

## **Second California Assessment: integrated climate change impacts assessment of natural and managed systems. Guest editorial**

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**Abstract** Since 2006 the scientific community in California, in cooperation with resource managers, has been conducting periodic statewide studies about the potential impacts of climate change on natural and managed systems. This Special Issue is a compilation of revised papers that originate from the most recent assessment that concluded in 2009. As with the 2006 studies that influenced the passage of California's landmark Global Warming Solutions Act (AB32), these papers have informed policy formulation at the state level, helping bring climate adaptation as a complementary measure to mitigation. We provide here a brief introduction to the papers included in this Special Issue focusing on how they are coordinated and support each other. We describe the common set of downscaled climate and sea-level rise scenarios used in this assessment that came from six different global climate models (GCMs) run under two greenhouse gas emissions scenarios: B1 (low emissions) and A2 (a medium-high emissions). Recommendations for future state assessments, some of which are being implemented in an on-going new assessment that will be completed in 2012, are offered.

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## 1 Introduction

The Second California Scenarios Assessment originates from Governor Arnold Schwarzenegger's Executive Order S-3-05, which charges the Secretary of the California Environmental Protection Agency to report to the Governor and the State Legislature by January 2006 and periodically thereafter on the impacts of global warming to California. The 2009 assessment builds upon previous climate model-based studies of possible climate change impacts on various sectors in the California region, including a broad assessment of possible ecological impacts by Field et al. (1999); an assessment of a range of potential climate changes on ecosystems, health, and economy in California described by Wilson et al. (2003); a study of how a "business-as-usual emissions scenario simulated by a low sensitivity climate model would affect water resources in the western United States" by Barnett et al. (2004); a multisectoral assessment of the difference in impacts arising from high versus low greenhouse gas (GHG) emissions in Hayhoe et al. (2004); and the First 2006 California (e.g., Franco et al. 2008; Cayan et al. 2008a).

Key elements of the 2009 Assessment presented in this Special Issue are the use of a common set of climate and sea-level rise scenarios that were provided to sectoral researchers in conjunction with demographic and urban projections for California counties for the rest of this century (Sanstad et al. 2011). The sectors investigated include: 1) water supply; 2) agriculture; 3) coastal resources; 4) ecosystem services; 5) forestry; 6) public health; and 7) energy demand and hydropower generation. Additional studies report on extreme events and potential environmental justice issues associated with climate change policies and impacts. Finally, a regional study for San Diego County demonstrated how state-wide studies could inform and coordinate with local or regional assessment efforts.

The Second Assessment included 39 individual studies, of which 25 are presented in this Special Issue. In this overview we present integrated summary findings from the combined effort and refer to some of the studies not included in this issue. Our emphasis will be on findings that either confirm previous conclusions, thus strengthening scientific confidence, or on those that deviate from previous studies, thus raising interesting questions for further study.

## 2 Climate scenarios

This section presents an overview of the climate and sea-level-rise scenarios used for the Second Assessment. As these are not included in this Special Issue, the reader should consult Cayan et al. (2009) for more information. In view of the uncertainty of the climate responses to greenhouse gases and other forcings and the variability amongst models in representing and calculating key Earth system processes, it is important to consider results from several climate models rather than rely on just a few. For this Assessment, the set of global climate models (GCMs) has been expanded compared to previous assessments for the region to include more GCMs that contributed to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment (IPCC 2007) using *Special Report on Emissions Scenarios* (SRES) A2 and B1 emission scenarios (Cayan et al. 2009).<sup>1</sup>

<sup>1</sup> The GCMs selected for the assessment include: the National Center for Atmospheric Research (NCAR) Parallel Climate Model (PCM); the National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluids Dynamics Laboratory (GFDL) model version 2.1; the NCAR Community Climate System Model (CCSM); the Max Plank Institute ECHAM5/MPI-OM; the MIROC 3.2 medium-resolution model from the Center for Climate System Research of the University of Tokyo and collaborators; and the French Centre National de Recherches Météorologiques (CNRM) models.

The two emissions scenarios considered are the same ones that were used for the 2006 California Climate Change Assessment (Cayan et al. 2008b). The A2 emissions scenario represents a differentiated world in which economic growth is uneven and the income gap remains large between the now-industrialized and developing parts of the world, and people, ideas, and capital are less mobile so that technology diffuses more slowly. The B1 emissions scenario presents a future with a high level of environmental and social consciousness, combined with a globally coherent approach to a more sustainable development. Each GCM differs, to some extent, in its representation of various physical processes from other GCMs, and so the different models contain different levels of warming, different patterns and changes of precipitation, and so on. The result is a set of model simulations having different climate characteristics, even when the models are driven by the same GHG emissions scenario. Consequently, climate projections from these simulations should be viewed as possible outcomes, each having uncertainties that stem from imperfect model representations that differ between climate models, uncertain future emissions, and unpredictable internal climate variability (Hawkins and Sutton 2009). In short, these modeling results provide a set of scenarios of plausible futures, but they are not detailed probabilistic predictions.

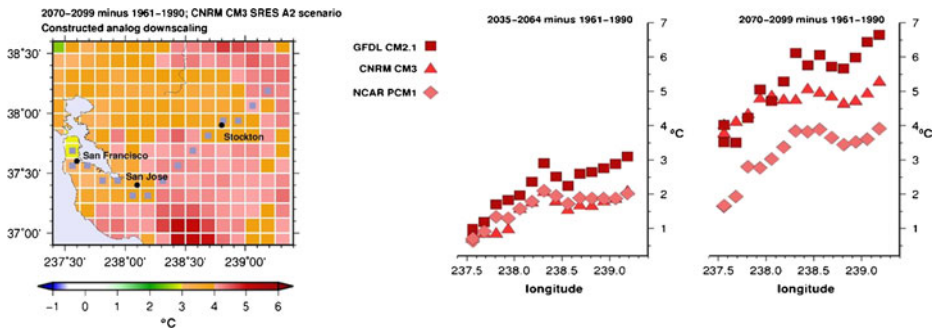
The six GCMs employed were selected on the basis of their ability to provide a set of relevant monthly, and in some cases daily, data. Another rationale was that the models provided a reasonable representation, from their historical simulation, of the following elements: seasonal precipitation and temperature, the variability of annual precipitation, and El Niño/Southern Oscillation (ENSO). It should be noted, however, that the historical skill criteria is probably not very well founded, since it has been shown that model historical skill is not well related to model climate change performance (Coquard et al. 2004; Brekke et al. 2008; Pierce et al. 2009).

Two downscaling methods were employed in the Second Assessment. These are (1) constructed analogues (CA), and (2) bias corrected spatial downscaling (BCSD). Maurer and Hidalgo (2008) and Maurer et al. (2010) compare the two methods and find that they both perform reasonably well, but they contain some noteworthy differences. Both methods have been shown to be skillful in different settings, and BCSD (Wood et al. 2004) has been used extensively in hydrologic impact analysis. The BCSD and CA methods both use coarse scale precipitation and temperature from reanalysis as predictors of the desired fine scale fields. The CA (Hidalgo et al. 2008) method provides downscaled daily large-scale data directly, and BCSD downscaled monthly data, with a random resampling technique based on historical patterns to generate daily values. Both methods yield reasonable and similar levels of skill in their resultant downscaled precipitation and temperatures for monthly and seasonal aggregated time scales. Daily precipitation is more problematic, wherein both methods produce about the same level of limited skill in simulating observed wet and dry extremes (Maurer and Hidalgo 2008). In the selected examples shown here, the results were obtained either by the BCSD or the CA method or both.

## 2.1 Warming

Overall, the six models' warming projections in mid-century range from about 1°C to 3°C (1.8°F to 5.4°F), rising by end-of-twenty-first century, from about 2°C to 5°C (3.6°F to 9°F). The upper part of this range is considerably greater than the historical rates estimated from observed temperature records in California (Bonfils et al. 2008).

There is considerable variability between the six GCMs, but the lower sensitivity model (PCM) contains the lowest temperature rise in both cool and warm seasons. The models do contain decade-to-decade variability, but this decadal component is not too large, and overall there is a steady, rather linear increase over the 2000–2100 period. All of the model



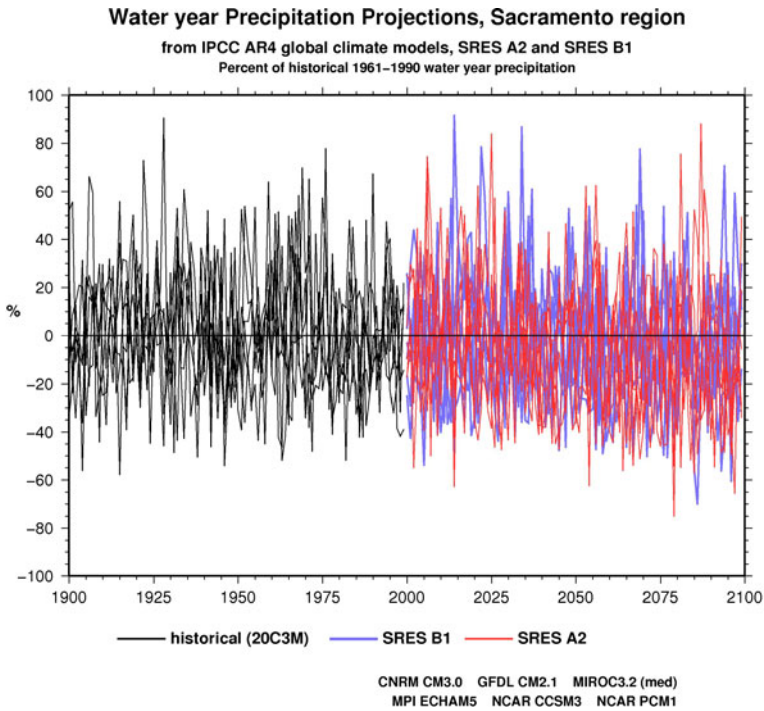
**Fig. 1** Amount of warming in July, (2045–2054 minus 1961–1990) and (2090–2099 minus 1961–1990), along a coast-to-interior transect for three GCMs under A2 simulation downscaled via Constructed Analogues (Maurer and Hidalgo 2008) to the region from San Francisco through the interior region of Central California. The transect is shown in the map on the left, which illustrates the amount of warming for July for the CNRM CM3 A2 simulation. Source: Cayan et al.(2009)

runs result in a loss of spring snowpack in California, confirming previous findings (e.g., Hayhoe et al. 2004; Cayan et al. 2008b), and the models produce substantial warming during the hydrologically sensitive spring period.

There is considerable asymmetry, both seasonally and spatially, in the amount of warming. Winter (January–March) temperature changes range from 1°C to 4°C (1.8°F–7.2°F) in the six GCMs, under A2 and B1 GHG emissions scenarios, averaged over 30 years at the end of the twenty-first century relative to the 1961–1990 climatology. The noteworthy trend here is that there is greater warming in summer than in winter. Summer (July–September) temperature changes range from 1.5°C to 6°C (2.7°F–10.8°F) over the six GCMs, under both emissions scenarios. During summer, the models suggest that climate warming of land surface temperatures is amplified in the interior of the California, resulting in a gradient of temperature changes along a coast-interior transect through the San Francisco Bay region. A distinct Pacific Ocean influence occurs, wherein warming is more moderate in the zone of about 50 kilometer (km) from the coast, but rises considerably—as much as 4°C (7.2°F) higher—in the interior landward areas as compared to the warming right along the coast, as shown in Fig. 1.

## 2.2 Precipitation changes

Precipitation in most of California is characterized by a strong Mediterranean pattern wherein most of the annual precipitation falls in the cooler part of the year between November and March. The climate change simulations from these GCMs indicate that California will retain its Mediterranean climate with relatively cool and wet winters and hot dry summers. Another important aspect of the precipitation climatology is the large amount of variability, not only from month to month but from year to year and decade to decade. This variability stands out when mapped across the North Pacific and western North America complex, and it is quite well represented by models in comparison to the observed level of variability from global atmospheric data, via the NOAA National Centers for Environmental Prediction (NCEP) Reanalysis. The climate model-projected simulations indicate that the high degree of variability of annual precipitation will also prevail during the next century, which would suggest that the region will remain vulnerable to drought. The example presented here (Fig. 2), oriented on Sacramento, do not capture the magnitude



**Fig. 2** Precipitation, by water year, 1901–1999 historical period (*black*) and 2000–2100 climate change period for SRES B1 (*blue*) and SRES A2 (*red*) GHG emission scenarios from six GCMs. The values plotted are taken directly from the GCMs from the grid point nearest to Sacramento. Source: Cayan et al. (2009)

of precipitation in the heaviest key watersheds in California. However, because winter precipitation in Sacramento is well correlated to that in the Sierra Nevada, these measures are representative of precipitation variability in the watersheds of the central Sierra Nevada and coast regions.

In addition to strong interannual-decadal variability contained within the climate simulations, there is a decided drying tendency. By mid- and late-twenty-first century, all but one of the simulations has declined relative to its historical (1961–1990) average. For the B1 simulation in mid-twenty-first century, two of the six simulations have a 30-year mean precipitation in Sacramento that is more than 5% drier than its historical average, and by late twenty-first century, three of the six have 30-year averages that decline to more than 10% below their historical average. By the late twenty-first century, the differences of 30-year mean precipitation from its historical average in three of the B1 simulations and four of the A2 simulations reaches a magnitude exceeding the 95% confidence level, as gauged from a Monte Carlo exercise that establishes the distribution of a historical samples. By the mid- and late-twenty-first century, only one of the simulations has 30-year mean precipitation that is wetter (slightly) than the historical annual average. Changes are stronger and more consistent in the southern part of the state than in the northern part of the state.

Cayan et al. (2009) used the Variable Infiltration Capacity (VIC) model driven from the outputs from the BCSD and CA downscaling techniques to estimate changes in river flows at representative stream gauges in California. As before, they report an accelerated early

melting of snow and a shift in the hydrograph towards more flows in the winter and less in the spring and summer months (see also Vicuna et al. 2011; Das et al. 2011).

Mastrandrea et al. (2011) examine how an interwoven set of extreme meteorological and hydrological events would change in each county in California using the climate projections described above. In general they find consistent increases in extreme heat such as, for example, the July 2006 heat wave would become an annual event by the of this century under the high emissions scenario.

### 2.3 Sea-level rise

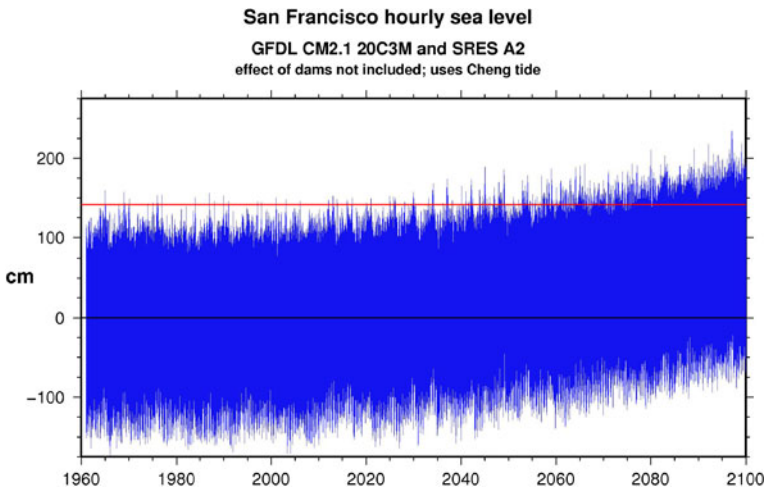
Over the past several decades, sea-level measured at tide gages along the California coast has risen at a rate of about 17–20 centimeters (cm) per century, a rate that is nearly the same as that from global sea-level rise estimates (Church and White 2006). In 2007, Rahmstorf demonstrated with his semi-empirical method that over the last century observed global sea-level rise can be linked to global mean surface air temperature. This provides a methodology to estimate global sea-level using the surface air temperature projected by the global climate model simulations, and also leads to larger rates of sea-level rise than those produced by other recent estimates (Cayan et al. 2008c). The estimates presented in the Second California Assessment include those using Rahmstorf's method, assuming that sea-level rise along the California coast will be the same as the global estimates. Also, the projections here include a second set of estimates that are a modification of Rahmstorf's method that attempts to account for the global growth of dams and reservoirs, which have artificially changed surface runoff into the oceans (Chao et al. 2008), in addition to the effects of climate change. In the simulations here, the sea-level estimates were adjusted so that for year 2000 their value was set to zero—this allows for comparison across the simulations of the amount of projected sea-level rise over the twenty-first century. By 2050, sea-level rise, relative to the 2000 level, ranges from 30 cm to 45 cm. By 2100, sea-level rise ranges from 0.5 to 1.4 m. As sea-level rises, there will be an increased rate of extreme high sea-level events, which occur during high tides, often accompanied by winter storms and periodically exacerbated by El Niño occurrences (Cayan et al. 2008c). It is important to note that, as decades proceed, these simulations also contain an increasing tendency for heightened sea-level events to persist for longer hours, which would imply a greater threat of coastal erosion and other damages. Hourly sea-levels simulations using the method of Cayan et al. (2008c) were updated with the new secular global sea-level projections described above (Fig. 3).

## 3 Impacts

As explained in section 2, the impacts researchers had at their disposal a relatively large set of climate and sea-level rise scenarios with at least daily temporal resolution and geographical resolution of about 12 km. However, only a handful of the researchers were able to make use of all of the scenarios, given the resource demands for their own impacts models. For this reason, as needed, the discussions in this section identify the specific scenario(s) used for the impacts being described.

### 3.1 Water supply

The Second California Assessment used two approaches to estimate potential impacts of climate change to the supply of water to different sectors of the economy. A group of



**Fig. 3** Hourly sea level simulated for San Francisco (Fort Point) location, using secular change estimated using the Rahmstorf (2007) method. Hourly sea-level model from Cayan et al. (2008c) includes this secular rise and superimposes predicted astronomical tides, barometric pressures winds, and ENSO from GFDL A2 simulation. Sea-level values are referenced to the long-term mean historical average. Source: Cayan et al. (2009)

researchers associated with the California Department of Water Resources utilized a simulation water supply model known as CalSim II (Chung et al. 2009) driven by 12 climate BCSD scenarios. The authors implicitly assumed that current water rights, regulations, laws, and management practices would not change for the rest of this century. CALSIM simulates the two major water supply infrastructures in California designed to transfer water from Northern California to Central and Southern California via the Sacramento-San Joaquin Delta (Chung et al. 2009). For the second approach, Connell-Buck et al. (2011) investigated potential impacts of changes in streamflows using the CALVIN model, which is an economic-engineering optimization model of the vast California's intertidal water supply system. The authors simulated water demand conditions in 2050 under a warm-dry scenario (GFDL CM 2.1 for the A2 global emission scenario) to explore the system response in California's Central Valley to severe drought in the midst of a warmer climate. In contrast to the projected warm dry conditions, a second run considered historical hydrological conditions, and a third run examined only warming without changes in total annual amount of streamflows from historical values but with a shift of the peak streamflows to earlier parts of the year to consider increased rain vs. snow and hastened snowmelt.

The CalSim II simulation model found substantial reductions in annual exports of water through the Sacramento-San Joaquin Delta. These reductions amount to 7–10% by mid-century and 21–25% at the end of the century resulting in increased annual Sacramento Valley groundwater pumping to supplement surface water supplies by 5–9% by mid-century and by 13–17% at the end of the century. Water shortage worse than the 1977 drought could occur in one out of every 6–8 years by mid-century and one out of every 3–4 years at the end of the century.

Connell-Buck et al. (2011) using CALVIN estimated difference of scarcity costs (cost associated with unmet target demand for water) by 2050. For the warming-only scenario (no change in total annual streamflows), the difference of scarcity costs by 2050 is almost

indistinguishable from those incurred with no climate change. However, the run which included declines in precipitation from the warm-dry GFDL simulation produced increased scarcity costs of about \$1.3 billion per year by 2050. More realistic economic losses could be much higher because the CALVIN model assumes perfect foresight, perfect water markets without the limitations of existing water rights, and a perfect operation of reservoirs and well-coordinated management of surface and groundwater resources. The modeling results suggest an important adaptation under dry conditions, wherein the drawdown and refill for reservoirs should advance by about 1 month earlier than in historical practice. Additionally, CALVIN demonstrated that statewide economic losses can be reduced substantially by transferring water from agricultural uses to consumptive uses in urban areas.

Together, these two studies suggest that without changes in California's present system of fresh water deliveries, serious water shortages would take place, but that technical solutions are theoretically possible. Moving to the idealized system represented by CALVIN, however, is challenged by serious structural, institutional, and political hurdles (Hanak et al. 2011).

### 3.2 Agriculture

Water supply and agriculture are very closely connected in California, given the copious amount of irrigation in the state. The agricultural sector consumes about 80% of the water withdrawals (DWR 2005). Prior studies have examined the connection between water supply and agriculture production (Wilson et al. 2003; Schlenker et al. 2007) but potential changes in crop yields have been estimated based on econometric relationships using average monthly temperature data during the growing season (Adams et al. 2003). This may be problematic because crop quality and yields, especially for perennial crops, also depend on weather conditions outside the growing season such a minimum number of hours below a threshold temperature required for dormancy for certain nuts and fruits in the cold winter season (Baldocchi and Wong 2008). Lobell and Field (2011) and Lee et al. (2011) attempted to address these limitations using, among other parameters, maximum and minimum temperatures through the year. They also increased the number of crops analyzed from prior studies.

Lobell and Field (2011) used county records for perennial crop harvests and weather from 1980 to 2005 which was complemented by Lee et al. (2011) using a well calibrated process-based crop model with daily time steps known as DAYCENT (Del Grosso et al. 2005) to simulate annual crops. Medellin et al. (2011) used all these results together with findings of prior studies on weather and yields for California as an input in their Statewide Agricultural Production Model (SWAP) to estimate how the agricultural sector would respond to both the changes in the availability of water estimated using the CALVIN model and a general warming that would be experienced by 2050. The authors performed an extensive sensitivity analysis of several assumptions in the SWAP model, concluding that their results seem to be robust. Medellin et al. assumed that California will maintain its role as a major provider of certain agricultural products in the United States, such as tree nuts, some fruits, and vegetables. For these crops, SWAP internally estimated changes in prices but for global commodities such as rice, grain, and corn, prices are provided exogenously to SWAP (California is a price taker). SWAP also considered the amount of land that would no longer be available for agriculture production due to its conversion to urban dwellings given the urban projections reported by Sanstad et al. (2011).

Results from Medellin et al. suggested a general shift to higher-value, less water intensive agricultural crops which would reduce the overall economic damages to the



agricultural sector. Nevertheless, revenues would fall by about \$3 billion a year or about 10% from what would be expected in 2050 without climate change. These results are in general agreement with those from a version of the SWAP model produced in 2003 (Howitt et al. 2003). The economic losses from the 2009 Assessment seem larger than Howitt et al. had produced, but the comparison is uneven given the differences in climate scenarios and model assumptions.

As reported before, using other climate scenarios with less drastic reductions in water supply would have significantly reduced economic impacts (Wilson et al. 2003) while relaxing other assumptions in CALVIN-SWAP, such as perfect adaptation in the water and agricultural sectors, should increase costs considerably. For example, these models used monthly time steps which do not allow the consideration of potential economic losses due to inland flooding which Lobell et al. (2011) reported as historically one of the main drivers for costly climatic extremes in the agricultural sector in California. In addition, Das et al. (2011) used the Variable Infiltration Capacity (VIC) macroscale hydrological model forced by downscaled GCM output to estimate how daily flood flows on the western slopes of the Sierra Nevada might change over the remainder of this century. Three-day averaged streamflows have been shown to be very well correlated with flooding events in California (Roos 1998; Florsheim and Dettinger 2007) and Das et al. (2011) used this metric to estimate the probability of floods in the rest of this century. By the second half of this century, all three models (NRM CM3, NCAR PCM, and GFDL CM 2.1) selected by the research team produced increases in the magnitude of floods for all the scenarios while the frequency of floods increased in the CM3 and PCM models but not in GFDL CM2.1. These increases are caused by multiple factors, including an increase in storm intensity and frequency and climate warming-related shifts in precipitation toward more rain rather than snow. This suggests that not considering impacts of flooding to the agricultural sector would underestimate economic losses. Nevertheless, the CALVIN-SWAP modeling studies conducted here provide useful insights about potential adaptation options. More detailed feasibility studies would need to investigate these options, including an analysis of how the regulatory and legal structure governing the agricultural and water sectors would have to change to allow for the implementation of technically promising adaptation options.

### 3.3 Coastal resources

The 2006 California Climate Change Assessment did not consider coastal impacts and only a few previous studies (e.g., Gleick and Maurer 1990; Newmann et al. 2003) had considered potential impacts of climate change on coastal resources in California. The Second California Assessment improved prior studies in various ways, such as going beyond simple static inundation estimates, using modern GIS tools, and considering coastal erosion of cliffs and other similar topographic features well above sea levels that in the past were assumed not to be affected by sea-level rise.

In the 2009 Assessment four studies investigated the potential impacts of sea-level rise on coastal resources. Adams et al. (2011) investigated how longshore sediment transport on the beaches in Southern California would change with changes in deep water wave direction in the Pacific Ocean. They reported that specific impacts on individual beaches depend on the direction of the waves originating in the open ocean far from California. This is important because other studies have reported a northward shift in cyclonic activities in the Pacific Ocean (Salathé 2006; Bender et al. 2011) which some GCMs suggest being a climate change signal (Yin 2005).

Revell et al. (2011) applied new methodologies using statewide data sets to evaluate potential erosion hazards on open ocean coastlines of California for a 1.4 m sea-level rise scenario. They also estimated future 100-year coastal flood elevations along open ocean and bay/estuarine shorelines extrapolating from current FEMA coastal flood maps. Although this is an exploratory analysis, this type of work is essential in providing coastal managers with information potentially useful in developing adaptation strategies. Knowles (2010) tackled the issue of potential inundation in the interior part of San Francisco Estuary and Bay using the highest resolution topographic data available in 2008 with the hourly sea-level rise projections of Cayan et al. (2009) driving a hydrodynamic model. In mapping potential inundation, Knowles (2010) found that the current 100-year peak flood events would become a yearly occurrence by the middle of this century. Heberger et al. (2011) used the geographical information system (GIS) provided by Revell et al. (2011) and Knowles (2010) to determine the resources and assets (using data cataloging infrastructure currently in place) along the open coast and estuarine shoreline of San Francisco Bay that would be affected. They reported that by the end of this century coastal flooding could threaten areas that currently are home to approximately half a million people and \$100 billion in property and assets. Assuming no additional protective measures, their maps show critical infrastructure, including roads, hospitals, schools, emergency facilities, wastewater treatment plants, airports, and power plants, currently at risk from flooding exacerbated by a 1.4 m sea-level rise. Widely publicized in the local media, their results engendered widespread recognition of the need for adaptation and initiated various planning activities in the San Francisco Bay region.

Finally, Pendleton et al. (2011) examined economic impact on beach recreation in Southern California associated with permanent beach loss caused by inundation due to sea-level rise of 1 m, and an extreme storm event such as occurred during the strong El Niño year of 1982/1983. Pendleton et al. used a model of beach visitation in Southern California to estimate how beach attendance would be impacted by the consequent beach closures in each case and to calculate the resulting economic cost in terms of lost revenue and lost consumer's surplus. They compared these costs with the costs of beach nourishment as an adaptation measure. In the case of sea-level rise of 1 m, the changes in attendance at the 51 beaches in Los Angeles and Orange Counties generated a loss of consumer's surplus amounting to about \$63 million per year. The costs are considerably higher than estimated costs of beach nourishment of about \$4 million per year suggesting that, in general, beach nourishment would be a cost effective adaptation option.

### 3.4 Ecosystem services

Even under current conditions it is extremely difficult and controversial to value, in economic terms, ecosystem services (Serafy 1998; McCauley 2006). Shaw et al. (2011) examined how climate change would affect two ecosystem services: 1) carbon sequestration in natural terrestrial ecosystems, and 2) non-irrigated forage production for livestock. Shaw et al. used the MC1 dynamic vegetation model together with the urban expansion reported in Sanstad et al. (2011) to estimate changes in carbon stocks in natural ecosystems. Using social cost of carbon figures reported in the literature by Tol (2007), Watkiss and Downing (2008), and Nordhaus (2008), they concluded that if a relatively mild form of climate change (climate scenarios from the PCM global change model) becomes a reality, carbon sequestration would result in a net benefit between \$38 million annually in the period from 2005 to 2034 and about \$22 billion annually by 2070. On the other hand, if a hotter and drier climate change scenario materializes, the social

costs would range from approximately \$600 million to \$5.2 billion annually for the period 2005–2034 and \$62 billion annually by 2070–2099. They estimated natural forage production to decline dramatically by the end of this century in all future climate projections, with potentially significant impacts on ranching agriculture and costs for adaptive measures.

### 3.5 Timber industry and wildfires

Westerling et al. (2011) applied an enhanced statistical model, originally developed for seasonal forecasts of fire risks (Westerling et al. 2003), to estimate how climate change would affect wildfires in California. The novel approach in their 2009 Assessment study was the use of projections of human settlement in the wildland-urban interface provided by the U.S. Environmental Protection Agency (Bierwagen et al. 2010). This is important because human population expanding into wildland areas is one of the explanatory variables traditionally used to estimate fire risks. The urban projections by Sanstad et al. (2011) were of little use for the study by Westerling et al., however, because their projections are only for core urban centers. Westerling et al. found increases in burned area that go up with time (i.e., increases as the magnitude of climate change increases), with estimates in burned area by the end of the 21st Century exceeding 100% of the historical area burned in much of the forested areas of Northern California in all A2 runs. The resulting risk in this new study is greater than previously reported (Westerling and Bryant 2008), most likely because the new study models a broader range of climate-vegetation-fire relationships, uses additional climate scenarios, employs multiple thresholds for defining the wildland-urban interface, and explores a range of population and development scenarios rather than assuming that human settlements in the future would be unchanged from current conditions. A companion study by Bryant and Westerling (2009) estimated costs from losses of property due to both increased wildfire risk and human encroachment in forested areas, which implied that alternative growth patterns would reduce the probability of property damage.

Another study by Hannah et al. (2011) modeled productivity of different forest trees coupled with economic models of landowner adaptation. Hannah et al. took into account that timber is a commodity with a global market and made use of global timber prices projected for this century as estimated by Sohngen et al. (2001). Hannah et al. reported, in general, increased timber production with climate change and a decrease in timber values, in line with Sohngen et al.'s findings that climate change increases global timber production, resulting in lower timber prices. In addition, they found that losses in California are not geographically homogeneous and driven mainly by assumptions about the price of timber in global markets. The findings of Hannah et al. agree with another study in the 2009 Assessment that used a new empirical model of timber production and found increased timber yields in California with climate change (Battles et al. 2009).

Hughes et al. (2011) downscaled the outputs from the NCAR CCSM3 global climate model using the Weather Research and Forecast (WRF) model to estimate how climate change would change dry, windy fall and winter Santa Ana events that have historically proceeded some of Southern California's largest wildfires which in turn produced the most substantial economic and property losses. The authors reported approximately a 20% decrease of Santa Ana events in the mid-21st century from historical conditions with an accompanying decrease in relative humidity, but with a simultaneous increase in temperature. The latter would normally favor the occurrence of more wildfires. Future work will need to include a fire behavior model to account for the effect of changes in wind regimes, relative humidity, and temperatures to reach more robust conclusions about the potential effects of climate change on fire risks in Southern California due to Santa Ana events.

### 3.6 Public health

Studies on public health that were part of the Second Assessment have been published elsewhere. In general they showed that the association between elevated temperatures and human mortality is independent of air pollution (Basu et al. 2008); that mortality effects are differentiated by age and ethnic group but not by gender or educational level (Basu and Ostro 2008); and that high temperatures have important morbidity effects measured by hospital admission data (Green et al. 2010). Furthermore, they showed that more days with conditions conducive to high tropospheric ozone levels will increase with climate change (Mahmud et al. 2008). This will result in an “air quality penalty” in the sense that more than the anticipated reduction of emissions of ozone precursors will have to be realized to be able to continue to improve air quality in California and eventually comply and maintain compliance with state and federal air quality standards. Assuming current control costs of nitrogen oxide and volatile organic compound, this air quality penalty will result in \$8 billion per year of additional expenditures by the middle of this century (Motallebi, personal communication).

Finally, Cayan et al. (2009) indicated that hot daytime and nighttime temperatures (heat waves) are increasing in frequency, magnitude, and duration from the historical period. Within a given heat wave, there is an increasing tendency for multiple hot days in succession, and the spatial footprint of heat waves is more and more likely to encompass multiple population centers in California. These findings heighten public health concerns in the coming decades.

### 3.7 Energy demand and hydropower generation

Auffhammer and Aroonruengsawat (2011) expanded upon previous studies (Miller et al. 2008; Franco and Sanstad 2008) in the 2009 Assessment by evaluating climate impacts on electricity demand. They used a unique data set consisting of household level residential electricity consumption to estimate potential changes in electricity demand in the residential sector at the U.S. mail zip code level. Their estimated impacts are much higher than what has been reported in the past (Miller et al. 2008). This may be due to the fact that the residential sector is more responsive to temperature than other sectors (e.g., industrial sector). Auffhammer and Aroonruengsawat (2011) reported increases in electricity demand in the residential sector of up to 55% by the end of this century if future climatic conditions are superimposed on the current stock of homes and their electricity consuming devices. The actual impacts could be much lower due to the implementation of new aggressive energy efficiency programs and by consumer responses to potential increases in electricity rates. At the same time, more urban development is projected to take place in the California Central Valley and other inland areas that are already experiencing higher summer temperatures and are expected to warm at a faster rate than coastal areas. Increases in temperatures will also favor an increased penetration of air conditioning units (Sailor and Pavlova 2003) or better building practices (insulation). Net electricity demand, however, will not necessarily grow in strict proportion to the increased penetration of air conditioning because new air conditioning units are likely to be more efficient and better suited to California’s dry summer conditions (Buntine et al. 2008). Electricity expenditures in the residential sector were about \$13 billion in 2009 (EIA State Energy Data System 2011) so that even fractional increases in demand will represent non-trivial economic losses.

The future amount of hydropower generation depends heavily on how climate change affects overall precipitation amounts. If a drier climate becomes reality, hydropower generation would decline, but go up if precipitation increases. Connell-Buck et al. (2011)

reported results from the CALVIN model suggesting a 4.5% decrease (\$20 million a year) in hydropower benefits in their warm-dry scenario from the low-elevation hydropower units associated with relatively large reservoirs. However, historically about 74% of the hydropower generated in California comes from high-elevation hydropower units that use snow as their main water reservoir (Aspen Environmental Group 2005). Madani and Lund (2009) reported reductions on the order of 14% for these units due to changes in runoff patterns, lower snowpack volumes, and limited storage capacity, under the warm-dry-scenario. Regardless of how climate change will affect precipitation amounts, a reduction of electricity generation during the hot summer months, a period traditionally relied on for hydroelectricity to satisfy peak cooling demand, is projected for all climate scenarios.

### 3.8 Differential vulnerability to climate change and policy

Shonkoff et al. (2011) reviewed literature on climate change and environmental justice issues to draw some preliminary conclusions about potential disproportional impacts to low income and minority groups with relatively limited resources available to adapt or to relocate if needed. They also discussed how efforts to reduce greenhouse gas emissions might preferentially benefit certain segments of California's population, but generally not low income and minority groups. For example, they argued, cap-and-trade program will not necessarily result in reduction of co-pollutants such as volatile organic compounds and hazardous air pollutants in areas that are currently considered environmental justice hotspots in California, i.e., areas where low-income and ethnic minority populations experience undue burdens from environmental pollutants and nuisances. An example of this outcome is the expected lack of change in emissions near oil refineries in Southern California because they were able to purchase emissions offsets generated from the destruction of old, polluting vehicles in lieu of installing equipment reducing emissions at these refineries. This type of argument was persuasive to the state judicial system in halting, at least temporarily, implementation of the cap-and-trade program designed by the California Air Resources Board to comply with the state's Global Warming Solutions Act of 2006.

### 3.9 Regional impacts foci

Finally, the 2009 Assessment included a regional climate impacts study conducted for San Diego County by local scientists. Messner et al. (2011) estimated climate change impacts by 2050 for that county covering the sectors included in the statewide Assessment. They paid special attention to water supply issues for the San Diego region, given the fact that San Diego County relies heavily on imported water from Northern California and from the Colorado River. Due to climate change and increased drought tendency, the region's reliance on imported water will significantly increase in the coming decades. As discussed extensively in scientific journals (e.g., MacDonald 2010), both sources of imported water are threatened by climate change.

## 4 Statewide assessment and its linkage to adaptation policies in California

An important goal of the recurrent production of assessments is to inform policy decisions with the best available science. As such, while it was an independent scientific endeavor, the Second Assessment has had a strong connection to state climate policy evolution in California. A steering committee formed by senior technical managers in different state agencies was involved from the start to help shape the overall design of the study. They also

participated in meetings with the researchers organized to discuss preliminary results. In several cases the members of the steering committee made substantial contributions by identifying important government data sets, providing insightful comments from their in-depth knowledge of California issues, and helping to produce research products that are pertinent to and useable in—as much as possible—actual resource management decisions. These interactions were very fruitful and, in some cases, have influenced long-term planning activities in California. For example, the California Department of Forestry and Fire Protection used the ecological model enhanced and used by Hannah et al. (2011) for their 2010 Forest and Range Assessment (CalFire 2010), which this agency is required to prepare and submit to the Governor and the Legislature every 5 years. For the first time, this agency was able to quantitatively consider climate change in their long-term management plan of resources under its jurisdiction.

Another important policy development for which the Second Assessment was instrumental was the preparation of the first statewide climate adaptation strategy for California. Mandated by Executive Order S-13-08, which was issued by Governor Schwarzenegger in November 2008, state agencies in charge of the management of natural resources, infrastructure and public health were directed to identify adaptation measures for those assets and populations likely to be affected by climate change. One of the motivating factors for the Executive Order was the release of a short synthesis of scientific findings between the First and Second California Assessment, which made the case that even if strong mitigation measures were implemented at a global scale, California would see substantial changes in its climate and impacted physical, natural, and social systems (Moser et al. 2008; Moser et al. 2009). The Governor released the strategy in December 2009 (California Natural Resources Agency 2009), which is seen by state authorities as a starting point in a long journey of continuously updating and refining the measures California must take to adapt to a changing climate. The close interaction between the scientists involved in this assessment and senior technical managers in state government enabled the consideration of the research findings presented in this Special Issue in the preparation of the 2009 California Climate Adaptation Strategy (CAS). One of the clear recognitions articulated in the CAS was that climate-scenario driven (top-down) impacts assessments alone are insufficient to fully understand the challenges to be expected from climate change. Thus, as one of its overarching recommendations, the CAS proposed an integrated, top-down and bottom-up vulnerability and adaptation assessment to inform ongoing adaptation policy developments. That set of studies is currently (2011) underway—building on, yet also significantly expanding on, past investigations—with results expected in the first quarter of 2012.

More recently, the California Ocean Protection Council issued interim guidelines on the assumptions that governmental agencies should use with regard to sea-level rise when issuing permits or for long-term planning work (OPC 2010). Results from the Second Assessment contributed to the preparation of these guidelines and some of the scientists involved in the second Assessment provided expert advice.

## 5 Discussion

Several lessons can be drawn from the Second California Assessment but we focus here on lessons related to research management and policy related issues. Papers included in this issue can be referred to for future scientific directions.

Some key aspects of regional climate change are still quite uncertain, as evidenced by the range that is contained across the scenarios that have been included. In particular, these

include the direction and magnitude of precipitation changes, the rate of sea-level rise and the intensity and frequency of future storminess. The impacts of these regional climate changes will cascade through a network of sectors and ecosystems and thus will require continued scrutiny from ongoing observational and model assessments.

In general, the studies indicate that climate change impacts in California will be distributed unevenly across social groups, industries and regions. While some may benefit from climate change in a relative sense, others will have to cope with predominantly negative impacts. For example, Pendleton et al. (2011) estimated increases in beach attendance and economic benefits for some beaches and economic losses at other beaches, as well as an overall negative economic impact for Southern California. Heterogeneous impacts imply the need for site-specific local studies informed by regional and/or statewide studies to be most useful to local and state-level decision makers. This point takes on a special urgency in light of the unequal distribution of socioeconomic impacts reported by Shonkoff et al. (2011). Given the relative paucity of literature on this topic and the important policy implications of this type of work, the study on equity implications of climate change and climate mitigation policies is an important research area in need of further development.

The San Diego study (Messner et al. 2011) and other similar regional/local efforts demonstrate that regional/local entities are willing and in some cases eager to engage with the research community. For example, this regionally focused study has been influential in motivating local adaptation planning efforts, and in shaping follow-up assessment work in other regions of California (e.g., the focus on San Francisco Bay in the 2011 assessment currently underway). How to collaborate with them without overburdening the scientists involved in the California Assessments and how to increase mutual understanding for the needs and limitations of both sides are issues that need to be continuously addressed in future endeavors.

Some of the statewide studies already contain information relevant for the local level. For example, the climate projections (Cayan et al. 2009) have a geographical resolution of about 12 km and the electricity demand estimates are resolved at the U.S. mail zip code level. Scenarios and findings of the impacts studies have begun to be made available at a website known as Cal-Adapt (<http://cal-adapt.org/>) through visually approachable, interactive tools that allow users to inspect research results at smaller scales and access output data for further use by local/regional decision makers. Ongoing monitoring and critical evaluation of the use of this website, its tools, and the available data is needed to assess their usefulness and to ensure appropriate use.

In some cases, economic impacts in California will strongly depend on forces from national and international markets. For example, the California timber industry, even if yields increase, may be negatively affected if world prices for timber decline as suggested by Sohngen et al. (2001). For this reason, it would be desirable to coordinate international and national studies in such a way that they inform each other. Moreover, more research into such “teleconnections” (Adger et al. 2009) is required to more realistically assess impacts from and societal responses to climate change. Effects on California will also derive from climate change effects in other regions and the responses in these other regions to them. An IPCC-level of effort that is purposefully designed to both review the state of the science and the creation of new knowledge through the coordination of regional and national studies is highly desirable. The recently started new U.S. National Climate Assessment is a good start in this direction (NCA 2011).

Many policymakers and agency personnel in California have recognized the value of concerted research efforts, regular updates on the state of climate change science, and the

growing attention to the salience and relevance of research findings to decision making. This is presenting new opportunities for novel research and also for ongoing learning about mutual needs and capabilities between researchers and practitioners. Tight state budgets and some political challenges to climate change impacts research threaten to narrow the breadth of ongoing assessments, but the demand for location-specific, decision-relevant climate and adaptation research is only growing.

For future research to continue to be policy-relevant, the identification of technically sound adaptation strategies is only one part of a long process that must come to grips with regulatory, legal, institutional and other non-technical barriers (Ekstrom et al. 2011). These technical and societal components of the adaptation strategy must be explored and addressed in an ongoing interaction with decision makers. Studies with models such as CALVIN and SWAP, while important, leave a number of unanswered questions on how to get closer to their idealized adaptation scenarios. Alternatively, to be more decision-relevant, studies must reflect the more realistic circumstances that decision makers face, and help them develop practically feasible adaptation options.

In closing, we and others have found that an ongoing, periodic assessment involving technical staff from state agencies is highly beneficial for both the scientists and for state agency decision makers. Despite the effort at the state and federal level, it is clear from the rapidly growing interest in adaptation planning, and the significant lag in adaptation science (NRC 2010), that a substantial amount of adaptation will take place at the local level without adequate scientific information to inform it. Continued scientific effort, sustained research investment, strategic science policy and research priority-setting, rapid building of the necessary science-practice bridging capacity, and proactive advice-seeking by decision makers, are essential to inform adaptation planning and implementation with the current scientific understanding of our rapidly changing climate, environment, and society.

**Disclaimer** This paper reflects the views of the authors and does not necessarily reflect the views of the California Energy Commission or the state of California.

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