moves upward through it. Intense upwelling provides copious nutrients resulting in a very high rate of primary productivity, but it is difficult for planktonic grazers to maintain populations because of their long generation times and rapid offshore transport by ocean surface waters. Consequently, there is a rapid buildup of phytoplankton biomass much of which may be unutilized and sink to the sea floor, forming thick accumulations of unoxidized organic matter and extensive areas where levels of dissolved oxygen are very low or lacking. Problem gases, generated in a meters-thick anoxic sludge, later effervesce and bubble to the surface. Emission to the atmosphere of gases such as methane, with a substantially greater global warming potential than CO_2, could contribute a new feedback loop, further increasing upwelling intensity and in turn creating additional eruptions of greenhouse gases.

Eruptions of gases may have a serious and widespread detrimental effect on the regional marine ecosystem and on important fisheries (Bakun and Weeks 2004). Mortalities of nearshore fish and invertebrates are likely to occur annually with varying intensity. A potential short-term benefit may accrue to seabirds feasting on the floating casualties. Conversely, abundant sardine stocks might be a mitigating factor opposing the process. Sardines filter and consume microscopic phytoplankton, and because they are very strong swimmers they are capable of overcoming the offshore surface flow in the upwelling zone to access the phytoplankton concentrations there. A resulting steep decline in primary productivity would reduce rates of deposition of organic matter on the continental shelf and, with a lag, the magnitude and frequency of gas eruptions.

Phenological and geographical changes. Upwelling intensity along the California coast is projected to continue to increase as increased CO_2 forcing intensifies the winds that drive upwelling by causing an increase in the land-ocean temperature gradient, i.e., temperatures on the land surface warm faster than on the ocean surface (Snyder et al. 2003). In Northern California, the increases are predicted to be concentrated in the warmest months (June–September); the peak of the upwelling season will shift to later in the year and the onset will occur up to a month later in the Southern California Bight, predicted results are inconclusive: equilibrium and transient models indicated decreased and slightly increased upwelling-inducing winds, respectively. Intensification of upwelling might lead to enhanced productivity along the California coast and possibly ameliorate increases in sea-surface temperature from greenhouse gas forcing. Conversely, any enrichment of food sources from upwelling might be offset by a decrease in concentration from increased mixing and offshore transport. This could potentially have an overall negative effect on marine organisms.

STORMINESS

Analysis of estimates of the variation in overall "storminess" from 1858–2000 show no substantial change along the central California coast (at San Francisco) since 1858 or over the last 50 years (Bromirski et al. 2003). Measures of extreme storm events, however, exhibited a significant increasing trend since 1950. The heightened level of extreme storminess during the last two decades is not exceptional compared to earlier periods (e.g., early 1900s and the late 1930s to early 1940s), and recent activity seems to have peaked during the El Niño event of 1997–98. If the observed historical pattern of interdecadal, quasi-cyclic winter storminess holds true, the heightened activity during the late 1990s should subside for the next decade or so.

Patterns of inferred storminess in central California suggest both mid-latitude and tropical associations to quasioscillatory interdecadal variability in the North Pacific. That is, there is a strong influence of broad-scale patterns of North Pacific atmospheric circulation in driving storminess along the California coast

EL NIÑO EVENTS

Using a global climate model with increasing greenhouse gas concentrations Timmermann et al. (1999) projected that in the future there will be more frequent El Niño–like conditions, higher year-to-year variability in sea-surface temperatures, and stronger cold events in the tropical Pacific Ocean.

By contrast, in evaluating various model projections of 21st century climate, Cayan et al. (2008b) concluded that the frequency of warm tropical events (El Niños) remains about the same as in historical simulations, and model El Niño events continue to be related to anomalous precipitation patterns over California.

THREATS TO WILDLIFE

1. Ocean acidification has the potential to dramatically change marine community composition and could have severe consequences for marine food webs.

2. Changes in the timing of upwelling could disrupt established patterns of reproductive phenology, leading to reproductive failure and perhaps diminished survival for some species.

Models at a Glance: Northern Marine

Citation	**Model**	**Emissions scenario**	**Outputs**
Cayan 2008b	PCM1, CM2.1	IPCC A1, A2, B1	Temperature, precipitation, snow accumulation, el Niño events
Diffenbaugh et al. 2004	CCM 3.6.6, RegCM2.5, BIOME4	2xCO2	California current activity
Snyder et al. 2003	RegCM2.5, CCSM1.3	IPCC A1	Land and sea surface temperatures, wind-stress curl
Timmermann et al. 1999	ECHAM4 climate model coupled to the OPYC3 global ocean general circulation and sea ice model	IPCC IS92a	El Niño frequency

Projected Effects of Climate Change in the Southern California Bight Marine Ecoregion

OCEAN ACIDIFICATION

Over the last 250 years, uptake of anthropogenic CO_2 by the oceans has lowered the pH of seawater by about 0.1, a process termed "ocean acidification" (Feely et al. 2004, Feely et al. 2008). Estimated future increases in atmospheric CO_2 could result in a decrease in surface-water pH of ~0.4 by the end of the century and a corresponding 50% decrease in carbonate ion concentration.

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In coming decades, ocean acidification could affect some of the most fundamental biological and geochemical process of the sea and seriously alter the basic structure of pelagic and benthic ecosystems. Presently, little is known about how intermittent exposure to corrosive undersaturated water might affect the development of larval, juvenile, and adult stages of aragonitic calcifying organisms or finfish that populate neritic and benthic environments in the region. Some experiments suggest that changes in saturation state may cause significant changes in overall calcification rates for many species of marine calcifiers. Other research suggests that many species of juvenile fish and shellfish are highly sensitive to above-normal CO_2 concentrations, i.e., higher mortality rates are directly correlated with higher CO_2 concentrations.

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Effects of submarine gas eruptions. On a global scale, projections indicate a progressive intensification of upwelling in response to greenhouse gas buildup. A 15% increase in characteristic magnitudes of upwelling-favorable winds, expected to occur over the next few decades, may cause a regime shift to a degraded marine ecosystem with widespread hypoxia and massive eruptions of noxious gases (methane, hydrogen sulfide) (Bakun and Weeks 2004). Hydrogen sulfide, in particular, is highly toxic to marine organisms and also strips dissolved oxygen from the water column as it moves upward through it. Intense upwelling provides copious nutrients resulting in a very high rate of primary productivity, but it is difficult for planktonic grazers to maintain populations because of their long generation times and rapid offshore transport by ocean surface waters. Consequently, there is a rapid buildup of phytoplankton biomass much of which may be unutilized and sink to the sea floor, forming thick accumulations of unoxidized organic matter and extensive areas where levels of dissolved oxygen are very low or lacking. Problem gases, generated in a meters-thick anoxic sludge, later effervesce and bubble to the surface. Emission to the atmosphere of gases such as methane, with a substantially greater global warming potential than CO_2, could contribute a new feedback loop, further increasing upwelling intensity and in turn creating additional eruptions of greenhouse gases.

Eruptions of gases may have a serious and widespread detrimental effect on the regional marine ecosystem and on important fisheries (Bakun and Weeks 2004). Mortalities of nearshore fish and invertebrates are likely to occur annually with varying intensity. A potential short-term benefit may accrue to seabirds feasting on the floating casualties. Conversely, abundant sardine stocks might be a mitigating factor opposing the process. Sardines filter and consume microscopic phytoplankton, and because they are very strong swimmers they are capable of overcoming the offshore surface flow in the upwelling zone to access the phytoplankton concentrations there. A resulting steep decline in primary productivity would reduce rates of deposition of organic matter on the continental shelf and, with a lag, the magnitude and frequency of gas eruptions.

Surface warming and sharpening of thermocline. From 1951 to 1993, ocean surface temperatures off southern California increased—by 1.2°C to 1.6°C depending on location—and the temperature difference along the thermocline has increased (Roemmich and McGowan 1995). Increased vertical stratification (more warming in surface layer) resulted in less lifting of the thermocline by wind-driven upwelling, and a shallower source of upwelled water (not less volume) provided less inorganic nutrients and hence supported a smaller zooplankton population. A sharper thermocline, with less vertical displacement from wind stress, reduces the fraction of the year when wind stress is strong enough to lift nutrient-bearing waters to the surface near the coast. Thus, by insulating nutrient-bearing layers from the sea surface, a moderate degree of surface heating can greatly reduce the nutrient supply.

Biomass of macrozooplankton has decreased by 80%, i.e., a moderate surface warming has resulted in a major decline in biota (Roemmich and McGowan 1995). This is a major perturbation because these plankton form a major part of the food web, may compete with larval fish for food, and are the main diet of some birds and many schooling, commercially important fish species. Because of high interannual variability (low frequency fluctuations with periods of years or decades), it is uncertain whether the decline occurred gradually over the whole period or more rapidly since the 1970s. If the zooplankton decline is a part of a natural cycle that reverses itself in coming years, then any impact may be similarly transient. If the zooplankton decline is anthropogenic in nature or is a natural trend of longer duration then the large magnitude of the response is a cause for concern for the coastal ecosystem.

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By contrast, in evaluating various model projections of 21st century climate, Cayan et al. (2008b) concluded that the frequency of warm tropical events (El Niños) remains about the same as in historical simulations, and model El Niño events continue to be related to anomalous precipitation patterns over California.

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Models at a Glance: Southern Marine

Citation	Model	Emissions scenario	Outputs
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Snyder et al. 2003	RegCM2.5, CCSM1.3	IPCC A1	Land and sea surface temperatures, wind-stress curl
Timmermann et al. 1999	ECHAM4 climate model coupled to the OPYC3 global ocean general circulation and sea ice model	IPCC IS92a	El Niño frequency

Literature Cited

Bakun, A., and S. J. Weeks. 2004. Greenhouse gas buildup, sardines, submarine eruptions and the possibility of abrupt degradation of intense marine upwelling ecosystems. Ecology Letters 7:1015-1023.

Bell, J. L., L. C. Sloan, and M. A. Snyder. 2004. Regional changes in extreme climatic events: A future climate scenario. Journal of Climate 17:81-87.

Bonfils, C., P. B. Duffy, and D. B. Lobell. 2007. Comment on 'Methodology and results of calculating Central California surface temperature trends: Evidence of a human-induced climate change?' Journal of Climate 20:4486-4489.

Brekke, L. D., N. L. Miller, K. E. Bashford, N. W. T. Quinn, and J. A. Dracup. 2004. Climate change impacts uncertainty for water resources in the San Joaquin River Basin, California. Journal of the American Water Resources Association 40:149-164.

Bromirski, P. D., R. E. Flick, and D. R. Cayan. 2003. Storminess variability along the California coast: 1858–2000. Journal of Climate 16:982-993.

Brooks, M. L., and J. R. Matchett. 2006. Spatial and temporal patterns of wildfires in the Mojave Desert, 1980-2004. Journal of Arid Environments 67:148-164.

Cayan, D. R., P. D. Bromirski, K. Hayhoe, M. Tyree, M. D. Dettinger, and R. E. Flick. 2008a. Climate change projections of sea level extremes along the California coast. Climatic Change 87:S57-S73.

Cayan, D. R., E. P. Maurer, M. D. Dettinger, M. Tyree, and K. Hayhoe. 2008b. Climate change scenarios for the California region. Climatic Change 87:S21–S42.

Christensen, N. S., and D. P. Lettenmaier. 2007. A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River Basin. Hydrology and Earth System Sciences 11:1417-1434.

Christy, J. R., W. B. Norris, K. Redmond, and K. P. Gallo. 2006. Methodology and results of calculating Central California surface temperature trends: Evidence of a human-induced climate change? Journal of Climate 19:548-563.

Collins, S. L., J. E. Fargione, C. L. Crenshaw, E. Nonaka, J. R. Elliott, Y. Xia, and W. T. Pockman. 2010. Rapid plant community responses during the summer monsoon to nighttime warming in a northern Chihuahuan Desert grassland. Journal of Arid Environments 74:611-617.

Daly, C., R. P. Neilson, and D. L. Phillips. 1994. A statistical topographic model for mapping climatological precipitation over mountainous terrain. Journal of Applied Meteorology 33:140-158.

Davis, F. W., D. M. Stoms, A. D. Hollander, K. A. Thomas, P. A. Stine, D. Odion, M. I. Borchert, J. H. Thorne, M. V. Gray, R. E. Walker, K. Warner, and J. Graae. 1998. The California Gap Analysis Project—Final Report. UC Santa Barbara, Santa Barbara, California.

Dettinger, M. D. 2005. From climate change spaghetti to climate-change distributions for 21st century California. San Francisco Estuary and Watershed Science 3:Article 4.

Dettinger, M. D., D. R. Cayan, M. Meyer, and A. E. Jeton. 2004. Simulated hydrologic responses to climate variations and change in the Merced, Carson, and American River basins, Sierra Nevada, California, 1900-2099. Climatic Change 62:283-317.

Diffenbaugh, N. S., M. A. Snyder, and L. C. Sloan. 2004. Could CO2-induced land-cover feedbacks alter near-shore upwelling regimes? Proceedings of the National Academy of Sciences of the United States of America 101:27-32.

Fabry, V. J., B. A. Seibel, R. A. Feely, and J. C. Orr. 2008. Impacts of ocean acidification on marine fauna and ecosystem processes. Ices Journal of Marine Science 65:414-432.

Feely, R. A., C. L. Sabine, J. M. Hernandez-Ayon, D. Ianson, and B. Hales. 2008. Evidence for upwelling of corrosive "acidified" water onto the continental shelf. Science 320:1490-1492.

Feely, R. A., C. L. Sabine, K. Lee, W. Berelson, J. Kleypas, V. J. Fabry, and F. J. Millero. 2004. Impact of anthropogenic CO2 on the CaCO3 system in the oceans. Science 305:362-366.

Florsheim, J. L., and M. D. Dettinger. 2007. Climate and floods still govern California levee breaks. Geophysical Research Letters 34:L22403.

Fried, J. S., M. S. Torn, and E. Mills. 2004. The impact of climate change on wildfire severity: A regional forecast for northern California. Climatic Change 64:169-191.

Hayhoe, K., D. Cayan, C. B. Field, P. C. Frumhoff, E. P. Maurer, N. L. Miller, S. C. Moser, S. H. Schneider, K. N. Cahill, E. E. Cleland, L. Dale, R. Drapek, R. M. Hanemann, L. S. Kalkstein, J. Lenihan, C. K. Lunch, R. P. Neilson, S. C. Sheridan, and J. H. Verville. 2004. Emissions pathways, climate change, and impacts on California. Proceedings of the National Academy of Sciences of the United States of America 101:12422-12427.

Howat, I. M., and S. Tulaczyk. 2005. Climate sensitivity of spring snowpack in the Sierra Nevada. Journal of Geophysical Research 110:F04021.

Hughes, M., and A. Hall. 2010. Local and synoptic mechanisms causing Southern California's Santa Ana winds. Climate Dynamics 34:847-857.

Hughes, M., A. Hall, and J. Kim. 2009. Anthropogenic reduction of Santa Ana winds. Draft paper from the California Climate Change Center. CEC-500-2009-015-D. Available at www.energy.ca.gov/2009publications/CEC-500-2009-015/CEC-500-2009-015-D.PDF.

IPCC. 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Johnstone, J. A., and T. E. Dawson. 2010. Climatic context and ecological implications of summer fog decline in the coast redwood region. Proceedings of the National Academy of Sciences of the United States of America 107:4533-4538.

Kimball, S., A. L. Angert, T. E. Huxman, and D. L. Venable. 2010. Contemporary climate change in the Sonoran Desert favors cold-adapted species. Global Change Biology 16:1555-1565.

Knapp, R. A., K. R. Matthews, and O. Sarnelle. 2001. Resistance and resilience of alpine lake fauna to fish introductions. Ecological Monographs 71:401-421.

Knowles, N., and D. R. Cayan. 2002. Potential effects of global warming on the Sacramento/San Joaquin watershed and the San Francisco estuary. Geophysical Research Letters 29.

Knowles, N., and D. R. Cayan. 2004. Elevational dependence of projected changes in the San Francisco estuary and watershed. Climatic Change 62:319-336.

Langley, J. A., K. L. McKee, D. R. Cahoon, and J. A. C. J. P. Megonigal. 2009. Elevated CO2 stimulates marsh elevation gain, counterbalancing sea-level rise. Proceedings of the National Academy of Sciences 106:6182-6186.

Lebassi, B., J. Gonzalez, D. Fabris, E. Maurer, N. Miller, C. Milesi, P. Switzer, and R. Bornstein. 2009. Observed 1970-2005 Cooling of Summer Daytime Temperatures in Coastal California. Journal of Climate 22:3558-3573.

Lenihan, J. M., D. Bachelet, R. P. Neilson, and R. Drapek. 2008. Response of vegetation distribution, ecosystem productivity, and fire to climate change scenarios for California. Climatic Change 87: S215-S230.

Lundquist, J. D., and D. R. Cayan. 2007. Surface temperature patterns in complex terrain: Daily variations and long-term change in the central Sierra Nevada, California. Journal of Geophysical Research-Atmospheres 112.

Maurer, E. P. 2007. Uncertainty in hydrologic impacts of climate change in the Sierra Nevada, California, under two emissions scenarios. Climatic Change 82:309-325.

Maurer, E. P., and P. B. Duffy. 2005. Uncertainty in projections of streamflow changes due to climate change in California. Geophysical Research Letters 32.

Maurer, E. P., I. T. Stewart, C. Bonfils, P. B. Duffy, and D. Cayan. 2007. Detection, attribution, and sensitivity of trends toward earlier streamflow in the Sierra Nevada. Journal of Geophysical Research-Atmospheres 112.

Mayer, K. E., and W. F. Laudenslayer Jr. 1988. A Guide to Wildlife Habitats of California, California edition. California Department of Forestry and Fire Protection, Sacramento.

McKechnie, A. E., and B. O. Wolf. 2010. Climate change increases the likelihood of catastrophic avian mortality events during extreme heat waves. Biology Letters 6:253-256.

Medellín-Azuara, J., J. J. Harou, M. A. Olivares, K. Madani, J. R. Lund, R. E. Howitt, S. K. Tanaka, M. W. Jenkins, and T. Zhu. 2008. Adaptability and adaptations of California's water supply system to dry climate warming. Climatic Change 87:S75-S90.

Melack, J. M., J. Dozier, C. R. Goldman, D. Greenland, A. M. Milner, and R. J. Naiman. 1997. Effects of climate change on inland waters of the Pacific Coastal Mountains and Western Great Basin of North America. Hydrological Processes 11:971-992.

Miller, N. L., and N. J. Schlegel. 2006. Climate change projected fire weather sensitivity: California Santa Ana wind occurrence. Geophysical Research Letters 33.

Mote, P. W., A. F. Hamlet, M. P. Clark, and D. P. Lettenmaier. 2005. Declining mountain snowpack in western north America. Bulletin of the American Meteorological Society 86:39-49.

Mount, J., and R. Twiss. 2005. Subsidence, sea level rise, and seismicity in the Sacramento–San Joaquin Delta. San Francisco Estuary and Watershed Science 3:Article 5.

Nakićenović, N., and R. Stewart, editors. 2000. Emissions Scenarios: Special Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York.

Pal, J. S., F. Giorgi, X. Bi, N. Elguindi, F. Solmon, X. Gao, S. A. Rauscher, R. Francisco, A. Zakey, J. Winter, M. Ashfaq, F. S. Syed, J. L. Bell, N. S. Diffenbaugh, J. Karmacharya, A. Konaré, D. Martinez, R. P. daRocha, L. C. Sloan, and A. L. Steiner. 2007. Regional climate modeling for the developing world: The ICTP RegCM3 and RegCNET. Bulletin of the American Meteorological Society 88:1385-1409.

Parisien, M. A., and M. A. Moritz. 2009. Environmental controls on the distribution of wildfire at multiple spatial scales. Ecological Monographs 79:127-154.

Parker, B. R., R. D. Vinebrooke, and D. W. Schindler. 2008. Recent climate extremes alter alpine lake ecosystems. Proceedings of the National Academy of Sciences of the United States of America 105:12927-12931.

Peterson, D. H., I. Stewart, and F. Murphy. 2008. Principal hydrologic responses to climatic and geologic variability in the Sierra Nevada, California. San Francisco Estuary and Watershed Science 6:Article 3.

Pope, K. L., J. Piovia-Scott, and S. P. Lawler. 2009. Changes in aquatic insect emergence in response to whole-lake experimental manipulations of introduced trout. Freshwater Biology 54:982-993.

Porinchu, D. F., S. Reinemann, B. G. Mark, J. E. Box, and N. Rolland. 2010. Application of a midge-based inference model for air temperature reveals evidence of late-20th century warming in sub-alpine lakes in the central Great Basin, United States. Quaternary International 215:15-26.

Pyke, C. R. 2005. Interactions between habitat loss and climate change: Implications for fairy shrimp in the Central Valley ecoregion of California, USA. Climatic Change 68:199-218.

Roemmich, D., and J. A. McGowan. 1995. Climatic warming and the decline of zooplankton in the California current. Science 267:1324–1326.

Shuford, D. W., and T. Gardali, editors. 2008. California Bird Species of Special Concern: A ranked assessment of species, subspecies, and distinct populations of birds of immediate conservation concern in California. Studies of Western Birds 1, Western Field Ornithologists, Camrillo, California and California Department of Fish and Game, Sacramento, California.

Sinervo, B., F. Mendez-de-la-Cruz, D. B. Miles, B. Heulin, E. Bastiaans, M. V. S. Cruz, R. Lara-Resendiz, N. Martinez-Mendez, M. L. Calderon-Espinosa, R. N. Meza-Lazaro, H. Gadsden, L. J. Avila, M. Morando, I. J. De la Riva, P. V. Sepulveda, C. F. D. Rocha, N. Ibarguengoytia, C. A. Puntriano, M. Massot, V. Lepetz, T. A. Oksanen, D. G. Chapple, A. M. Bauer, W. R. Branch, J. Clobert, and J. W. Sites. 2010. Erosion of lizard diversity by climate change and altered thermal niches. Science 328:894-899.

Snyder, M. A., J. L. Bell, L. C. Sloan, P. B. Duffy, and B. Govindasamy. 2002. Climate responses to a doubling of atmospheric carbon dioxide for a climatically vulnerable region. Geophysical Research Letters 29:Article No. 1514.

Snyder, M. A., and L. C. Sloan. 2005. Transient future climate over the western United States using a regional climate model. Earth Interactions 9:Article No. 11.

Snyder, M. A., L. C. Sloan, and J. L. Bell. 2004. Modeled regional climate change in the hydrologic regions of California: A CO2 sensitivity study. Journal of the American Water Resources Association 40:591-601.

Snyder, M. A., L. C. Sloan, N. S. Diffenbaugh, and J. L. Bell. 2003. Future climate change and upwelling in the California Current. Geophysical Research Letters 30:Article No. 1823.

Spalding, M. D., H. E. Fox, G. R. Allen, N. Davidson, Z. A. Ferdaña, M. Finlayson, B. S. Halpern, M. A. Jorge, A. Lombana, S. A. Lourie, K. D. Martin, J. M.

E. Mcmanus, C. A. Recchia, and J. Robertson. 2007. Marine ecoregions of the world: a bioregionalization of coastal and shelf areas. Bioscience 57:573-583.

Stewart, I. T., D. R. Cayan, and M. Dettinger. 2005. Changes toward earlier streamflow timing across Western North America. Journal of Climate 18:1136-1155.

Stralberg, D., D. Jongsomjit, C. A. Howell, M. A. Snyder, J. D. Alexander, J. A. Wiens, and T. L. Root. 2009. Re-Shuffling of Species with Climate Disruption: A No-Analog Future for California Birds? Plos One 4.

Timmermann, A., J. Oberhuber, A. Bacher, M. Esch, M. Latif, and E. Roeckner. 1999. Increased El Niño frequency in a climate model forced by future greenhouse warming. Nature 398:694-697.

Westerling, A. L., and B. P. Bryant. 2008. Climate change and wildfire in California. Climatic Change 87:S231-S249.

Westerling, A. L., D. R. Cayan, T. J. Brown, B. L. Hall, and L. G. Riddle. 2004. Climate, Santa Ana winds and autumn wildfires in southern California. EOS, Transactions American Geophysical Union 85:289-296.

Wiens, J. A., D. Stralberg, D. Jongsomjit, C. A. Howell, and M. A. Snyder. 2009. Niches, models, and climate change: Assessing the assumptions and uncertainties. Proceedings of the National Academy of Sciences of the United States of America 106:19729-19736.

Yates, D., H. Galbraith, D. Purkey, A. Huber-Lee, J. Sieber, J. West, S. Herrod-Julius, and B. Joyce. 2008. Climate warming, water storage, and Chinook salmon in California's Sacramento Valley. Climatic Change 91:335-350.