SCENARIOS OF CLIMATE CHANGE IN CALIFORNIA: AN OVERVIEW

A Report From:
California Climate Change Center

Prepared By:
Dan Cayan, Scripps Institution of Oceanography, University of California, San Diego
Amy Lynd Luers, Union of Concerned Scientists
Michael Hanemann, University of California Berkeley
Guido Franco, California Energy Commission
Bart Croes, California Air Resources Board

WHITE PAPER

Arnold Schwarzenegger, *Governor*

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies

The California Climate Change Center (CCCC) is sponsored by the PIER program and coordinated by its Energy-Related Environmental Research area. The Center is managed by the California Energy Commission, Scripps Institution of Oceanography at the University of California at San Diego, and the University of California at Berkeley. The Scripps Institution of Oceanography conducts and administers research on climate change detection, analysis, and modeling; and the University of California at Berkeley conducts and administers research on economic analyses and policy issues. The Center also supports the Global Climate Change Grant Program, which offers competitive solicitations for climate research.

The California Climate Change Center Report Series details ongoing Center-sponsored research. As interim project results, these reports receive minimal editing, and the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the Center seeks to inform the public and expand dissemination of climate change information; thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

For more information on the PIER Program, please visit the Energy Commission's website www.energy.ca.gov/pier/ or contact the Energy Commission at (916) 654-5164.

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1.0 Summary of Key Findings and Recommendations

- Climate change impacts will affect all of the sectors considered in this report: sea-level rise, agriculture, snowpack and water supply, forestry, wildfire risk, public health, and electricity demand and supply.
- The more that greenhouse gases (GHGs) accumulate in the Earth's atmosphere over the next century, the greater the warming and the more severe and costly the impacts will be. This study considered three future GHG emissions scenarios—low, medium high, and high emissions—and explored associated climate changes through three modern climate models of differing sensitivity to GHG concentrations.
- Although climate model results are inconclusive as to whether California's precipitation will change over the next century, all climate models show increases in temperature, with the aggregate of several model runs containing a range of warming from 2000 to 2100 from about +2ºC to about +6ºC (+3.6ºF to about +10.8 ºF). Increases in temperature alone would impact the California hydrological cycle, with consequences upon the state's water supply, hydroelectric power supply, agriculture, recreation, and ecosystems.
- Climate change could produce compounding impacts—for instance, in the San Francisco Bay Delta, heightened sea levels and high river inflows from warmer storms would place levee systems in greater jeopardy of flooding.
- Some of the most dramatic climate change impacts will be experienced as increased frequency and severity of extreme events, such as heat waves, wildfires, flooding, and conditions conducive to air pollution formation.
- Even under lower GHG emissions scenarios, some impacts of climate change are inevitable. As a result, although adaptation is not the solution to climate change, it is a necessary complementary strategy to manage some of the projected impacts.
- Although there are many opportunities for California to increase its capacity to cope with many climate change impacts, these can be costly, and they require time and planning.
- More analysis—and in some cases, more information—is needed to better understand the vulnerability of California's health, economy, and environment to climate change. In particular, greater attention must focus on social dimensions of climate change for both assessing and implementing the state's mitigative and adaptive potential. Critical to this work will be evaluating and addressing the distributional and equity implications of climate changes in California.

2.0 Motivation and Overview of The Scenarios Project

Governor Arnold Schwarzenegger's Executive Order S-3-05 of June 1, 2005, called for specific emission reductions and a periodic update on the state of climate change science and the emerging understanding of potential impacts on climate-sensitive sectors such as the state's water supply, public health, agriculture, coastal areas, and forestry. In response to this Executive Order, the California Energy Commission (Energy Commission) and the California Environmental Protection Agency (Cal/EPA) commissioned an assessment of the potential impacts of climate change on key state resources ("the Scenarios Project").

The Scenarios Project was conducted under the direction of the California Climate Change Center ("the Center"), which has engaged in a long-term, California-specific climate research program. The assessment builds on earlier work that came out of the Center and other previous studies. In particular, it extends the work of a recent study that compared the projected impact of climate change in California under differing emissions scenarios (Hayhoe et al. 2004). This assessment draws upon experts within and outside of the Center to produce a collection of separate research reports on the projected impacts of climate change under multiple scenarios across six different sectors: coasts, water resources, agriculture, public health, forestry, and electricity production and demand.

This report summarizes the findings from the individual research reports and compares them with the earlier findings from the Hayhoe et al. (2004) study. This summary report compares the impacts on key sectors under multiple future scenarios of temperature changes and links these impacts to GHG emission trajectories, assuming different climate sensitivities.

3.0 Core Research Papers

This document summarizes and integrates the results of several studies listed in the following table. The California Institute for Energy and Environment (CIEE, associated with the Office of the President, University of California) is conducting an external review on all the papers listed in this table. Dr. Edward Vine is managing the peer review process. These papers are available at www.climatechange.ca.gov/.

Research Papers	
Dan Cayan et al.	Climate Scenarios for California
Dan Cayan et al.	Projecting Future Sea Level
Dennis Baldocchi et al.	An Assessment of Impacts of Future CO_2 and Climate on Agriculture
Brian Joyce et al.	Climate Change Impacts on Water for Agriculture in California: A Case Study in the Sacramento Valley
Josue Medellin et al.	Climate Warming and Water Supply Management in California
Department of Water Resources	Progress on Incorporating Climate Change into Management of California's Water Resources*
Andrew Paul Gutierrez	Analysis of Climate Effects on Agricultural Systems
Timothy Cavagnaro et al.	Climate Change: Challenges and Solutions for California Agricultural Landscapes
James Lenihan et al.	The Response of Vegetation Distribution, Ecosystem Productivity, and Fire in California to Future Climate Scenarios Simulated by the MC1 Dynamic Vegetation Model
Anthony Westerling and Benjamin Bryant	Climate Change and Wildfire in and Around California: Fire Modeling and Loss Modeling
Jeremy Fried et al.	Predicting the Effect of Climate Change on Wildfire Severity and Outcomes in California: A Preliminary Analysis
Max Moritz and Scott Stephens	Fire and Sustainability: Considerations for California's Altered Future Climate
John Battles et al.	Climate Change Impact on Forest Resources
Deborah Drechsler et al.	Public Health-Related Impacts of Climate Change for California
Amy Lynd Luers and Suzanne Moser	Preparing for the Impacts of Climate Change in California: Opportunities and Constraints for Adaptation
Technical Notes	
Sebastian Vicuña et al.	Climate Change Impacts on High Elevation Hydropower Generation in California's Sierra Nevada: A Case Study in the Upper American River
Guido Franco and Alan Sanstad	Climate Change and Electricity Demand in California
Sebastian Vicuña	Predictions of Climate Change Impacts on California Water Resources Using CalSim-II: A Technical Note

* The Department of Water Resources (DWR) coordinated the peer-review process for this paper. It will be available from DWR.

4.0 Introduction

It is now apparent that the increasing atmospheric concentration of GHGs, resulting from human activities, is changing the climate in ways that pose serious risks to California's health, economy, and environment. However, the most severe impacts that are expected with greater temperature rises could be avoided if the rate of GHG emissions is reduced. To help identify the potentially avoidable climate impacts in California, this paper summarizes some of the impacts expected under lower, medium, and higher ranges of projected warmings, as determined by different GHG emissions scenarios and different global climate models.

Linking temperature changes with particular levels of GHG emissions is a useful way to gauge the level of emissions reductions needed to avoid serious climate change impacts. However, current understanding of the climate system permits only limited precision in linking specific temperature changes to specific emission scenarios. Among a collection of more than a dozen national and international global climate models, *all* project increased temperatures as a result of higher emissions of GHG. However, the models differ in their sensitivity to changes in atmospheric GHG concentrations. For example, temperature rises between 1.5°C to 4.5°C (2.7°F to 8.1°F) have been projected for a doubling of CO_2 concentration above pre-industrial levels (IPCC 2001). The range in temperature response is the result of differences in the way that the models represent certain processes of the climate system, such as the way that they simulate clouds and radiation (Stephens 2005).

Society can neither control, nor at present precisely determine, the sensitivity of the earth's climate system to rising GHG concentrations. As a result, society must consider the implications of a range of climate sensitivities when evaluating the risks of climate change and devising policies to manage the one factor we can control: our own GHG emissions.

This paper summarizes the findings of the California Climate Change Center Scenarios Project ("the Project") and compares these new projections with those reported in an earlier study produced by many of the same researchers (Hayhoe et al. 2004). The projections in this summary are based upon three GHG scenarios—a lower emissions, medium-high emissions, and higher emissions scenario. The effect of different estimates of the sensitivity of the climate system to GHG forcing is explored by comparing the temperature projections from three different global climate models—each containing somewhat different representations of some crucial physical processes that result in different levels of climate sensitivity.

The following sections describe the emission scenarios and climate projections, and report on the projected impacts of the specific climate projections across six sectors: coasts, water resources, agriculture, forests/fire, public health, and electricity. The paper concludes with a discussion of the implications of these projections for mitigation and adaptation, and points out some outstanding problems that require further information or research.

5.0 Climate Change Scenarios

5.1. Emission Scenarios

The Intergovernmental Panel on Climate Change's (IPCC's) *Special Report on Emissions Scenarios* (SRES) developed a set of possible future emissions scenarios based on different assumptions about global development paths (Nakicenovic et al. 2000). This report contrasts the results from recent analyses for California of three SRES emissions scenarios—a lower emissions scenario (B1), a medium-high emissions scenario (A2), and a higher emissions scenario (A1fi) (Figure 1):

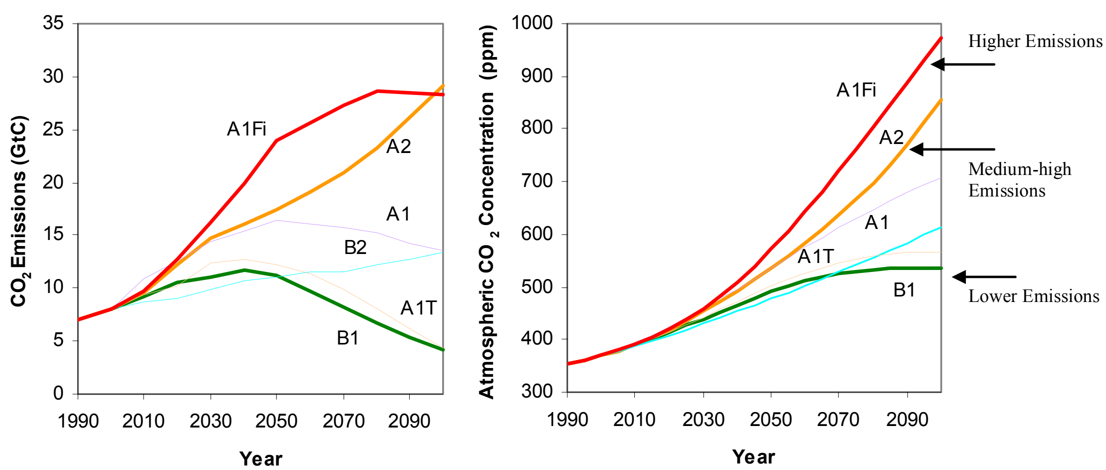

Figure 1. IPCC SRES Emission Scenarios

Six IPCC SRES Emissions Scenarios are presented here. The bold lines represent the three scenarios used in the analysis presented here (B1, A2, A1fi), the other lines represent IPCC scenarios not used in this study, yet presented here to illustrate how the trajectories selected for this study fit within the family of curves developed by the IPCC (Nakicenovic et al. 2000). The trajectories in this figure do not exactly match those in official IPCC documents (Nakicenovic et al. 2000) because the results we report here are based on revised emissions projections subsequently made available by IPCC; these are available at http://sres.ciesin.columbia.edu/. In addition, the authors used a new version of MAGICC available from www.cgd.ucar.edu/cas/wigley/magicc/index.html. However, the differences between this figure and similar figures provided by the IPCC are minor, and do not affect the discussion in this paper.

- The lower emissions scenario (B1) characterizes a world with population growth similar to the highest emissions scenarios, but with rapid changes toward a service and information economy and with the introduction of clean and resource-efficient technologies. The B1 scenario has CO_2 emissions peaking just below 10 gigatonnes per year (Gt/yr) in mid-century before dropping below the current-day level of 7 Gt/yr by 2100. Under the B1 scenario, the CO_2 concentration would double, relative to its pre-industrial level, by the end of this century.
- The medium-high emissions scenario (A2) projects continuous population growth, with slower economic growth and technological change than in the other scenarios. For the medium-high emissions scenario (A2), CO_2 emissions continue to climb throughout the century, reaching almost 30 Gt/yr, about four times the present rate of emissions. By the end of the century CO_2 concentration would reach more than triple its pre-industrial level.
- The higher emissions scenario (A1fi) represents a world of rapid fossil-fuel-intensive economic growth, global population that peaks mid-century then declines, and the introduction of new and more efficient technologies towards the end of the century. The higher emissions scenario (A1fi) rises faster than the A2 scenario, reaching about 25 Gt/yr, more than three times the present rate of emissions, by 2050. The A1fi scenario concludes the century with approximately the same annual emissions as the A2 scenario. However, the A2 and A1fi scenarios differ in two ways that have important implications for the projected changes. First, the emissions pathways of A1fi and A2 diverge by mid-century, with A1fi rising rapidly and then flattening out toward the end of the century. Second, the total cumulative emissions in the A1fi scenario are almost 20% higher at the end of century than in the A2 scenario.

To capture a range of uncertainty among climate models, this chapter reports on projections from three state-of-the-art global climate models (GCMs) that capture a range of climate sensitivities:

- The Parallel Climate Model (PCM1) from the National Center for Atmospheric Research (NCAR) and the U.S. Department of Energy (DOE) groups (Washington et al. 2000), a low-sensitivity model, with a climate sensitivity of approximately 1.8°C (3.2°F)[1]
- The Geophysical Fluids Dynamic Laboratory (GFDL) CM2.1 (NOAA Geophysical Dynamics Laboratory, Princeton New Jersey) model (Delworth et al. 2005), a medium-sensitivity model with climate sensitivity of approximately 3°C (5.4°F)
- The U.K. Met Office Hadley Centre Climate Model, version 3 (HadCM3) (Pope et al. 2000), with a slightly higher climate sensitivity of 3.3°C (5.9°F)

Each of the three GCMs produced a reasonably good simulation of key features of California's observed climate and representations of tropical Pacific ENSO variability.

[1] *Climate sensitivity* is defined as the change in temperature resulting from a doubling of CO_2 concentration above pre-industrial levels.

The models were also chosen for having available simulation datasets at monthly and daily time scales in order to carry out the impact studies undertaken in the scenarios analysis.

Global climate models calculate weather, ocean, and land surface variables over a discrete global grid too coarse to adequately depict the complex structure of temperature and precipitation that characterizes the California setting. The results presented here rely principally on a statistical technique using properties of observed data (Wood et al. 2002), that was employed to correct model biases and "downscale" the model data to a finer level of detail—a grid of approximately 12 kilometers (km) (7 miles). This downscaling technique, which was employed in previous climate change assessments, was used to satisfy study requirements for impact studies, including modeling the water and energy balance. To derive land surface hydrological variables consistent with the downscaled forcing data, a macroscale, distributed, physically based hydrologic model—the variable infiltration capacity (VIC) model (Liang et al. 1994; Liang et al. 1996)—was used.

5.2. Climate Projections

5.2.1. Temperature

Temperatures in California are projected to rise significantly over the twenty-first century. As shown in Table 1 and Figure 2, magnitudes of the warming vary because of the uncertainties in the climate sensitivity, as expressed by differences between models and in the emission scenarios. The rises (2000 to 2100) vary from approximately 1.7°C–3.0°C (3.0°F–5.4°F) in the lower range of projected warming, 3.1°C–4.3°C (5.5°F–7.8°F) in the medium range, and 4.4°C–5.8°C (8.0°F–10.4°F) in the higher range (Cayan et al. 2006a). To comprehend the magnitude of these projected temperature changes, over the next century the lower range of projected temperature rise is slightly larger than the difference in annual mean temperature between Monterey and Salinas, and the upper range of project warming is greater than the temperature difference between San Francisco and San Jose, respectively.[2]

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[2] The difference in annual mean temperatures between Monterey (65.3ºF or 18.5ºC) and Salinas (67.8ºF or 19.9ºC) is 2.5ºF (1.4ºC) and the difference between San Francisco Mission Dolores (63.6ºF or 17.6ºC) and San Jose (71.0ºF or 22ºC) is 7.4ºF (4.4ºC).

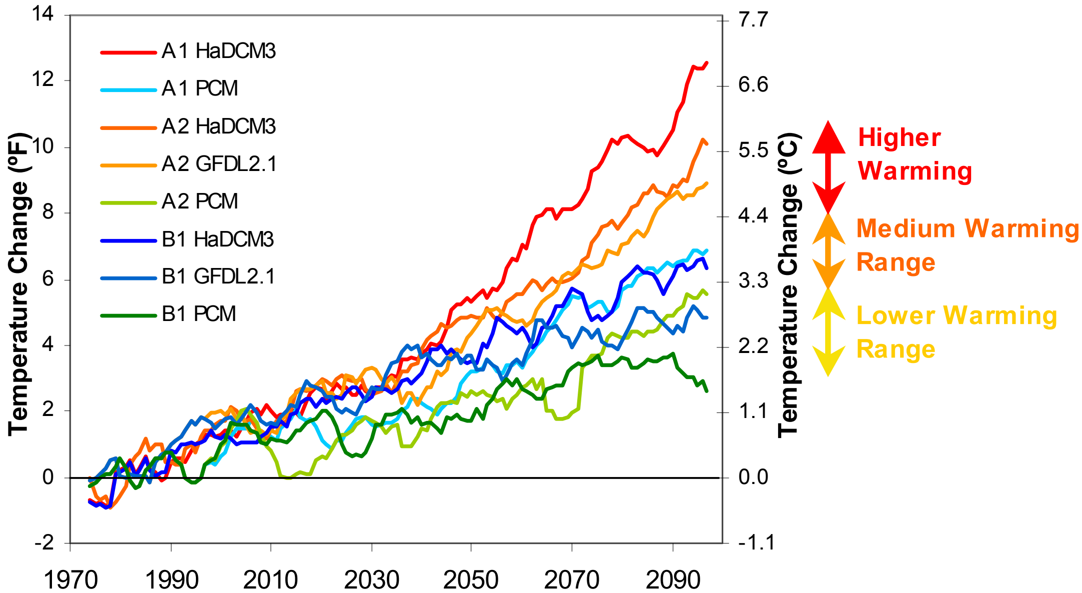


Figure 2. Change in California annual mean temperature

Change in California annual mean temperature (7-year running mean) (°F/°C) by year, from 1970–2099, relative to 1961–1990 average.

An important aspect of the model results is that all of the GHG scenario simulation, (except the low-emission scenario simulated by the low response model) exhibit higher warming in summer than in winter. In the medium-high emission (A2) scenario with the low sensitivity and medium sensitivity models, temperature increases by the end of the twenty-first century are 1.5°C–3.5°C (2.7°F–6.3°F), greater in summer than in winter (Cayan et al. 2006a). This result has important implications for impacts such as ecosystems, agriculture, water and energy demand, and the occurrence of heat waves, which have public health consequences.

5.2.2. Precipitation

There is no clear trend in precipitation projections for California over the next century. However, from the recent IPCC model projections—including several models that were not selected for the present study—there are considerable differences, from wetter to drier, between models and between emissions scenarios. The center of this distribution of simulations yields relatively little change, with a tendency for a slight decrease in precipitation, as is the case for the GFDL and the HadCM3 simulations (Cayan et al. 2006a).

Table 1. Potential warming ranges for California

	GCMs	Lower °C (°F)	Medium °C (°F)	Higher °C (°F)
Projected End of Century Range of Warming*		1.7°C–3°C (3.0°F–5.4°F)	3.1°C–4.4°C (5.5°F–7.8°F)	4.4°C–5.8°C (8.0°F–10.4°F)
Lower GHG Emissions B1	PCM	1.7 (3.0)		
	GFDL	2.2 (4.0)		
	HadCM3		3.1 (5.6)	
Medium-High GHG Emissions A2	PCM	2.6 (4.7)		
	GFDL		3.9 (7.0)	
	HadCM3			4.5 (8.1)
Higher GHG Emissions A1fi	PCM		3.3 (6.0)	
	HadCM3			5.8 (10.4)

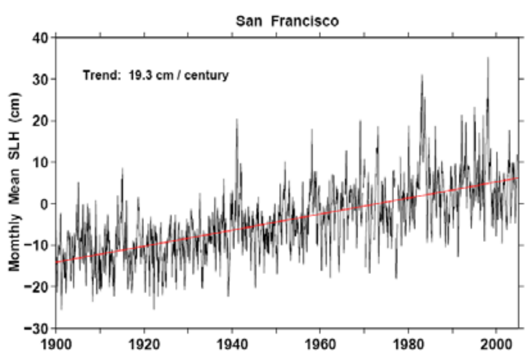
*The temperature ranges were defined here for illustration only. The division was made simply by dividing evenly (low, medium, high) range of change in California's average annual temperatures as projected by the three GCM and emissions scenarios reported on in this summary (1.7°C–5.8°C (3.0°F–10.4°F)). The projected warming ranges presented here are for 2070–2099 relative to 1971–2000. However, some of the impacts summarized in this report used a different historical climatological baseline of 1961–1990. The difference between the 1961–1990 and 1971–2000 baselines leads to a small difference in projected temperature rise for the different scenarios and models. The difference in baselines amounts to approximately a 0.2°C (0.36°F) difference in the full range of projected end-of-century temperature rise.

There is no evidence from the projections indicating that the Mediterranean seasonal precipitation regime in California will change. All of the simulations examined here indicate that the very dominant portion of precipitation continues to be derived during winter from North Pacific storms. Summer precipitation changes only incrementally, and actually decreases in some of the simulations, so there is little evidence for a stronger monsoon influence. For the scenarios reported here, each of the model runs is characterized by large interannual to decadal fluctuations of precipitation, but not much change in annual precipitation over the 2000–2100 period. Little change in variability over the period of the model runs is evident in the simulations. The frequency of warm tropical events (El Niños) remains about the same as was exhibited in the historical simulations. As in observations, GCM El Niño events are related to anomalous precipitation patterns near the California region (Cayan et al. 2006a).

6.0 Coastal Sea Level

Coastal observations and global model projections indicate that California's open coast and estuaries will experience rising sea levels during the next century. Sea level rise already has affected much of the coast in Southern California, Central California, and the San Francisco Bay and estuary. These historical trends, quantified from a small set of California tide gages, have approached 2 mm/year (0.08 in/yr), which are rates very similar to those estimated for global mean sea level. So far, there is little evidence that the rate of rise has accelerated, and indeed the rate of rise at California tide gages has actually flattened since about 1980. However, projections indicate that substantial sea level rise, even faster than the historical rates, could occur during the next century.

As discussed in Cayan et al. (2006b), recent climate change simulations project significant global sea level rise during the next century, as the result of thermal expansion as the oceans warm and as runoff from melting land-based snow and ice accelerates. Sea level rise projected from the models increases in proportion to the amount of global warming. By the 2070–2099 period, sea level rise projections range from 13–62 cm (5.1–24.4 in) higher than the 2000 level for simulations following the lower emissions scenario (B1), from 18–76 cm (7.1–29.9 in) for the medium-high emission scenario (A2), and from 21–89 cm (8.5–35.2 in) for the higher emissions scenario(A1fi). These are illustrated in Figure 3, together with the last century of observed sea level at the San Francisco tide gage.



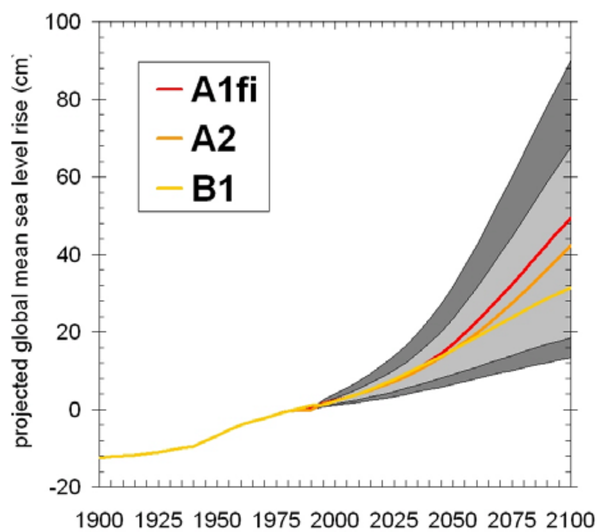


Figure 3. Observed change in sea level rise in San Francisco and projections of global mean sea level rise

Projected sea level rise from climate model estimates for three GHG emissions scenarios, A1fi (higher emissions), A2 (medium-high emissions), and B1 (lower emissions). San Francisco observed sea level, with trend of 19.3 cm/century (7.6 in/century), is shown for comparison. (Cayan et al. 2006b). In the graph on the right, light gray and dark gray represent uncertainty from thermal expansion and ice melt, respectively.

In addition to relatively steady long-term trends and astronomical tides, sea levels along the California coast undergo inter-annual and weather scale fluctuations that carry sea level elevations above and below the predicted tides and trends. These slower sea level rises are crucial because they boost the sea level excursions associated with the shorter term tidal, weather, and climate fluctuations. The most impressive examples of high sea level episodes in recent decades occurred during the winters of the massive El Niño events of 1982–1983 and 1997–1998 (Flick 1998). Thus, much of the potential damage from rising sea levels will occur during the occasions when high water stands due to tides, weather and climate anomalies are made higher (or more frequent) by the gradually rising mean sea levels. Importantly, GCMs include El Niños and La Niñas, as well as longer-lasting Pacific decadal variability, both in historical simulations as well as in projections that are being used to investigate twenty-first century climate changes.

Cayan et al. (2006b) considered two climate models and three emission scenarios to provide a set of future weather and short-period climate fluctuations, and a range of potential long-term sea level rises. Moderate to very large sea level rises were projected. The middle to higher end of this range would substantially exceed the historical rate of sea level rise (15–20 cm (5.9–7.8 in) per century) observed at San Francisco and San Diego during the past 100 years. Using a model of the combined contributions of tides, weather, climate, and long-term global warming on hourly sea levels, the potential for sea level rise impacts was assessed from the occurrence of hourly extremes. Considering a range of scenarios, and a range of possible sea level trends (Figure 4), Cayan et al. (2006b) find that, if warming is near the low end of the temperature range of projections so that sea level rise trends are also near the low end, then the occurrence of extremely high sea level events will increase, but not greatly, and sea level extremes under the various emissions scenarios (B1, A2, A1fi) are not much different from each other. On the other hand, if warming is greater, then sea level rise trends are at the higher end in each scenario, causing extreme events and their duration to increase markedly, especially for the medium-high and higher GHG emissions scenarios (A2, A1fi). Because of uncertainties in the climate sensitivity, it is not clear how rapidly sea levels will rise, even under the lowest emission scenarios. However, the California coast has already experienced rises of sea level that approach 15–20 cm (6–8 in) over the last century, so it seems prudent to consider scenarios where projected rise rates equal or exceed these historical sea level rise rates.

Coastal sea level extremes are also exacerbated by other processes, such as heavy surf from wind-driven waves, and these effects tend to be active during the same storms that causing anomalously high sea levels. Near San Francisco and Crescent City, when sea level fluctuations, above tide predicted levels, reach anomalies that exceed the 99th percentile of their measurements, the average in peak wave height at nearby wave-measuring buoys maintained by NOAA climbs to about double its ambient level. Because wave energy is proportional to the *square* of the wave height, the wave height increase during anomalous sea level episodes is equivalent to a coincident increase in wave energy by a factor of four. This observational evidence indicates that when anomalous sea level is highest, wave energy has an increased likelihood of reaching very high levels. When waves and anomalously high sea level coincide with high tides, the chances for coastal damage are heightened. Continuing increases in mean sea level due to global change makes this problem even more severe.

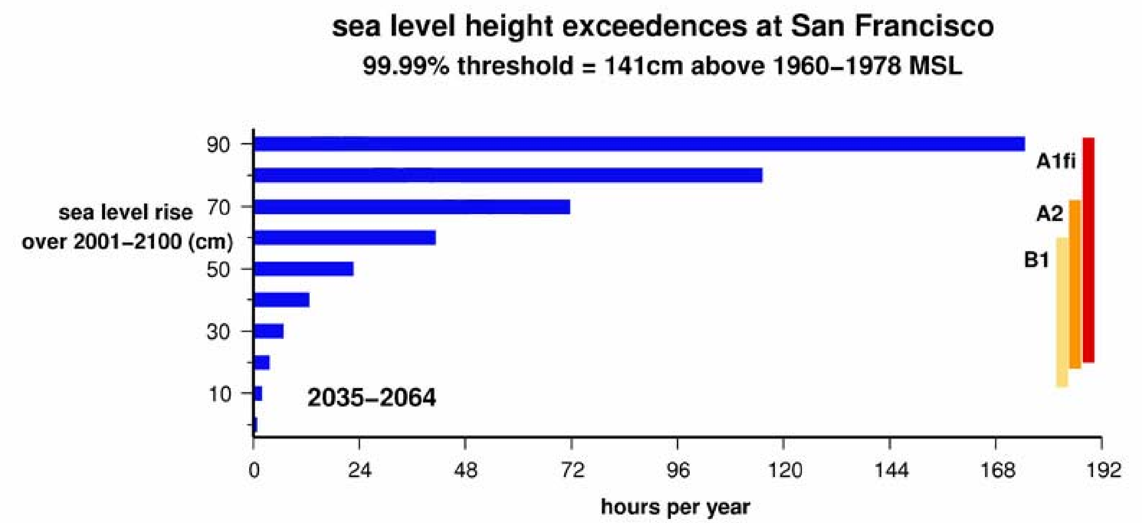


Figure 4. Projected number of hours per year, when San Francisco sea level height (SLH) exceeds 99.99% of its historical threshold

Projected number of hours per year, averaged over 2035–2064, when San Francisco sea level height exceeds historical (1960–19780 99.99 percentile observed threshold. Estimates are calculated from GFDL model weather and ENSO variability superimposed on predicted tides and a range of long term sea level rise as approximated by linear trends, from 0 to 90 cm over 2000–2100. Range of trends that have been estimated from climate models is indicated for three different GHG emission scenarios (Cayan et al. 2006b).

Sea level rise also threatens the Sacramento/San Joaquin Delta of the San Francisco Bay estuary. Historically, major floods have produced breaches in levees that protect low-lying, subsiding island tracts in the Delta and riverine and estuarine margins elsewhere, despite many engineered changes to the rivers. As sea levels rise, flood stages in the Delta would be expected to rise also, putting increasingly more pressure on Delta levees. The threats from sea level rise are particularly significant, because as Mount and Twiss (2005) have noted, the forces that rising sea/river levels bring to Delta levees increase as the *square* of the rises, rather than "just" linearly with the rises. Furthermore, the combination of flood and high sea-level stands are particularly dangerous in the Delta, where it is the combination of sea level and river stages that determine the water height. Storms are primary causes of the highest water levels both from barometric and wind effects on the sea levels and from the (freshwater) floods that they can generate. A count of the number of projected extremely high sea level episodes at San Francisco that coincide with potential storm/flood episodes is depicted in Figure 5 by cases when sea level is unusually high and atmospheric surface pressure is unusually low. This simulation indicates that, at least during the earlier decades of the next century, the largest increases in the frequency of extremely high sea level episodes as sea levels rise will coincide with periods of enhanced storm-flood risks.

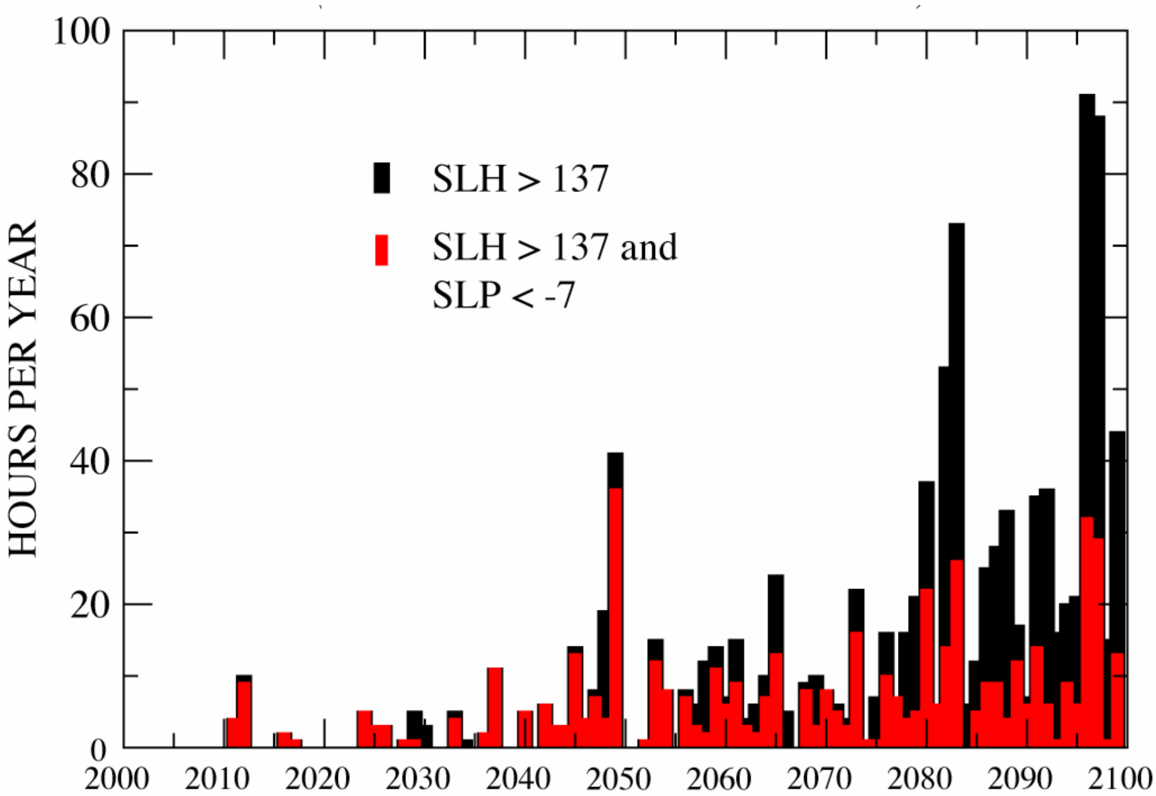


Figure 5. Projected total exceedances of San Francisco hourly sea level height

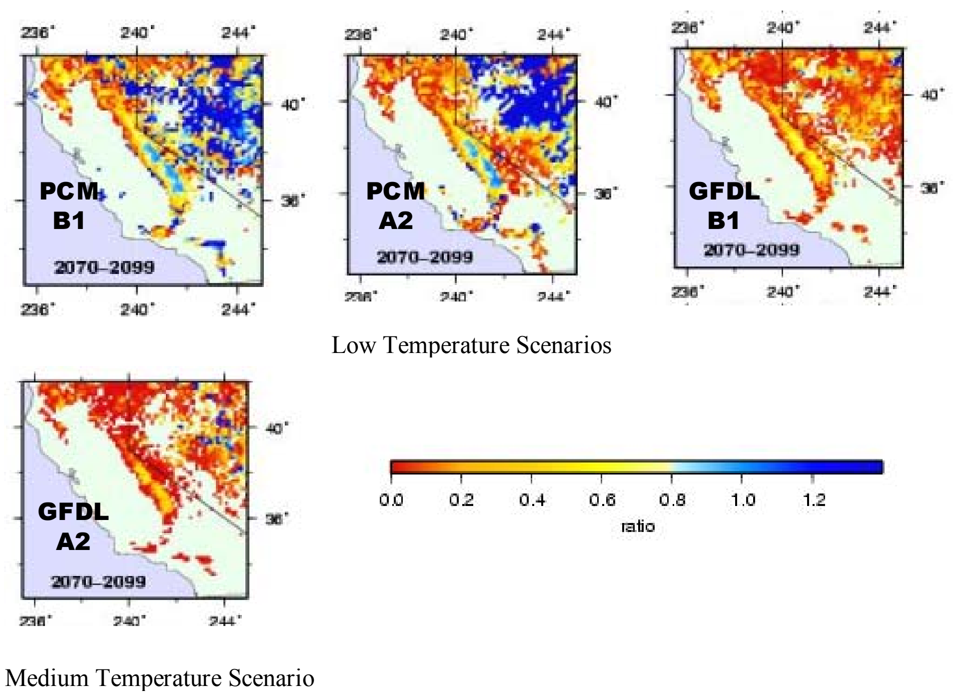
Projected total exceedances of San Francisco hourly sea level height above historical 99.99 percentile (black), and number that are coincident with sea level pressure (SLP) anomalies less than -7 mb. This figure was generated using projected sea level from GFDL model weather and Nino3.4 SST with a linear trend of 30 cm over 2000–2100 (Cayan et al. 2006b).

7.0 Water Resources

Although most climate model simulations project relatively moderate changes in precipitation over this century, rising temperatures are expected to lead to diminishing snow accumulation in mountainous watersheds, including the Sierra Nevada. Warmer conditions during the last few decades across the western United States have already produced a shift toward more precipitation falling as rain instead of snow (Knowles et al. 2005), and snowpacks over the region have been melting earlier in the spring (Mote et al. 2005; Stewart et al. 2005). Delays in snow accumulation and earlier snowmelt will have cascading affects on water supplies, natural ecosystems, and winter recreation.

7.1. Snowpack

The Variable Infiltration Capacity (VIC) distributed land surface hydrology model was used to simulate snowpack throughout the century (Cayan et al. 2006a). Projected reductions in snowpack increase with temperature, with the larger losses of spring snowpack in the higher range of projected warming (Figure 6). Each of the simulations shows losses of spring snow accumulation, largely over the Sierra Nevada, become progressively larger over the twenty-first century. In the Sierra Nevada by the 2035–2064 period, snowpack could decrease 12% to 47% from historical levels under the lower range of projected warming, and decrease 26% to 40% in the higher range of projected warming, with precipitation changes playing a partial role in the reductions for the lower temperature cases. By the end of century, snowpack could decrease by as much as 90% in the higher amount of warming—almost double the losses expected under the lower warming cases.



Source (Cayan et al. 2006a)

Figure 6. April 1 snow water equivalent 2070–2090 fraction of 1961–1990.

7.2. Water Supply

Declining snowpack will aggravate the already overstretched water resources in California. The snowpack in the Sierra Nevada provides natural water storage, equal to about half the storage capacity in California's major human-made reservoirs, holding the winter precipitation in the form of snow and releasing it in the spring and early summer as the snow melts. This loss in storage could mean more water shortages in the futures. However, the full effect of this storage loss will depend in part on whether reservoirs can be managed to capture the earlier snowmelt while not losing flood control capacity or, at the higher elevations, hydropower generation capacity.

Two different methods were used to project the effects of the alternative climate scenarios on water supply. One approach used the VIC model to simulate inflows into major reservoirs in the Sacramento Valley as drivers for their respective water resource management models, CALSIM and CALVIN[3] (Chung et al. 2006; Medellin et al. 2006; Vicuña et al. 2006; Vicuña 2006). The second approach used the Water Evaluation and Planning (WEAP) system (Joyce et al. 2006).

These two approaches differ in how they process the climate change scenarios.[4] Under most scenarios, both modeling approaches project streamflows to decrease slightly by mid-century, with more dramatic changes by the end of the century. Flows into the major Sierra Nevada reservoirs could decline between 25%–30% under the medium range of projected warming and the simulated decline in precipitation—almost double the decrease projected under the lower range of projected warming. However one model run produces a slight increase in precipitation and a corresponding rise in projected streamflows.

The Sacramento Four River Index (also called the *Sacramento 40-30-30 Index*) was used to classify the probability of water year types under the different climate change scenarios.[5]

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[3] CALSIM was used to assess hydrologic impacts in the Central Valley; CALVIN also covers the portions of the state outside the Central Valley

[4] CALSIM and CALVIN require as input a given time series of monthly stream flows—both use a modified version of the historical stream flow over the period 1922–1994. Climate change is incorporated into the given historical series by the "perturbation ratio" method: for a given time period of interest (2035–2064 or 2070–2099), a given stream location, and a particular month, one computes the average ratio of the VIC streamflow in that month over the period of interest to the VIC streamflow for the corresponding month over a base period (1961–1990). The monthly ratios are then used to adjust, or "perturb," the monthly stream flows in the historical series 1922–1994. In contrast, the WEAP approach uses raw time series of precipitation and temperature in a watershed hydrology model and directly generates a time series of streamflows. The perturbation approach is tied more closely than the WEAP approach to the historic inter-annual pattern of year-to-year variation in drought and wetness, although both approaches can generate changes in drought persistence.

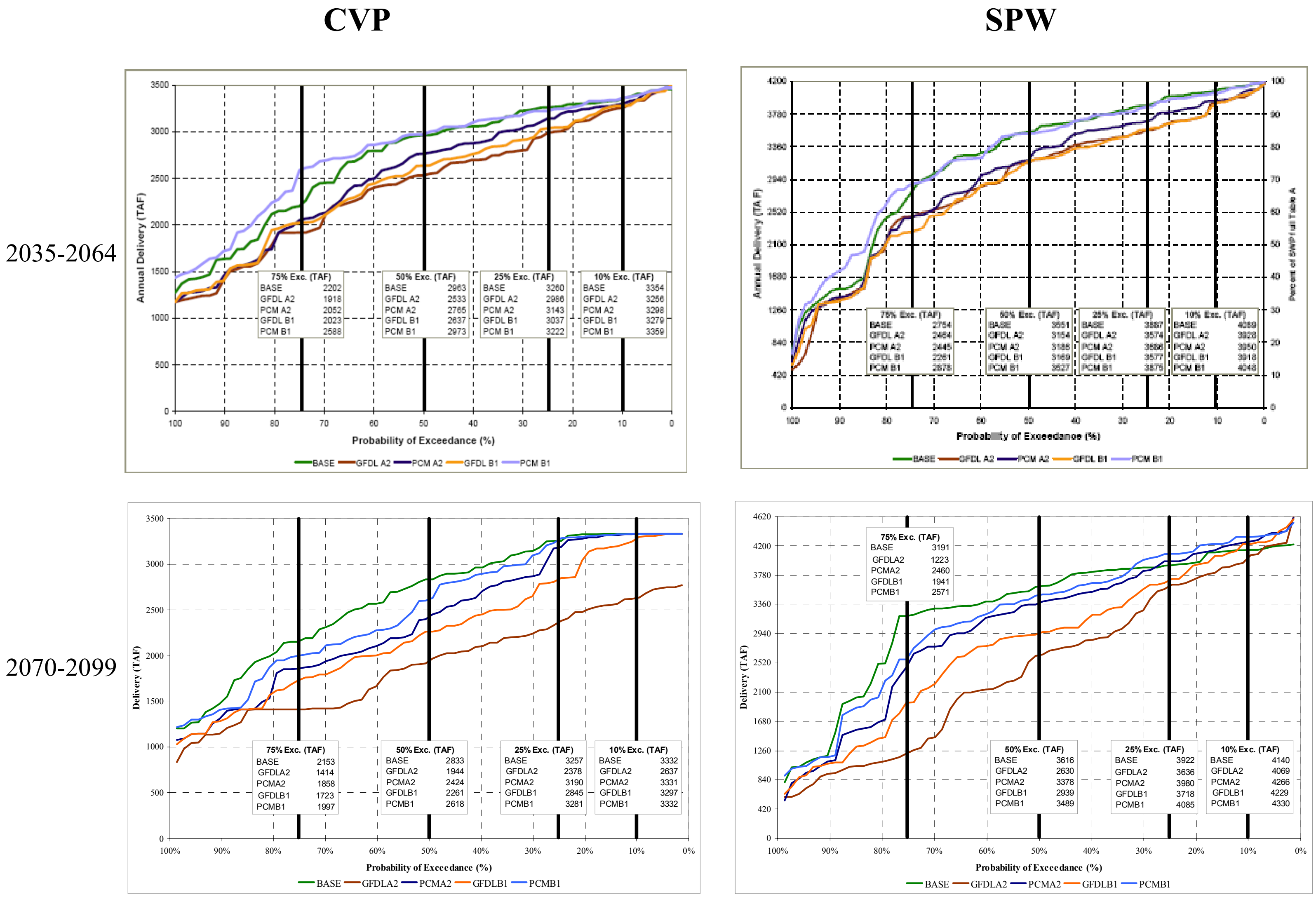
[5] The Sacramento River Index was developed by the State Water Resources Control Board for regulatory purposes, and requires the forecasting by May of each year of the current year's April–July unimpaired runoff in the Sacramento Valley. When a retrospective analysis is conducted using the historical hydrology, as here, the actual April–July runoff is known, but not the prospective forecast, and therefore the index cannot be calculated in exactly the same way. The research here uses the Brekke et al. (2004) retrospective approximation for calculating the index.

This river index classifies the years into five categories: Wet, Above Normal, Below Normal, Dry, and Critical. Because the River Index pays greater attention to the aggregate stream flow then the timing of flow, it is more influenced by changes in precipitation then temperature. The projections for the less dry model (PCM) indicate that toward the end of the century, under the higher-emissions scenario, up to 50% of the years between 2070–2099 could be critically dry years, as compared to 18% in the historical period (Vicuña 2006; Hayhoe et al. 2004). Under the lower-emissions scenario in the less-dry model, little or no change in the frequency of critically dry years is expected. In contrast, from the projections using the drier models (HadCM3 and GFDL), even under the lower-emissions scenarios the frequency of critically dry years would increase, up to twice as often as historical conditions.

CALSIM was used to assess the consequences of the climate change scenarios on carryover storage at CVP and SWP reservoirs and for deliveries to CVP and SWP (Chung et al. 2006; Vicuña 2006). Toward the end of the century, the change in the volume and timing of runoff reduce the ability of the major projects to deliver water to agricultural users south of the Delta. These deliveries fall by 15%–30% under the lower range of projected warming, and 40%–50% under the medium and higher ranges of projected warming (Vicuña 2006) (Figure 7), with the drier model simulations showing the largest decreases. The projected changes in water supply would be further exacerbated by increased demand due to warmer temperatures. By the end of century, warmer temperatures are expected to increase the crop demand between 2% and 13%, in the lower and medium warming cases, respectively; there could be a similar effect on urban demand for outdoor lawn watering (Baldocchi et al. 2006).

7.3. Winter Recreation

Declines in Sierra snowpack will also have widespread implications for winter tourism. Warming could affect the starting and closing dates of the ski season. Toward the end of the century, in lower temperature scenarios, the ski season at lower and middle elevation settings could shorten by as much as a month, while projected climatic changes under the higher temperature scenario suggest that the minimum snow conditions for ski resort operation might never occur, and resorts would be forced to rely entirely on snowmaking or move their operations (Hayhoe et al. 2004).



(Chung et al. 2006; Vicuña 2006)

Figure 7. Exceedance probability plot for Central Valley Project and the State Water Project

7.4 Potential Strategies for Reducing the Impacts on Water Resources

To compensate for the loss of natural storage in the snowpack, the existing man-made storage capacity will have to be managed more effectively, and also augmented. Modern probabilistic seasonal and short-term hydrology forecasting methods and more sophisticated decision algorithms could help reservoir managers better balance the competing demands of storage for water supply, hydropower, and flood control (Yao and Georgakakos 2001).[6] Besides this, it is likely that some form of additional storage will eventually be needed, whether above ground or below ground in the form of enhanced conjunctive use. More generally, it is likely that a portfolio of adaptation responses will be needed, including more conservation and increased efficiency in water use. The transmission systems for moving water around the state will also need to be both firmed up (to protect against seismic risks in the Delta, for example) and also enhanced to provide greater flexibility and connectivity in meeting water users' demands.

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[6] A demonstration project is underway with funding from the CALFED Bay-Delta Program, the National Oceanic Atmospheric Administration (NOAA), and the Public Interest Energy Research Program (PIER). If that project is successful, it will pave the way for the operational use of these new management tools.

8.0 Agriculture

Agriculture, along with forestry, is the sector of the California economy that is most likely to be affected by a change in climate. California agriculture is a $68 billion industry.[7] California is the largest agricultural producer in the nation and accounts for 13% of all U.S. agricultural sales, including half of the nation's total fruits and vegetables. Regional analyses of climate trends over agricultural regions of California suggest that climate change is already in motion. Over the period 1951 to 2000, the growing season has lengthened by about a day per decade, and warming temperatures have resulted in an increase of 30 to 70 growing degree days per decade, with much of the increase occurring in the spring (Feng and Hu (2004). Climate change affects agriculture directly through increasing temperatures and rising CO_2 concentrations, and indirectly through changes in water availability and pests.

8.1. Temperature

Temperature influences crop growth through its impact on photosynthesis and respiration, as well as on growing season length and water use. Temperature also serves as a controlling factor for developmental processes, such as flowering and fruit maturation, which may be threatened if lengthening of the growing season introduces asynchrony between the timing of flowering and the life cycle of important insect pollinators.

Crop growth models show that a warming from a low to a higher temperature generally raises yield at first, but then becomes harmful (Doering et al. 2002). Possible effects of excessively high temperature include: decreased fruit size and quality for stone fruits, premature ripening and possible quality reduction for grapes, reduced fruit yield for tomatoes, increased incidence of tipburn for lettuce, and similar forms of burn for other crops. For example, rising temperatures are likely to produce adverse effects on quantity and quality for a number of California's agricultural products. For example, milk production has been found to decline when temperatures rise above 25°C (77°F), and Hayhoe et al. (2004) projected that in California milk production could decline up to 20% if temperatures rise to the higher warming range. Hayhoe et al. (2004) also projected a decline in wine grape quality as a result of increasing temperatures, where grapes in the major wine growing regions were expected to shift from optimal quality to marginal or impaired as temperatures rise to the higher warming range. Similarly, Baldocchi and Wong (2006) found that as temperatures rise from to the lower and medium warming ranges the number of chill hours declines, threatening the future viability of many species of fruit trees in the state.[8]

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[7] This is the 1998 figure for the total sales of agricultural and processing products in California (Kuminoff et al. 2001).

[8] Tree crops have become an increasingly prominent part of Central Valley agriculture over the three decades; the economic cost associated with the loss of a tree crop due to extreme weather conditions is likely to be significantly larger than that associated with the loss an annual field crop.

8.2. Carbon Dioxide (CO_2)

From a variety of studies in the literature, photosynthesis increases when a plant is exposed to a doubling of CO_2. However, whether this translates into increased yield of economically valuable plant product is uncertain and highly variable. Also, elevated CO_2 levels are associated with decreased concentrations of mineral nutrients in plant tissues, especially a decrease in plant nitrogen, which plays a central role in plant metabolism. Some crops may benefit in quality from an increase in CO_2; for example the fruit flavor of strawberries improves. Some crops are harmed by an increase in CO_2—for example grain protein in crops decreases and, in the case of wheat, breadmaking quality decreases (Cavagnaro et al. 2006).

8.3. Pests and Weeds

Growth rates of weeds, insect pests, and pathogens are also likely to increase with elevated temperatures, and their ranges may expand. A relatively new area of research involves the use of physiologically based dynamic models to fully understand the effects of weather (e.g., temperature, rainfall, solar radiation) on species dynamics. Gutierrez et al. (2006) used a dynamic model to estimate the potential impacts of a pest (pink bollworm, PBW) on cotton cultivation in the state. At the present time this pest is of importance only in the southern desert valleys (e.g., the Imperial and Coachella valleys), because winter frost restricts PBW's invasion to the million acres of cotton grown in the San Joaquin Valley. However, if winter temperatures rise by 2°C to 2.5°C (3.6°F to 4.5°F), as projected under the medium- to higher ranges of projected warming, the distribution of PBW would likely expand northward (Figure 8).

8.4. Potential Strategies for Reducing the Impact on Agriculture

Because of the greater priority being given to urban users in the event of water shortage, the agricultural sector is likely to bear a disproportionate share of water scarcity due to any climate-induced reduction in surface water supply. Farmers will likely respond by increasing their pumping of groundwater where this is available, shifting to higher value/less water-using crops, adopting higher efficiency methods of irrigation, and fallowing some farmland. Over time, new seed varieties could be developed that are better adapted to the changed climate and pest conditions, and entirely new crops may be found to meet pharmaceutical or energy supply needs. However, some of these adaptations may require publicly supported research and development if they are to materialize.

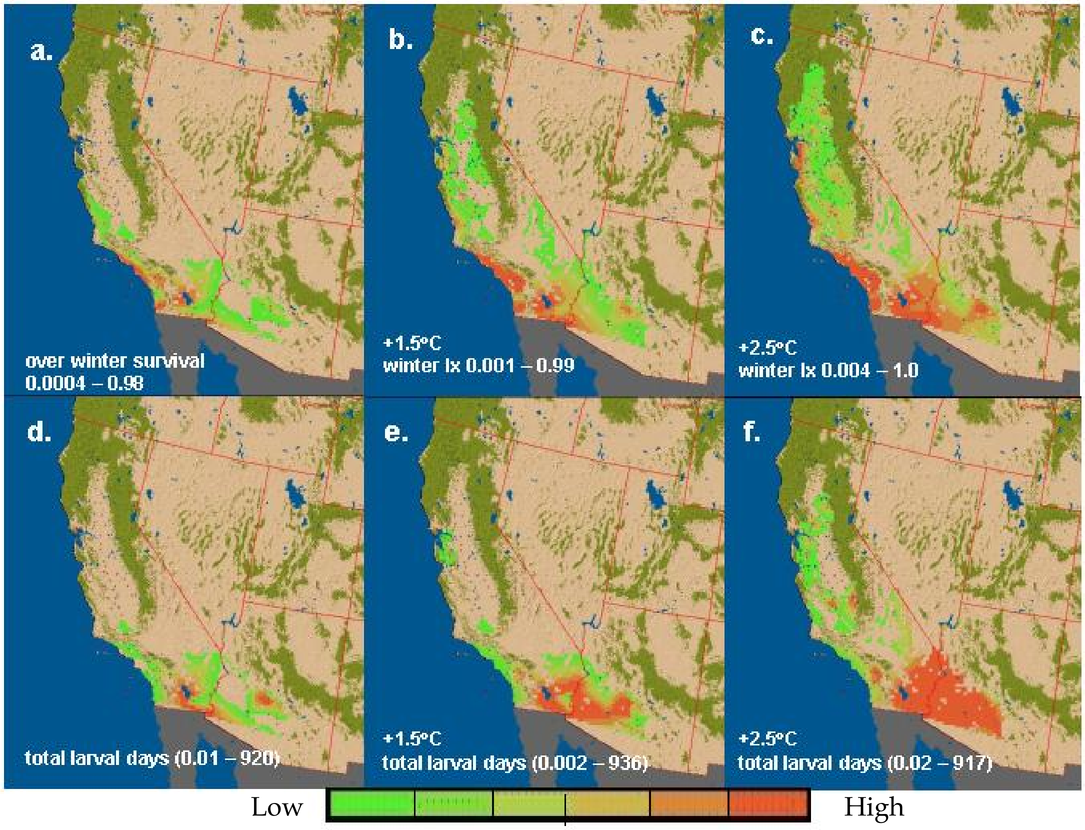


Figure 8. Cotton/pink bollworm (PBW): Predicting areas of favorableness

The effects on winter survival (a-c) and total seasonal pest PBW larval densities (larval days, d-e) under current weather (a,d) and with 1.5ºC (2.7ºF) (b,e) and 2.5ºC (4.5ºF) (c,f) increases in daily temperatures respectively (Gutierrez et al. 2006).

9.0 Forests and Natural Landscapes

Climate changes and increased CO_2 concentrations are expected to alter the extent and character of forests and other ecosystems (Field et al. 1999; McCarty et al. 2001; Aber et al. 2001). The distribution of species is expected to shift; the risk of climate-related disturbance such as wildfires, disease, and drought is expected to rise; and forest productivity is projected to increase or decrease—depending on species and region. In California, these ecological changes could have significant implications for both market (e.g., timber industry, fire suppression and damages costs, public health) and non-market (e.g., ecosystem services) values.

9.1. Natural Landscapes

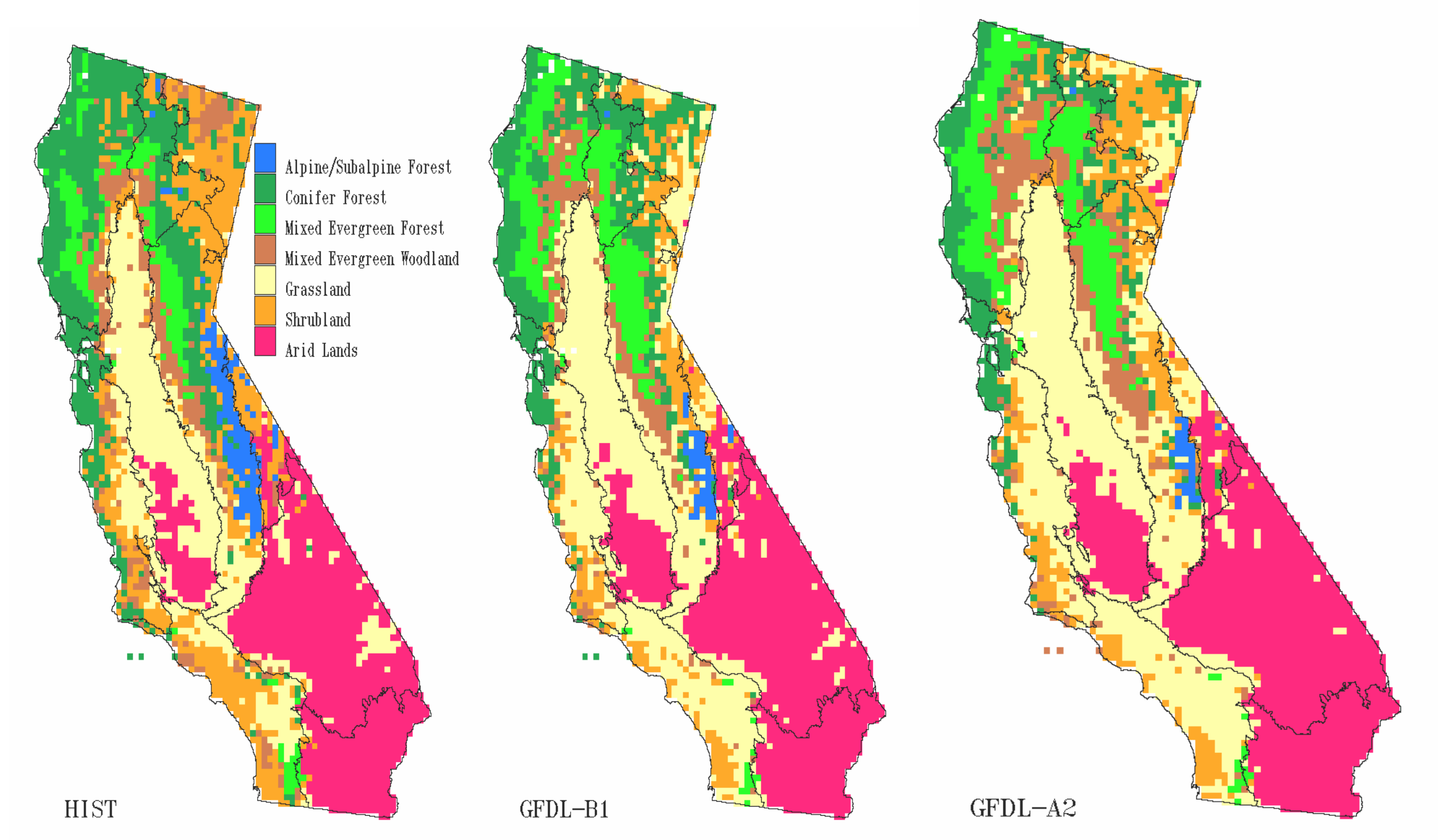
Lenihan et al. (2006) used the MC1 Dynamic Vegetation Model to simulate the response of vegetation distribution and ecosystem productivity to observed historical climate and to project the response to several scenarios of potential future climate change for California (Lenihan et al. 2006; Hayhoe et al. 2004). MC1 simulates lifeform mixtures and vegetation types; ecosystem fluxes of carbon, nitrogen, and water; and fire disturbance. The MC1 projections indicate that the ecosystems most susceptible to temperature rise are the alpine and subalpine forest cover. In addition, changes in fire frequency are expected to contribute to an increase in the expanse of grasslands, largely at the expense of woodland and shrubland ecosystems (Figure 9).

9.2. Wildfires

Fire is an important natural disturbance within many California ecosystems that promotes vegetation and wildlife diversity, releases nutrients and eliminates heavy fuel accumulations that can lead to catastrophic burns. The changing climate could alter fire regimes in ways that could have social, economic, and ecological consequences (McKenzie et al. 2004; Fried et al. 2004; Brown et al. 2004).

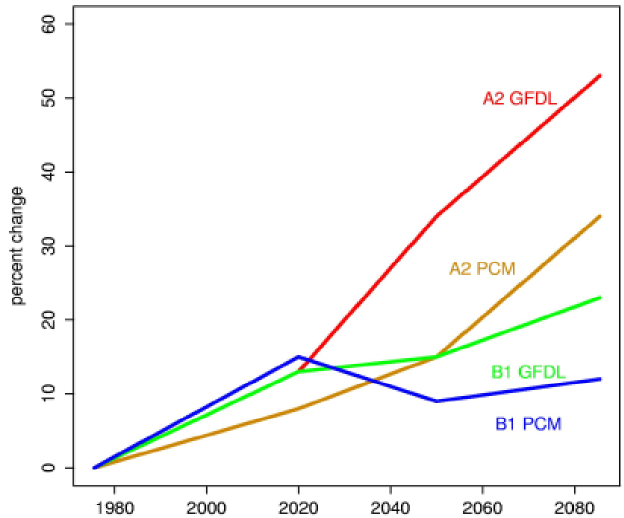
Westerling and Bryant (2006) estimated future statewide wildfire risk from a statistical model based on temperature, precipitation, and simulated hydrologic variables. These are conservative estimates because they do not include effects of extreme fire weather, but implications are nonetheless quite alarming. Projections made for the probabilities of "large fires"—defined as fires that exceed an arbitrary threshold of 200 hectares (approximately 500 acres)—indicate that the risk of large wildfires statewide would rise almost 35% by mid-century and 55% by the end of the century under a medium-high emissions scenario, almost twice that expected under lower emissions scenarios (Figure 10). Estimates of increased damage costs from the increases in fire season severity (Westerling and Bryant 2006) are on the order of 30% above current average annual damage costs.

A second study explored, through a case study in Amador and El Dorado Counties, the effects of projected climate change on fire behavior, fire suppression effort, and wildfire outcomes (Fried et al. 2006). Climate and site-specific data were used in California Department of Forestry and Fire Protection (CDF) standard models to predict wildfire behavior attributes such as rate of spread and burning intensity. The predicted wildfire



(Lenihan et al. 2006)

Figure 9. Vegetation distribution under historical conditions and multiple climate change scenarios at end of century



(Source: Westerling and Bryant 2006)

Figure 10. Percent change in the expected minimum number of large fires per year in California

outcomes were aggregated using the California Fire Economics Simulator version 2 (Fried and Gilless 1999), a stochastic computer model developed for CDF's fire protection planning program. The study found an increase in the projected area burned (10%–20%) and number of escaped fires (10%–40%) by the end of century, under the drier climate scenarios (GFDL). However, the less dry model showed little change.

Neither of these approaches for modeling the effects of climate change on wildfires considers the effects of the potential changes in wind conditions that may result from a changing climate, because the winds produced by GCMs are too coarse to be useful over most of the complex terrain in the California region. However, the strength and direction of winds can greatly influence fire behavior (Fried et al. 2004). Although initial studies suggest that future climate change may decrease early fall Santa Ana Wind conditions in some regions (Miller and Schlegel 2006), further research is needed to more thoroughly characterize potential changes in wind conditions and their possible effects on wildfires in the state.

9.3. Pests and Pathogens

Pests and disease have historically had a significant effect on California forests. The changing climate may exacerbate these effects, by expanding the range and frequency of pest outbreaks. For example, the introduced pathogen, pine pitch canker (*Fusarium subglutinans* f. sp. *pini*), once limited to coastal areas of California has expanded to the El Dorado National Forest in the Sierra Nevada. Rising winter temperature in the Sierra Nevada would make conditions more favorable for pitch canker, and could result in increased disease severity and economic loss (Battles et al. 2006).

9.4. Forest Productivity

Past studies project increases in forest productivity with continued climatic change (Mendelsohn 2003; Lenihan et al. 2003). However increasing evidence suggests that given the uncertainties concerning how trees will respond to elevated CO_2 concentrations (Körner et al. 2006), and the increased risk and susceptibility to catastrophic loss, the implications for the forest productivity and the timber industry may be less optimistic.

The recent assessment by Battles et al. (2006) of the expected impacts of climate change on the California forest sector used an industry standard planning tool to forecast 30-year tree growth and timber yields for forest stands in El Dorado County under a high and medium level of projected warming. Conifer tree growth was reduced under all climate change scenarios. In the medium level of projected warming, productivity in mature mixed-species stands was reduced by 20% by the end of the century. The reductions in yield were more severe (30%) for pine plantations.[9] Projections further indicate that the reduced growth rates could lead to substantial decreases in tree survival rates.

9.5. Potential Strategies for Reducing Impacts on Wildfire Risk and Forestry

Existing fire management strategies will be severely challenged by the interacting effects of expected changes in population and land use, and the projected changes in wildfire frequency and severity resulting from climate change. However, there are actions that can be taken in the near-term to improve our ability to live within California's fire-prone landscapes, while maintaining the functioning and structure of the ecosystems upon which we depend. For example, Moritz and Stephens (2006) suggest: (1) the adoption of a risk-based framework for fire management; (2) the reintroduction of fire to fire-prone ecosystems; (3) the creation of flexible policies that differentiate between the diverse ecosystems in California; and (4) a reevaluation of building and land use planning in the wildland-urban interface.

Battles et al. (2006) point to a number of strategies to offset declining forest yields. For example, silvicultural treatments could be designed to compensate growth losses to climate change with improvements in stand conditions. Planting mixtures of species, maintaining several age classes, reducing tree density, and pruning trees at strategic intervals are examples of cultural practices that could improve timber yields. Retaining a mixture of species and ages in the mixed conifer forests may alleviate some of the risks associated with the projected climatic changes. Single-species stands are at most risk. Spatially mixed forests limit the spread of both pathogens and insects. Decreasing tree densities reduce fuel loads and competition, and promote structures that are more resilient to catastrophic events like fire and epidemics.

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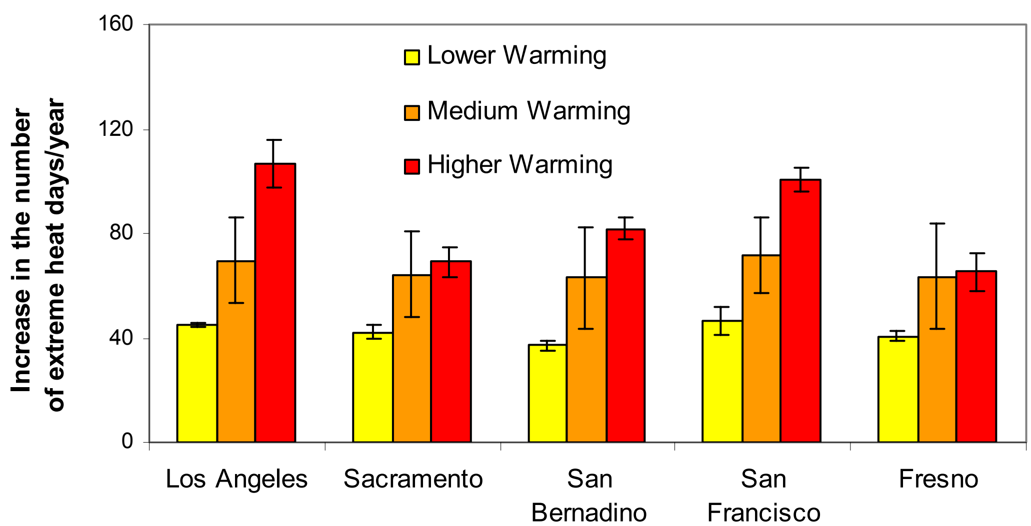
[9] The projections do not consider possible changes in vegetation distribution over the time period. However, Lenihan et al. (2006) analysis suggests that the composition for the study site considered in this study is expected to change very little over the next century.

10.0 Public Health

Climate change will affect the health of Californians by increasing the frequency, duration, and intensity of conditions conducive to air pollution formation, oppressive heat, and wildfires. The primary concern is not the change in average climate, but rather the projected increase in extreme conditions that are responsible for the most serious health consequences. In addition, climate change has the potential to influence asthma symptoms and the incidence of infectious disease.

10.1. Heat-related Deaths

Analyses of various climate change scenarios indicate that the future will have a greater number of extremely hot days and fewer extremely cold days, which may lead to two to six times as many heat-related deaths for the five cities studied (Drechsler et al. 2006). For the higher range of projected warming, the number of days over 31°C (90°F) in Los Angeles and over 35°C (95°F) in Sacramento will increase by up to 100 days by the end of the century—a striking increase over historical rates of occurrence, and almost twice the increase projected under the low-temperature path (Drechsler et al. 2006) (Figure 11).



(Source: Drechsler et al. 2006)

Figure 11. Projected increase in the number of extreme heat days relative to 1961–1990. *Extreme heat* is defined as the average temperature that is exceeded less than 10% of the days during the historical period (1961–1990), or approximately 36 days a year.

Individuals likely to be most affected include the elderly, the already ill, and the economically disadvantaged (CDC 2005a,b; Kilbourne 2002; Kaiser et al. 2001). Other identified risk factors for temperature-related health effects include social isolation, not leaving the home daily, and for heat-related death, living on the upper floors of multi-story buildings (Naughton et al. 2002). The number of deaths attributed to heat have declined over the past 30 years in the United States, primarily due to the increasing number of households with central air conditioning, which appears to be the strongest protective factor (Davis et al. 2003; Donaldson et al. 2003). Kilbourne (2002) suggested that municipal housing codes be modified to require functional air conditioners in rental housing, in addition to existing requirements for heat. The U.S. Department of Commerce expects that air conditioning will be universal in the United States by 2050 (McGheehin and Mirabelli 2001), which will increase demand for electricity for residential cooling—especially on peak demand summer days in the future. In 2100, California will need at least 10% more electricity, compared to today's total generation capacity, for air conditioning alone on peak demand summer days (Miller et al. 2005). Ongoing studies are investigating the contribution of air pollution increases to deaths attributed to heat and refining the air conditioning demand estimates.

10.2. Air Pollution-related Death and Disease

Californians experience the worst air quality in the nation, with over 90% living in areas that violate either the state ambient air quality standard for ozone or particulate matter (PM) (CARB 2005a). The annual health impacts of these standard violations include 8800 premature deaths (3000–15,000 probable range), or 4% of all death; 9500 (4600–14,000) hospitalizations and emergency room visits; 2,800,000 (2,400,000–3,200,000) lost work days; and 4,700,000 (1,200,000–8,600,000) school absence days (CARB and OEHHA 2002, 2005; CARB 2005b). An annual value of $2.2 billion ($1.5–2.8 billion) is associated with hospitalizations and the treatment of major and minor illnesses related to air pollution exposure in California (CARB 2005b). In addition, the value of premature deaths resulting from exposure to air pollution in excess of the state's PM and ozone standards is $69 billion ($34–133 billion) (CARB 2005b). Current motor vehicle and industry control programs cost about $10 billion per year.[10] Ozone (from the precursors methane and nitrogen oxides, NO_X) and PM (especially elemental carbon), and to a lesser extent carbon monoxide and volatile organic compounds (VOCs), contribute to climate change (IPCC 2001).

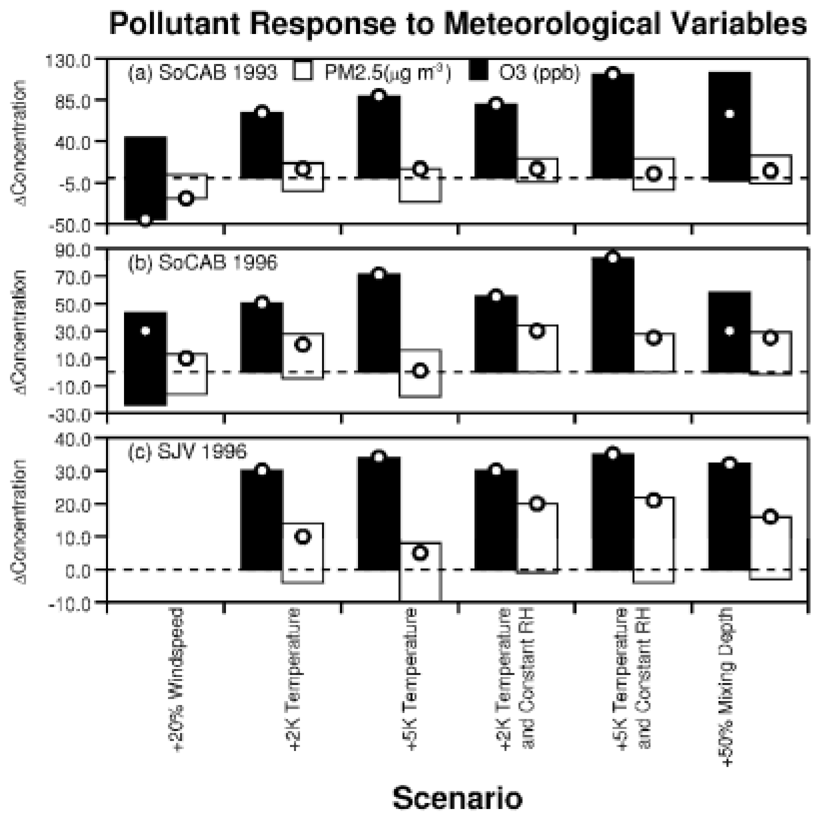
Two recent reports from the National Research Council of the National Academies note that higher temperatures lead to increased emissions and formation of air pollution (NRC 2001, 2004). Maximum ozone levels are about double the current air quality standards and climate change will slow progress toward attainment by increasing emissions, accelerating chemical processes, and increasing summertime stagnation episodes. Model estimates of the effect of altered climate applied to current (2005) pollutant emission patterns show that temperature alone may alter emissions. For the medium-high emissions scenario, summer-time on-road VOC emissions from motor vehicles for the 2005 baseline are estimated to increase by 4% to 5% using temperature

[10] The nationwide annual cost for air pollution control in 2000 was estimated to be $44 billion in 1986 dollars (USEPA 1991). Between 1986 and 2000, nationwide control costs grew about 3.85% annually. Assuming that control costs continued to grow at the same rate from 2000 to 2004, the annual control cost in 2004 is estimated to be about $53 billion in 1986 dollars. Using the Consumer Price Index (CPI), the nationwide annual cost of air pollution control is estimated to be $88 billion in 2004 dollars (the 2005 CPI is not yet available). Assuming California accounts for 12% of this expenditure (proportional to its population), the annual cost of air pollution control for California is about $10 billion.

projections for mid-century and by 13% to 16% for end-of-century temperature projections (Drechsler et al. 2006). These estimates also suggest small decreases in NO_X (Drechsler et al. 2006). Estimates for the low-emissions scenario are similar for mid-century and less than half for 2100. The medium-high emissions scenario results in a positive feedback loop for GHG emissions from on-road motor vehicles, with 4% to 5% increase in methane and 8% to 9% increases in CO_2 by 2100. These emissions estimates are strictly a test of sensitivity to temperature, as they do not take into account future changes in motorist behavior (e.g., increased air conditioning usage or increased miles driven), future growth in the number of vehicles or changes in the fleet mix, future emission controls, or possible technological advances in vehicle design. Constable et al. (1999) estimate that a doubled CO_2 atmosphere will result in a doubling of national biogenic VOC emissions. While California power plants are well controlled, higher temperatures lead to increased NO_X emissions (3% per ˚F, or 1.8% per ˚C) due to increased air conditioning usage (Drechsler et al. 2006).

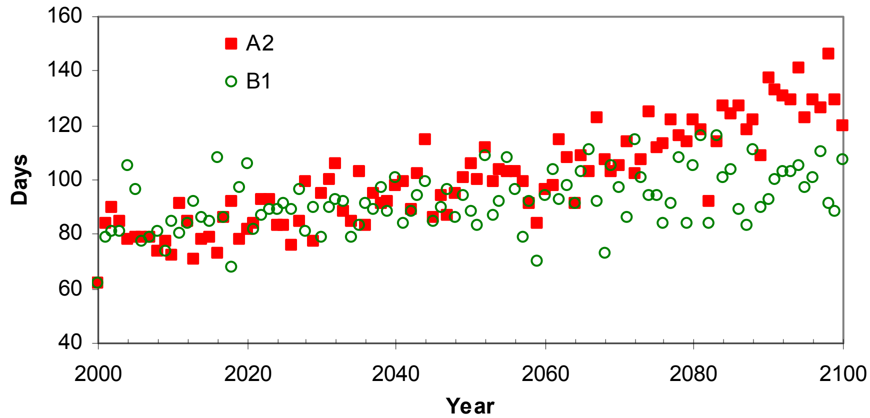
A sensitivity study of three air pollution episodes in the South Coast Air Basin and San Joaquin Valley (Kleeman and Cayan 2006) found that increased temperatures favor the formation of ozone but discourage the formation of ammonium nitrate (a major component of PM). The decrease in PM caused by increased temperatures will be offset by other factors, most notably the increase in background ozone concentrations. The IPCC (2001) estimates that global background ozone concentrations could increase to 40–80 ppb by the year 2100 (up to double the current background value), largely due to emissions outside of California. Background ozone strongly contributes to the nighttime formation of particulate nitrate through the production of N_2O_5 in the upper atmosphere during the evening hours. A preliminary study by Kleeman and Cayan (2006) suggests that if global background ozone levels double, there would be an increase in $PM_{2.5}$ concentrations in California (Figure 12), despite the corresponding increase in temperature. Increased humidity also favors the formation of ozone and ammonium nitrate. Increased wind speed reduces ozone and PM concentrations by enhancing dilution of precursor emissions. Increased mixing depth also reduces PM concentrations, but leads to an increase in surface ozone concentrations because less NO_X is available to titrate the ozone that is produced aloft and mixed to the surface. The converse would be true for lowered wind speeds and mixing heights.

Statistically downscaled climate data from two simulations of one global climate model (GFDL) using two global emissions scenarios (a medium-high (A2) and a lower (B1) scenario), indicates that the number of days meteorologically conducive to pollutant formation could rise by 75% to 85% in the high ozone areas of Los Angeles (Riverside) (Figure 13) and the San Joaquin Valley (Visalia, the high ozone area downwind of Fresno) by the end of the century under a medium-high emissions scenario, but only 25% to 35% under the lower emissions path (Kleeman and Cayan 2006). In addition, global background ozone (primarily formed from the GHG methane and NO_X from fuel combustion) is projected to increase by 4-10 ppb (low scenario) to more than 20 ppb (high scenario) at 2100 (Prather et al. 2003). If background ozone increases by the amount projected for the high scenario, the state 8-hour-average ozone air quality standard of 70 ppb would be impossible to attain in much of California, even with near-zero local emissions. The future trend for PM is not as clear, because increasing temperatures reduce some particle types while others show no change or increase slightly. Rainy days, wildfires, global dust storms, humidity, and other factors also affect PM, and are the subject of ongoing study (Kleeman and Cayan 2006).



(Source: Kleeman and Cayan 2006)

Figure 12. Summary of pollutant response to meteorological perturbations when background ozone concentrations are doubled to 60 ppb during pollution episodes that occurred in: (a) Southern California on September 9, 1993; (b) Southern California on September 25, 1996; and (c) the San Joaquin Valley on January 6, 1996. The bars represent the range of concentration change at any location in the modeling domain in response to the indicated perturbation. The circles represent the concentration change at the location of the maximum concentration for each pollutant.



(Source: Kleeman and Cayan 2006)

Figure 13. Projected days at Riverside meteorologically conducive to exceedances of the 1-hour California ambient air quality standard for ozone of 0.09 ppm.

10.2.1. Wildfires

Wildfires affect public safety and have the potential to significantly impact public health through their smoke. For example, a survey of 26% of all tribal households on the Hoopa Valley National Indian Reservation in northern California showed a 52% increase in medical visits for respiratory problems during a large fire in 1999, compared to the same period of 1998. More than 60% of those surveyed reported an increase in respiratory symptoms during the smoke episode, and 20% continued to report increased respiratory symptoms two weeks after the smoke cleared (Mott et al. 2002). The projected increases in fire season severity could lead (Westerling and Bryant 2006) to more "bad air" days. However, quantitative estimation of the impacts of future wildfire events is extremely difficult. The impacts of any fire are unique to that event, and are influenced not only by the magnitude, intensity, and duration of the fire, but also the proximity of the smoke plume to a population.

10.3. Asthma

Another concern of climate change is the effect on asthma prevalence and attacks. This impact is difficult to predict for several reasons. The most common asthma triggers are dust mites and molds, both of which are higher indoors than outdoors. Both require a relatively humid environment for survival. Consequently, if the climate becomes drier, or drought periods increase, these triggers will become less important. However, both will respond to higher humidity with increased growth, and these triggers may become more significant. Many asthmatics are allergic to various plant pollens. Plants and trees typically have pollination seasons that last a few weeks per year. To the extent that pollen seasons lengthen or become more intense in response to climate change, increased asthma exacerbation could result.

10.4. Infectious Disease

Climate change also has the potential to influence the incidence of infectious disease spread by mosquitoes, ticks, fleas, rodents, and food (Colwell and Patz 1998). More study is needed, because research to date has focused on short-term changes in weather patterns (primarily in ambient temperature and rainfall), rather than long-term changes.

10.5. Potential Strategies for Reducing Public Health Impacts

Some of the public health impacts can be reduced through adaptation measures, but costs are significant and special attention will need to be given to those most vulnerable to the health effects. For example, building climate change considerations into efforts to attain the health-based air quality standards will be necessary in the long-term if the standards are to be met. In addition, heat emergency action plans can help reduce those affected by extreme heat waves (Bernard and McGeehin 2004). Chicago and Milwaukee have developed effective heat emergency plans that could serve as models for California. In both cities, heat-related death rates were considerably lower during the 1999 heat wave, during which the action plans developed in response to the 1995 heat wave were activated (Naughton et al. 2002; Weisskopf et al. 2002). However, Bernard and McGeehin (2004) reviewed heat emergency plans from 18 cities, and found that many plans were inadequate, and that many other at-risk cities had no heat emergency action plans. These findings point to the urgency of developing heat emergency action plans for California before the need arises, and the inclusion of objective criteria for assessing the effectiveness of the plans.

11.0 Electricity Generation and Demand

Changes in temperature and other meteorological variables will affect both the generation of and demand for electricity. The demand for natural gas to warm our homes and buildings will also be affected, most likely resulting in reduced demand in the winter. This section summarizes what is known about the potential effects of climate change on electricity in California and presents some new results for the climate scenarios discussed in previous sections.

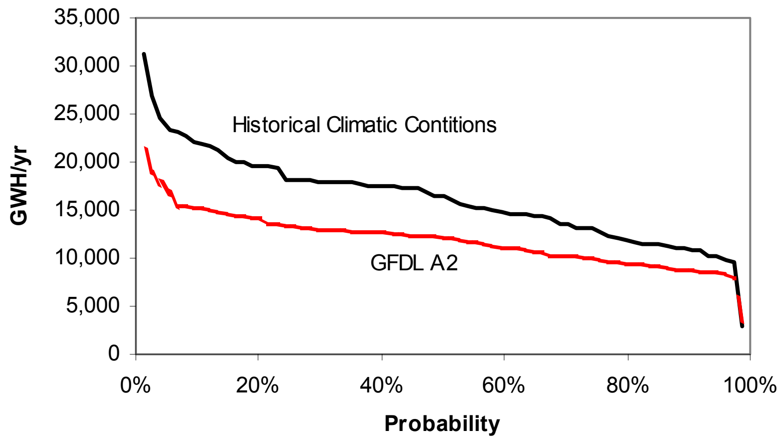
11.1. Electricity Generation: Hydropower

Changes in precipitation levels, should they occur, and changes in the patterns and timing of snowmelt would alter the amount of electricity that hydroelectric facilities could generate. It would also affect seasonal availability, with less water available for hydroelectric generation in the late spring and summer months, when demand is the highest. In addition, there is a high likelihood that changes in precipitation and runoff patterns would lead to changes in broader water policies and end-use priorities, such as water supply and flood control, which could place further limitations on hydroelectric production. Currently, hydropower generation contributes about 15% of California's in-state electricity production, with a range from 9% to 30%, due to variations in climatic conditions. Because it is used predominantly during on-peak periods, hydropower's value outweighs its simple energy contribution. In addition, the state also receives a significant amount of surplus power hydroelectric facilities from the Pacific Northwest, which will also be affected by climate change.

Two recent studies project losses in annual hydropower generation on the order of 10% to 30% by the end of this century, if precipitation levels in California decline (Lund et al. 2003; Vanrheenen et al. 2004). An important caveat about these studies is that they only addressed generation associated with relatively low elevation units, representing about 44% of the total generation capacity from hydropower facilities in the state.

For this study an economic-engineering optimization model of the state water system (CALVIN) was run to estimate the potential impacts of climate change on water resources assuming hypothesized year 2050 level of development with the climate conditions estimated for the end of the century (2070–2099) by the GFDL model for the A2 emissions scenario. As with previous studies, this study indicates that reductions of hydropower generation for relatively low elevation units on the order of 30% would occur, which is a response to a reduction of about 28% in streamflows. Figure 14 presents the frequency distribution of hydropower generation from the major water supply reservoirs modeled in CALVIN. As a point of reference, in the 1990 to 2002 period, California generated from 20,000 gigawatt-hours (GWh) to 51,000 GWh in a given year (Medellin et al. 2006).

Another recent study prepared by the California Department of Water Resources (DWR) used climate projections for the middle of this century (Chung et al. 2006). The DWR modeled the State Water and Central Valley Projects which, as indicated above, represent about 27% of the state's hydroelectric capacity. This study indicates that reductions in electricity generation of approximately 7% would occur for most of lower and medium range of projected warming. However, for the PCM B1 scenario, the least dry scenario, DWR estimated an increase in generation on the order of 4%.



(Source: Medellin et al. 2006)

Figure 14. Probability of producing at a minimum level of generation in a year in major water supply reservoirs modeled in CALVIN: period centered in 2050.

All the studies reported so far address potential impacts on hydropower units that are located in relatively low elevations and served by a large reservoir storage capacity. These can be used to partially offset the trend to an early melting of the snow stored in the Sierra Nevada. Hydropower units in relatively medium and low elevations have little reservoir storage capacity and rely more heavily on the accumulated snow as a natural reservoir. A substantial fraction of the mountain snowpack that supplies water to these units in the spring and summer is located above 1200 meters (3900 feet). This zone is the most vulnerable area to higher temperatures and is expected to experience the most dramatic spring snow losses (Knowles and Cayan 2004). At the present time, the quantitative evaluation of the potential impacts on the medium and high elevation units remains is an unexplored area of study. However, a recent exploratory study of a system owned and operated by the Sacramento Municipal Utility District (SMUD) in the Upper American River Watershed indicates that, as with lower elevation hydro units, electricity generation would go down in response to lower precipitation levels but the existing reservoir system would be able to store enough water to allow generation of electricity in the hot summer months when it is most needed (Vicuña et al. 2006). This occurs despite earlier streamflow runoff caused by climate change. It is unclear how this and other similar systems would respond under scenarios with increased precipitation levels. The most important variables that will determine impacts are storage capacity of the system relative to the volume of stream inflows and the timing of runoff as it compares to the pattern and timing of energy demand.

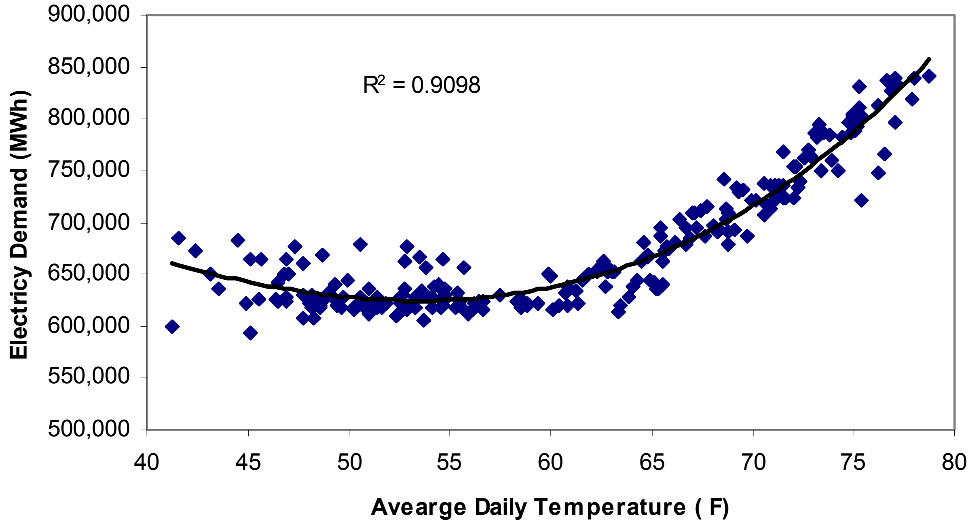
It is important to emphasize that even relatively small changes in in-state hydropower generation result in substantial extra expenditures for energy generation, because this "free" generation must be purchased from other sources. For example, assuming a decrease of 10% from the current average in-state generation level from this renewable energy source, and assuming a price of about 10 cents per kilowatt-hour, this decrease would result in an additional $350 million per year in net expenditures to purchase sufficient electricity to replace the electricity that otherwise would be generated using hydroelectric resources.

11.2. Electricity Demand

One of the few papers that have been published on the potential effect of climate change on electricity demand in California, (Baxter and Calandri 1992) indicates significant increases in electricity requirements. This study was guided by energy forecast models that were developed for or by the Energy Commission to estimate electricity demand taking into account increased population and economic activity. Under their worst-case scenario (a 1.9ºC (3.4ºF) increase), electricity requirements in 2010 would increase by about 7,500 GWh, and would require an additional peak capacity of 2,400 MW. This trend would represent an increase of about 2.6% and 3.7% in energy and peak generation capacity, respectively, from their 2010 base case.

Since it is impossible to know how the energy system and socioeconomic conditions in the state will evolve in the next 100 years, the study described below investigates how future climate projections would affect electricity demand assuming the current infrastructure and demographics. In practice, higher temperatures will increase the penetration of air conditioning units for cooling, but, more important, this approach fails to consider the trend toward more development in the interior parts of California that experience higher temperatures. For these reasons, actual impacts could be higher than what is reported in this section.

Figure 15 shows daily demand of electricity for the area serviced by the California Independent System Operator (CalISO) in 2004 as a function of the simple average of daily temperatures in San Jose, Sacramento, Fresno, and Los Angeles. Figure 15 only includes demand during weekdays, and excludes holidays.

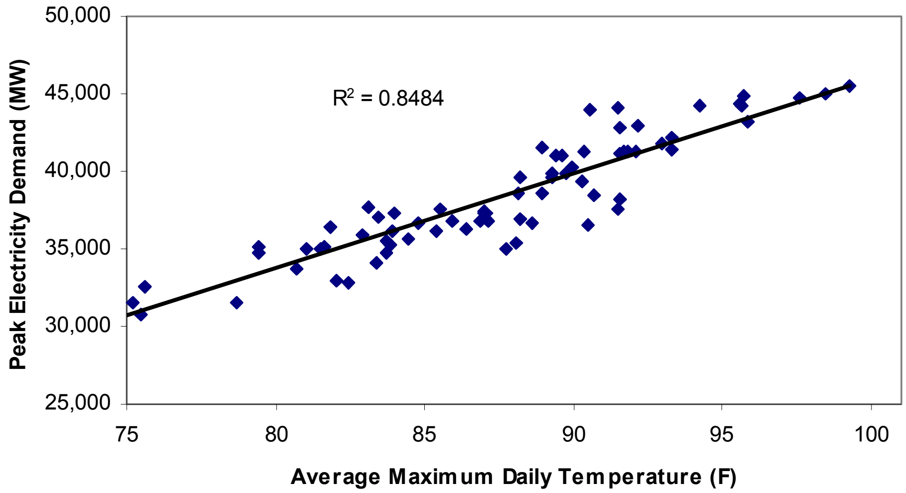


(Source: Franco and Sanstad 2006)

Figure 15. Electricity demand in the CalISO area as function of average temperatures: 2004

Peak electricity demand occurs mostly in the summer months, and it is a strong function of maximum daily temperatures. Figure 16 presents the daily peak energy demand in the CalISO region as function of the average daily maximum temperature measured in San Jose, Sacramento, Fresno, and Los Angeles. It only includes non-holiday weekdays. Electricity consumption during weekends and holidays tends to be lower.

Franco and Sanstad (2006) used these relationships between demand and temperature, to estimate the impact of higher temperatures on annual electricity and peak summer demands (see Table 2). Estimated changes in electricity demand were determined from multiple temperature projections as reported by Cayan et al. (2006a) for grid points close in the cities listed in the previous paragraphs. To calculate changes in peak demand, they used averaged maximum annual temperatures for the periods listed in Table 2.



(Source: Franco and Sanstad 2006)

Figure 16. Peak electricity demand in the CalISO area as a function of maximum daily temperature: June-September 2004

Table 2. Estimated incremental changes in annual electricity and peak load demands for lower, higher, and medium range of projected warming relative to 1961 to 1990 base period

Time Period	Projected Warming Range	Change in Annual Electricity Demand (%)	Change in Peak Demand (%)	Climate Model	Emission Scenario
2005–2034	Low	0.9	1.4	PCM	Low (B1)
		2.5	1.5	GFDL	Low (B1)
		1.2	1.0	PCM	Medium-High (A2)
	Medium	2.9	3.6	GFDL	Medium-High (A2)
	High	3.4	4.8	HadCM3	Higher (A1fI)
2070–2099	Low	3.1	4.1	PCM	Low (B1)
		5.8	7.3	GFDL	Low (B1)
		5.3	5.6	PCM	Medium-High (A2)
	Medium	11.0	12.1	GFDL	Medium-High (A2)
	High	20.3	19.3	HadCM3	Higher (A1fI)

Annual expenditures of electricity demand in California represent about $28 billion (U.S. EIA 2005). Therefore, even the relatively small increases in energy demand shown in Table 2 would result in substantial extra financial expenditures for energy services in the state. For example, assuming a linear increase in electricity expenditures from the recent historical period, a 3% increase in electricity demand by 2020 would translate to about $1.2 billion nominal dollars a year in additional electricity expenditures.

11.3. Potential Strategies for Reducing Impacts on Electricity Sector

The impacts of climate change on the electricity system will depend in part on how the electricity system evolves in the future. For example, an increased penetration of photovoltaic (PV) systems would reduce the impacts of peak demand because this energy source closely matches the diurnal demand for electricity (Borenstein 2005), but other technologies could also be used to satisfy an increased demand. Energy efficiency programs will reduce electricity demand counteracting some of the negative effects of increased ambient air temperatures. Finally, reducing the heat island effect with the use of more reflective surfaces (e.g., for roofs and pavement) and planting trees that provide shade to homes and buildings will also allow the state to better cope with the expected temperature increases.

12.0 Implications for Mitigation and Adaptation

Continued climate change would have widespread impacts on California's economy, ecosystems, and the health of its citizens. The analyses summarized in Figure 17, however, suggest that many of the more severe impacts projected under the medium and higher warming ranges could be avoided by following the lower emissions pathway. However, if the actual climate sensitivity to GHGs reaches the level of the more sensitive global climate models employed here, an even lower emissions path than the B1 scenario may be required to avoid the medium warming range. How much would GHG emissions have to be reduced to stay below the lower emissions pathway (B1) and insure against temperatures rising to the medium and higher warming ranges presented in this study? The Governor's Executive Order #S-3-05 calls for an 80% reduction in GHG emissions below 1990 levels by 2050. If the industrialized world were to follow California's lead, and assuming the industrializing nations followed the B1 pathway, global emissions would remain below the lower emissions scenario (B1),[11] increasing the likelihood that California and the world would be on track to avoid the more severe impacts by preventing temperatures from rising to the medium warming range.[12] This estimate of the impact of an 80% reduction by the industrialized world has on global emissions depends crucially on the development patterns of the developing world. The SRES B1 scenario assumes development proceeds with a "high level of environmental and social consciousness" with a transition to "alternative energy systems" (Nakicenovic et al. 2000). Emission reductions targets such as the one set by the Governor's Executive Order could spur the innovation necessary to lead the world to a transition to alternative energy systems.

However, even if global emissions stay below the lower emissions scenario (B1), some impacts from climate change are inevitable. Evidence indicates that even if actions could be taken to immediately curtail GHG emissions, the potency of GHGs that have already built up, their long atmospheric lifetimes, and the inertia of the Earth's climate system could result in average global temperatures rising an additional 0.6°C (1.1°F) (Wigley 2005; Meehl et al. 2005). As a result, some impacts from climate change, in California and across the globe, are now unavoidable. Consequently, although it is not the solution to global warming, it is becoming clear that adaptation is an essential complementary strategy to manage some of the projected impacts of climate change.

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[11]This was calculated as follows: (1) Organisation for Economic Co-operation and Development (OECD) population and total emissions were based on SRES B1 IMAGINE runs (Nakicenovic et al. 2000). OECD total emission in 1990 were 2.83 GtC; (2) Eighty percent below this value is 566 MtC; (3) Total global emissions was calculated by adding the 566 MtC to the total emissions for non-OECD countries, as projected by SRES B1. This value is approximately 10 GtC; (4) This 10 GtC/yr was compared to the global emission projected in the B1 scenario (approximately 11 GtC/yr).

[12] As illustrated in Figure 1, beyond 2050, global emissions will need to decrease substantially below 10 GtC/yr to stay on the B1 pathway out to the end of the century. The SRES B1 pathway assumes global emissions decrease to 4.23 GtC/yr by 2100. However, stabilizing atmospheric concentrations will require even lower emissions as natural uptake is estimated between 0.7–2.9 GtC/yr (IPCC 2001).

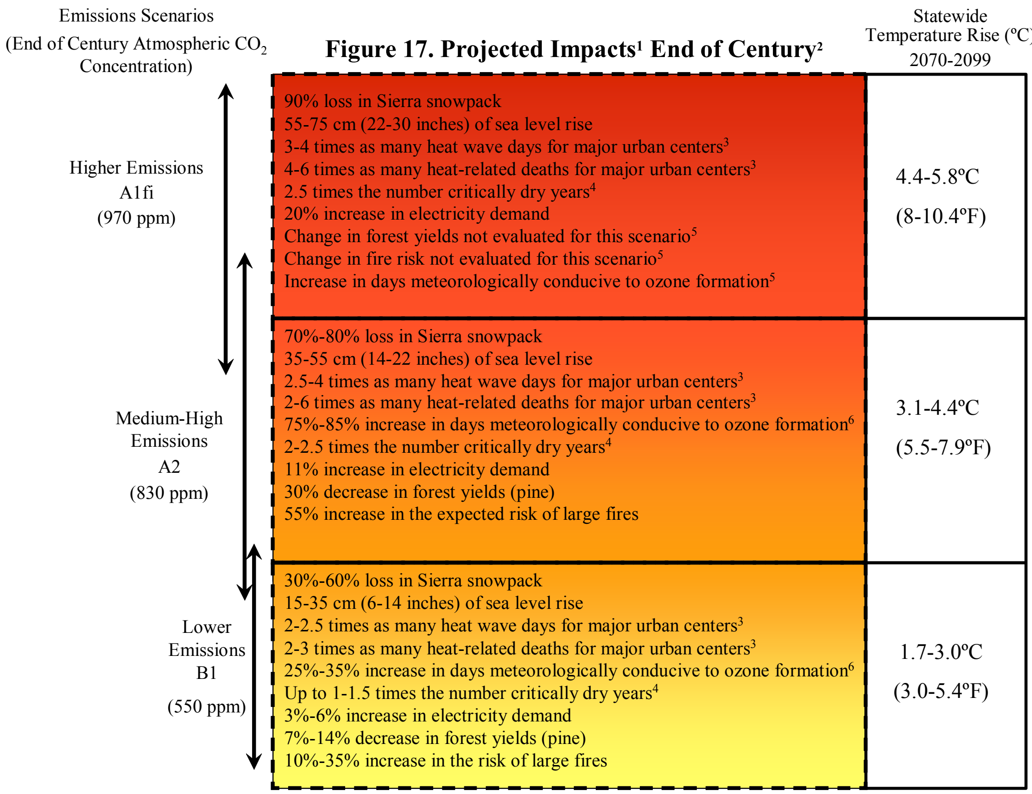

Figure 17. Projected impacts[1] end of 21st century.[2] Impacts presented relative to 1971–2000.

[1] The impacts summarized in this figure reflect projections from different models, based on the current scientific understanding of the relevant social and biophysical processes. Because our scientific understanding is still developing in some key processes that would affect the sectors studied, we provide here some guidance to our levels of confidence of these projections. We assign high confidence to the direction of change in all of impacts described in Figure 17. However, in some sectors we have less confidence in the magnitude of change, because the projections are based on specific assumptions about future development patterns or societal response to projected changes. For example, changes in the number of heat-related deaths could decrease if different assumptions were made about the effectiveness of adaptation measures such as air conditioner use. Furthermore, neither the projection for heat-related deaths nor the projected increases in energy demand take into account population growth, and thus the magnitude of the impact may be significantly higher than the projections presented here. Similarly, the projections for wildfire risk may be conservative, in that they assume constant population and existing vegetation, land-use, and management patterns.

[2] The projected warming ranges presented here are for 2070–2099, relative to 1971–2000. However, some of the impacts summarized in this report used a different historical climatological baseline of 1961–1990. The difference between the 1961–1990 and 1971–2000 baselines leads to a small difference in projected temperature rise for the different scenarios and models. The difference in baselines amounts to approximately a 0.2°C (0.36°F) difference in the full range of projected end-of-century temperature rise.

[3] Los Angeles, San Bernardino/Riverside, San Francisco, Sacramento, and Fresno.

[4] Measures for the San Joaquin and Sacramento basins.

[5] Impacts expected to be more severe as temperatures rise. However, the higher range of projected warming was not assessed for the project.

[6] For high ozone locations in Los Angeles (Riverside) and the San Joaquin Valley (Visalia).

While there are many opportunities for California to increase its capacity to cope with the projected changes, these often can be costly and require time and planning. Furthermore, there are critical limits to adaptation, especially in addressing the threats of abrupt climate changes or in dealing with those impacts on natural, unmanaged species and ecosystems, which may not be able to keep up with the increasingly rapid and severe climate changes expected if emissions go unabated. In addition, managing the impacts of climate change may be particularly challenging when different kinds of changes are experienced together. For example, how would California manage in years where it was subjected simultaneously to an extreme heat wave, an energy blackout, and widespread wildfires, during an extended drought? While at present we are unable to predict the probability and all of the consequences of such an event, in preparing for change we must consider the potential compounding effects of multiple impacts.

Finally, the ability to cope and adapt is differentiated across populations, economic sectors, and regions within the state. As a result, without appropriate mitigating actions, climate change will likely aggravate existing equity issues within California and the rest of the United States. For example, the most vulnerable populations to the health impacts of climate change are children, elderly people, and the poor—the same groups that already face the greatest health and environmental risks.

In order to realize the state's adaptive and mitigative response potential, the state will need to continue to generate public discussion, build awareness, and foster the political will necessary to manage climate change.

13.0 The Need for Climate Change Information for California

There are key unknowns in the cascade of effects of climate change that inhibit better planning and policy actions. For example, better monitoring is needed of California's climate and climate-sensitive sectors to detect and understand a complex chain of impacts. In particular, more work is needed on ecological impacts both in terrestrial and aquatic systems, in the development of more detailed, probabilistic climate projections for the state, and to determine how climate changes and environmentally related policies might impact the California economy, recreation, and tourism. A more comprehensive analysis of the effects of climate change on energy supply and demand, within and outside of California, is needed. The effect of climate change on water resources, including more quantitative understanding of water supply and water demand for the rich complex of agricultural and natural ecosystems in the state is still not well understood. A geographically detailed analysis of the impacts of sea level rise on the California coast and the San Francisco Bay and Delta will be needed to assess potential impacts and conduct planning on local and regional scales. The impact of climate and climate change on temperature-related deaths, air pollutant emissions and quality impacts, and other aspects of human health will require more data and further study. Population growth, urbanization, and technological innovation are among a number of important factors that directly affect these areas. Given the serious potential consequences of climate change on the state's resources, the research community should continue to produce the tools, methods, and information that will be needed to develop robust coping or adaptation strategies in California.

Moreover, additional information is needed to help identify and understand the social and institutional constraints to managing climate change. The international and some national research efforts increasingly have turned away from simple impact assessments towards a "vulnerability" assessment approach that focus on identifying what makes certain populations and sectors susceptible to impacts of climate change. The vulnerability framework considers climate change within the context of multiple interacting stresses—such as population growth, land-use change, and institutional change. California's climate research should begin to include this research framework to identify the most vulnerable populations and regions of the sate, and develop strategies to build their resilience to climate variability and change, and related stresses.

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