Climatic Change (2012) 111:5–16
DOI 10.1007/s10584-011-0240-4

Climate change in California: scenarios and approaches for adaptation

Michael D. Mastrandrea · Amy L. Luers

Received: 13 August 2009 / Accepted: 21 June 2011 / Published online: 8 October 2011

Abstract Even with aggressive global action to reduce greenhouse gas emissions, the climate will continue to change for decades due to previous emissions and the inertia in biogeophysical and social systems. Therefore, as a complement to mitigation actions, society must also focus on enhancing its capacity to adapt to the unavoidable impacts of climate change that we are already experiencing and will continue to experience over the next few decades. Resource managers, regional planners, and government agencies need to consider climate risks in their planning. We provide an overview of climate change scenarios for California and suggestions on the use of climate projections in state and regional planning efforts in the future.

1 Introduction

Californians are well acquainted with climate-related hazards such as floods, wildfires, heat waves, and droughts. Over time, the state's communities and economy have developed strategies to manage climate stresses and to thrive within the state's diverse climatic zones. However, the rapidly changing climate threatens to exceed the limits of society's traditional strategies for managing climate conditions and coping with climate extremes. Already, extended droughts strain the region's water management systems, severe heat waves lead to the loss of lives and revenues, and extreme floods such as those during the El Niño years of 1987, 1992 and 1997 cause extensive economic damages to private and public property.

While none of these extreme events can be directly attributed to human-induced climate change, their consequences highlight California's vulnerabilities to climate variability and

M. D. Mastrandrea (✉)
Woods Institute for the Environment, Stanford University, Yang and Yamazaki Environment & Energy Bldg, MC 4205, 473 Via Ortega, Stanford, CA 94305, USA
e-mail: mikemas@stanford.edu

A. L. Luers
Google, 900 Alta Avenue, Mountain View, CA, USA
e-mail: amyluers@google.com

change. And among other impacts, extreme events are projected to become more frequent and intense as the climate continues to change (Meehl et al. 2007; Mastrandrea et al. 2009). Moreover, adaptation to extreme events can be more challenging than adaptation to gradual changes in mean climate states, and can disproportionately affect vulnerable populations that experience higher exposure (e.g., extreme heat and low-income populations without access to air conditioning or individuals living in flood-prone areas) or higher susceptibility (e.g., extreme heat and elderly individuals) to such events.

There is now growing momentum worldwide to address climate change by reducing emissions of greenhouse gases. However, because of the inertia in social and geophysical systems, even with aggressive global action to reduce emissions the climate will continue to change for decades because of previous decades' emissions. Scientific research suggests that even if actions could be taken to immediately stop the rise in atmospheric greenhouse gas concentrations, the inertia of the climate system is such that 0.5°C or more of global average warming above current levels would still occur (Meehl et al. 2005; Wigley 2005; Meehl et al. 2007). Under the lowest scenario assessed by the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), the B1 scenario, global average temperature would still increase 1.1–2.9°C relative to 1980–99 by the end of the century (Meehl et al. 2007). As a result, no matter what emissions-reducing steps are taken, society has to focus on enhancing its capacity to cope with the unavoidable impacts that we are already experiencing and will continue to experience over the next few decades. Alongside mitigation, then, policies focused on adaptation are also needed.

For what climate changes should managers and planners prepare? Climate scientists have developed a range of potential climate change scenarios based on different assumptions about future greenhouse gas emissions and different assumptions about how the climate will respond to rising concentrations of greenhouse gases in the atmosphere (Meehl et al. 2007). The range of projections and subsequent impacts assessments presented in the literature has been helpful in characterizing the risks that society faces. However, the literature provides less guidance on how to interpret these projections for on-the-ground adaptation planning. In this paper, we provide an overview of climate change scenarios for California and provide suggestions on how these might be used in state and regional planning efforts in the future (see also, Mastrandrea et al. 2010).

2 California's changing climate

In recent decades, California and the western United States have experienced clear signs of a changing climate. For example, with rising winter and spring temperatures, spring snow levels in lower- and mid-elevation mountain areas have dropped, and snowmelt is occurring and spring flowers are blooming 1–4 weeks earlier (Cayan et al. 2008a). Over this century, California's climate is expected to change considerably. Not only does this mean further increases in average temperatures, but also changes in rain and snow (precipitation) patterns, rising sea levels, and changes in the frequency and/or severity of extreme events such as heat waves, droughts, and fires.

Climate projections depend in large part on two factors: (1) how much and how quickly greenhouse gases are emitted into the atmosphere; and, (2) how the climate, oceans, and terrestrial systems respond to rising atmospheric concentrations of these gases. Different greenhouse gas emissions scenarios, mentioned above, account for the first source of uncertainty. The second source of uncertainty is represented by the behavior of different climate models, which project different levels of temperature increase and different patterns of climate system response (e.g., precipitation changes) for the same emissions scenario. Figure 1 summarizes many impacts on California that are projected for different levels of temperature increase. On the left side of the figure, arrows denote the temperature increase projected by the end of the century under three different IPCC emissions scenarios (California Climate Change Center 2006). The length of each arrow represents the range of projections by different climate models for each emissions scenario.

2.1 Temperature

By mid-century, the average annual temperature of the state is projected to rise ~1 to 3°C (~1.8 to 5.4°F), under either the A2 (higher) and B1 (lower) emissions scenarios (Cayan et al. 2009). Temperature projections do not diverge significantly in this timeframe across these scenarios because of the inertia in the response of the climate system. The implications of the two scenarios for the second half of the century, however, are very different. Studies indicate that by the end of the century, if global greenhouse gas emissions proceed at a medium to high rate (A2), annual mean temperatures in California are expected to rise ~2.5 to 5°C (4.5 to 9°F) (Cayan et al. 2009). In contrast, a lower emissions rate would keep the projected warming to ~2 to 3.5°C (3.6 to 6.3°F). The divergence of projections for higher and lower emissions scenarios by the end of the century is an indication of the long-term benefits of mitigation policy. But through mid-century, arguably

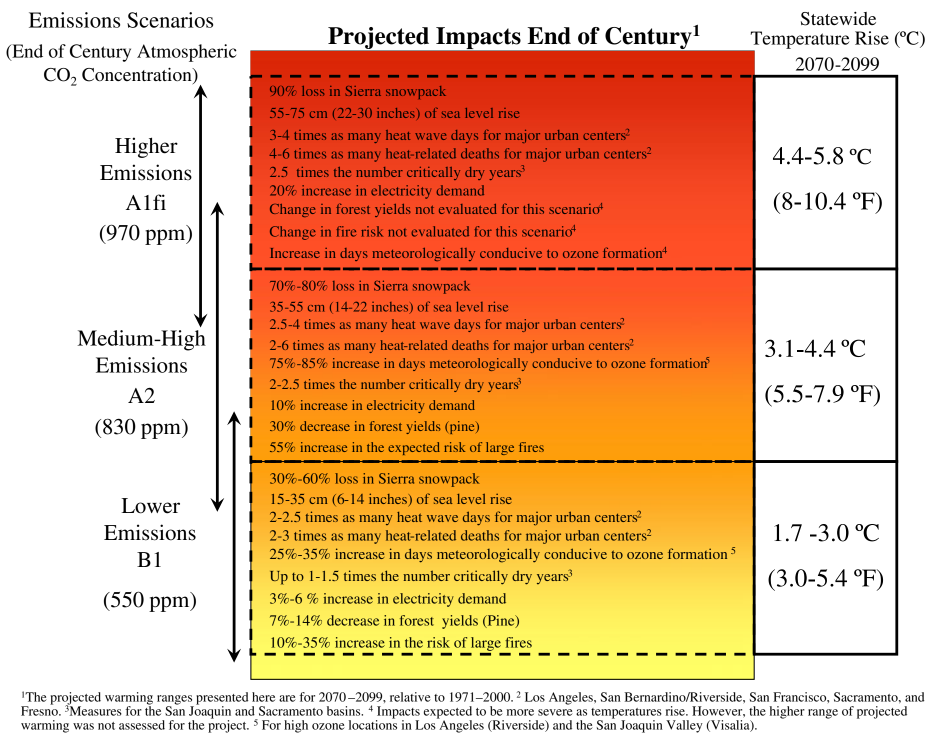

Fig. 1 Projected Climate Impacts, Late 21st Century. Arrows on left correspond to temperature projections for three emissions scenarios in a range of climate models. Atmospheric concentrations of CO_2 (in parts per million (ppm)) for the year 2100 under each scenario are also provided. Source: Adapted from California Climate Change Center 2006

a timeframe more relevant for adaptation policy, this divergence is far more modest, providing a narrower range of possible outcomes. In the discussion that follows, we focus on mid-century projections where available. Further discussion of projections for the end of the century can be found in many of the references cited here.

The rise in average annual temperature affects seasonal temperatures very differently. Spring and winter temperatures have increased more than the annual average over the second half of the 20th century, while summer temperatures have increased more slowly (Cayan et al. 2008a). In contrast, studies project that this pattern will reverse in the future, with summer temperatures rising most rapidly (Cayan et al. 2008a). Greater warming in summer is common to all continental areas across climate model projections, and may be affected by earlier and greater drying of continental land surfaces (Cayan et al. 2008a). Inland temperatures are also projected to rise faster than coastal temperatures, due to the stabilizing influence of the ocean, with as much as a 4°C (7.2°F) difference between coastal and interior temperature increases (Cayan et al. 2009). Rising summer temperatures are particularly of concern in terms of impacts on agriculture, energy demand, public health, and many ecosystems. By mid-century, Sacramento region summer temperatures are projected to rise ~3 to 6°C (5.4 to 10.8°F) for the higher A2 scenario, and ~1.5 to 4°C (2.7 to 7.2°F) for the lower B1 scenario.

2.2 Precipitation

In general, projections of precipitation change exhibit more variation across different climate models than projections of temperature increase, and the same is true in California. Precipitation is influenced by local or regional geographical variations, proximity to features such as mountains or bodies of water, and temperature differences across regions. All of these interacting influences are more difficult to include accurately in models, and precipitation often varies widely at scales below the grid-box scale of global climate models. Scientists have devised downscaling techniques to produce projections at scales finer than the model grid (e.g., Wood et al. 2004; Hidalgo et al. 2008). Nevertheless, uncertainty regarding projections of precipitation remains higher than for temperature.

The most prevalent pattern in annual California precipitation across the range of available projections is a decrease in overall precipitation through the end of the century, with drying more intense under the higher A2 emissions scenario (Cayan et al. 2009). For the Sacramento region, drying is seen by mid-century in all models (6 out of 6) under the higher A2 scenario, and under 5 out of 6 models under the lower B1 scenario. By the end of the century, all models project at least slight drying under both scenarios. For the Los Angeles region, 5 out of 6 models show drying by both mid-century and end-of-century, with a generally greater magnitude of drying than for the Sacramento region. Model projections suggest no change in the Mediterranean seasonal pattern of precipitation California currently experiences, with most precipitation falling between November and April. The high year-to-year variability in annual precipitation that California currently experiences is also projected to continue, suggesting that the region will remain prone to drought conditions (Cayan et al. 2009). This variability, coupled with the reduction in overall precipitation, is likely to increase California's vulnerability to drought.

Warming temperatures are also projected to decrease the amount of precipitation falling as snow and increase the amount falling as rain. This pattern is expected to continue to drive the already observed earlier spring melting of snowpack (Kapnick and Hall 2009), and lead to a decrease in snow accumulation in the Sierra Nevada (Hayhoe et al. 2004; Cayan et al. 2008a). In California, the higher elevations of the Sierra Nevada are in the southern portion of the range, so these effects are expected to be largest in the central and northern parts of the state (Cayan et al. 2008a). By mid-century the amount of water stored as snow on April 1 is projected to decrease by 12 to 27% under a less sensitive model (less warming for a given emissions scenario), and 37 to 42% under a more sensitive model, with much larger decreases later in the century (Cayan et al. 2008a). The most significant losses are projected to be at lower elevations (<2000 to 3000 ft). Figure 2 shows the spatial distribution of projected snowpack losses in 2030, 2060, and 2090, compared to the 1995 to 2005 average, for a less sensitive model with lower projected temperature increases than other models (Knowles and Cayan 2002). This model also projects decreases in total annual precipitation.

2.3 Sea level rise

Warming temperatures are contributing to global sea level rise in two ways. First, water expands when it warms, and a warming atmosphere is causing the ocean to warm as well. Second, warmer temperatures are also melting glaciers and the ice sheets in Greenland and Antarctica, adding water to the ocean that previously has been stored in these reservoirs of ice. In California, records suggest an observed rate of sea level rise over the past few decades of 17 to 20 cm (6.7 to 7.9 in.) per century, which is similar to the global estimate (Cayan et al. 2008b). The rate of global sea level rise has accelerated in recent years (Bindoff et al. 2007), and while a similar trend has not been observed in California, projections suggest the potential for substantially greater sea level rise over this century.

The magnitude of future sea level rise is dependent on the level of future warming and remaining uncertainties in the response of the system to warming. While sea level rise due to the expansion of warming water and some components of melting ice can be reliably projected (with some uncertainty), an important component of the future rate of melting of the large ice sheets in Greenland and Antarctica cannot be satisfactorily quantified with current modeling tools—specifically, the rate of discharge of ice from these ice sheets into the surrounding oceans, which has accelerated in recent years. A recent analysis based on

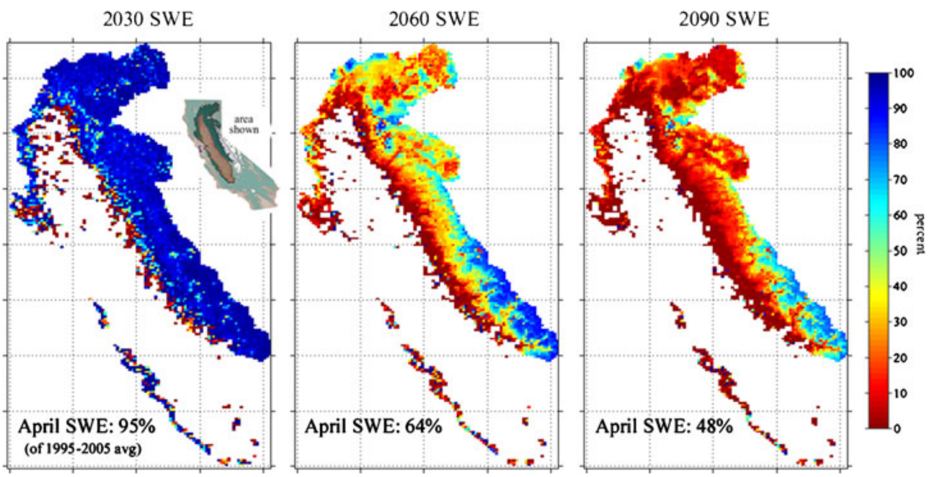

Fig. 2 Springtime snow water equivalent (SWE) under projected temperature increases of 0.6°C (2020 to 2039), 1.6°C (2050 to 2069), and 2.1°C (2080 to 2099), expressed as a percentage of average present (1995–2005 average) conditions. Source: Knowles and Cayan 2002

an observed linear relationship between temperature increase and the rate of sea level rise over the 20th century suggests a larger range (across emissions scenarios) of ~20 to 40 cm (8 to 16 in) by mid-century and ~50 to 140 cm (20 to 55 in) by the end of the century (Rahmstorf 2007). A further analysis that attempts to account for the global growth of dams that change the amount of freshwater runoff into the oceans projects even higher sea level rise by 2050 of 30 to 45 cm (12 to 18 in) (Cayan et al. 2009). Figure 3, from Cayan et al. (2009), displays projections using both methods, under the B1, A2, and A1FI emissions scenarios (A1FI emissions are higher than A2).

While these projections are uncertain, they signify that sea level rise greater than 1 m by the end of the century cannot be ruled out under strong warming scenarios. Furthermore, research indicates that warming over this century has the potential to destabilize the Greenland Ice Sheet, increasing the magnitude and rate of global sea level rise and eventually contributing 6.6 to 23 ft (2 to 7 m) of sea level rise, although complete melting could take many centuries (Schneider et al. 2007). Studies suggest this process could be initiated by sustained global average warming of 3.6 to 8.1°F (2 to 4.5°C) (Meehl et al. 2007), well within the range of temperature increase expected by late in this century under high emissions scenarios, although it is unclear for how long this warming must be sustained to destabilize the Greenland Ice Sheet.

2.4 Extreme events

While changes in average temperature, precipitation, and sea level will very likely occur gradually, the frequency and intensity of extreme events such as heat waves, droughts, and floods can change substantially with even small average changes. This implies that changes in extreme events are among the most immediate climate challenges faced by California.

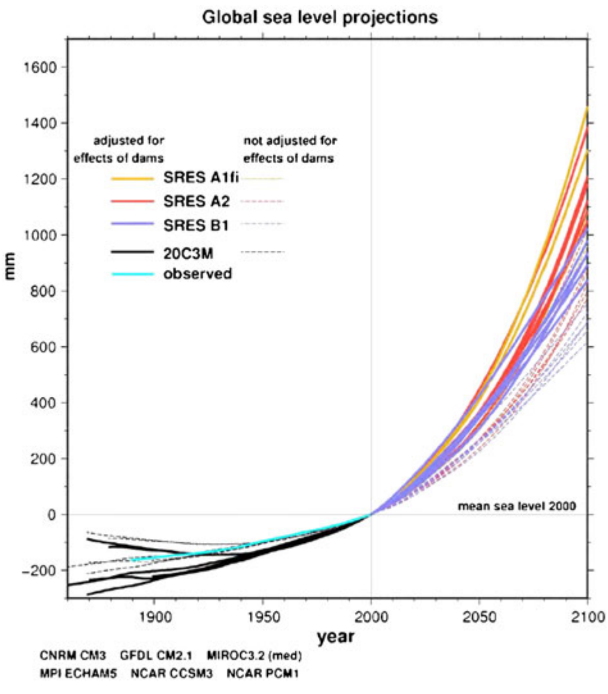

Fig. 3 Projected global sea level from six climate models, for the SRES A1FI, A2 and B1 emission scenarios. Results are shown using both the Rahmstorf 2007 method (dashed curves), and a version adjusted for the effect of reservoirs and dams (solid). Source: Cayan et al. 2009

Understanding how these events are changing is of critical importance for adaptation planning.

Rising average temperature will lead to more frequent and intense periods of extreme heat compared to the range of historical experience (Cayan et al. 2009; Mastrandrea et al. 2009). For example, statewide, the frequency of extreme temperatures currently estimated to occur once every 100 years (a very severe heat wave by current standards) is projected to increase at least ten-fold in many regions of California, even under a moderate emissions scenario (Mastrandrea et al. 2009). Under a higher emissions scenario, these temperatures are projected to occur close to annually in most regions. Additionally, the length of individual events is expected to increase. For example, the frequency of events with five or more days above the 95th percentile of May-September daily maximum temperatures is projected to increase ten-fold or more by mid-century (Cayan et al. 2009). The amount by which this threshold is exceeded is also expected to increase considerably, with significant implications for public health, fire risk, air quality, agricultural production, and natural ecosystems.

Projected changes in the frequency and intensity of precipitation events are more mixed. Earlier projections indicated the potential for an increase in the frequency of heavy precipitation events in Northern California, even without a change in overall precipitation (Cayan et al. 2008a). More recent projections (which also correspond to the projections of overall drying described above) project a decrease in the frequency but no clear signal in the intensity of precipitation events (Cayan et al. 2009). Rainy days, when precipitation is greater than 3 mm, are expected to decrease, but trends in days when precipitation is above 15 mm or 25 mm exhibit smaller positive and negative trends in different model projections (Cayan et al. 2009).

California is already experiencing increasing occurrence of extreme highs in sea level, driven by average sea level rise. This pattern is not consistent along the entire coast. For example, their occurrence has decreased slightly at Crescent City, but this is due to tectonic activity causing coastal uplift along parts of the northern California coast (Cayan et al. 2008b). In San Francisco, the occurrence of extremes has increased twentyfold since 1915, and in La Jolla, thirtyfold since 1933. These two latter locations are more tectonically stable. The frequency and duration of sea level extremes is expected to increase as sea level continues to rise, with the potential to exceed coastal and San Francisco Bay-Delta flood defenses designed for historical conditions (Cayan et al. 2008b). In addition, climate change increases the potential for more intense storms, further threatening coastal and floodplain areas.

Climate change also has the potential to cause large-scale changes in the climate system that would affect California, such as shifts in the El Niño-Southern Oscillation cycle, but as yet there is no consensus regarding the effects of climate change on such processes (Meehl et al. 2007).

3 Managing climate risks

Given the changes ahead, resource managers, regional planners, and other decision makers will need to consider climate risks in their planning. California's vital resources and natural landscapes are already under increasing stress due to California's rapidly growing population, which is expected to increase from 35 million today to nearly 60 million by 2050 (California Department of Finance 2007). Continued climate changes will put further pressures on these systems and have widespread consequences for California's society, economy, and environment. Of particular concern are potential impacts on California's public health, water supply, agriculture, coastal areas, natural ecosystems, and energy and transportation infrastructure, which are sensitive to changes in temperature, precipitation, sea level, and water availability (Climate Action Team 2009; California Climate Change Center 2006; Hayhoe et al. 2004; Wilkinson 2002; CEC 1989). Table 1 summarizes these

Table 1 California sectors sensitive to climate change, with examples of climate impacts and adaptation actions

Sector	Example climate impacts	Example adaptation actions Short-term	Example adaptation actions Long-term
Public Health	Decreased air quality	Strictly enforce existing air quality standards and educate public on connections between air quality and climate change.	Implement ongoing monitoring to identify hotspots of vulnerability and enable flexible responses to surprises.
Water Supply	Reduced Sierra snowpack and earlier annual melting; Less reliable water supply; Increased water demand	Implement water conservation programs, expand conjunctive use, and support infrastructure investments for storm-water and wastewater recovery.	Increase flexibility of water transfer mechanisms and improve groundwater basin management.
Agriculture	Increasing threats to agricultural production due to less reliable water supply and increases in high temperature extremes	Increase water use efficiency for irrigation and enhance access to localized climate information,	Expand research, development, and deployment of heat and drought-tolerant crops.
Marine/Coastal	Inundation of coastal areas and increased coastal storm impacts and erosion	Assess the vulnerabilities of existing and planned coastal infrastructure and support enhanced disaster response planning including coastal armoring to protect critical infrastructure and softer strategies that preserve habitats and beaches.	Modify planning and zoning processes to reduce development in areas most vulnerable to sea level rise.
Ecosystems	Loss of habitat, biodiversity; species extinction	Reduce existing non-climatic pressures on ecosystems—such as habitat fragmentation and pollution. Prioritize development of natural reserves containing a range climate conditions and habitat types.	Expand monitoring of networked protected areas to support species migration and adaptive responses to change.
Forestry	Increased wildfire risk; increased pest outbreaks	Decrease non-climatic pressures on forests such as air pollution. Use fire-resistant building materials in vulnerable areas.	Modify planning and zoning processes to reduce development in fire-prone areas. Monitor to understand trends in vulnerability.
Energy	Increased electricity demand	Strengthen energy efficiency in building codes and implement pricing schemes to reduce peak electricity demand.	Enhance capacity to meet peak demand through renewable energy sources.

sectors, relevant climate change impacts examples, and examples of potential adaptation strategies in the short and long term. These examples are not intended to be prescriptive or comprehensive, but simply to provide possible options for context. A more detailed discussion of these sectors and potential adaptation strategies can be found in the California Climate Adaptation Strategy (California Natural Resources Agency 2009) and in the papers that follow in this special issue.

Californians are well-accustomed to planning under uncertainty, with earthquakes, floods, droughts, and wildfires all being familiar risks to the state. But climate change poses both familiar and novel challenges for risk management. Many managers and planners dealing with resources affected by climate variability assess the risk of specific events (e.g. floods or droughts) based on past variability (assuming a "stationary" climate). For example, a flood event might be determined to be a 1-in-100 year event by determining the frequency of events of various magnitudes in the past (in this case determining the magnitude of flooding that occurs "once every 100 years," or more accurately, 1% of the time). This approach assumes that this distribution of event magnitudes is constant over time, and that past climate variability is an effective indicator of future conditions. But the climate is changing and will continue to change for the foreseeable future, and this approach is no longer sufficient (Milly et al. 2008).

The uncertainty in future projections makes it impossible to generate the same frequency profiles for future conditions; climate projections cannot replace historical data within the same framework. In other words, defining a 1-in-100 year event loses meaning when we know that conditions will not be constant over the next 100 years. As a result, mainstreaming future climate risks into regional planning and resource management requires the development of modeling tools and methods to incorporate this new type of uncertainty. One way that frequency profiles based on historical data can still be of use is to compare projected conditions with the current frequency profile (see, e.g., example given above in Extreme Events section and Mastrandrea et al. 2009). Levees or seawalls, for example, may be engineered to withstand the historical 1-in-100 year tide level in a certain location. It is important to know how much more frequently that level may be reached in the future to assess the vulnerability of existing infrastructure. Coupled with this, however, should be projections of the intensity of future extremes beyond the current 1-in-100 year threshold, which potentially include more intense extremes than have been experienced in the past. Both types of information can help guide the design specifications for the next generation of infrastructure.

Guidelines for drawing useful information from the suite of climate projections will likely vary by sector, depending largely on the planning horizon for the sector and the lifetime of planning decisions. Over the near-term, an effective strategy is likely to be identifying and pursuing "no regrets" actions, options "that would be justified under all plausible future scenarios, including the absence of human-induced climate change" (see, e.g., Willows and Connell 2003; Smith et al. 2009). These are actions that enhance society's ability to cope with climate variability, such as strategies to protect vulnerable populations during severe heat waves, development of crop varieties or technologies that reduce water use for agriculture or implementing "greywater" recycling to reclaim wastewater from domestic activities and thus improve the ability to cope with drought, or strengthening of levees for flood protection. As mentioned above, one of the largest near-term climate challenges California is likely to face is the potential for more intense and/or more frequent extreme events than those seen historically, since extreme events can change substantially with small average changes (Meehl et al. 2007). Such an approach will build resilience while new information continues to come in regarding the trajectory of future climate change, reducing the probability of maladaptations—actions that actually lower the capacity to cope with future conditions when those future conditions materialize. Climate change may provide impetus for prioritization of such actions, but they are actions that are desirable even without climate change. Even “no regrets” actions, however, may be difficult to implement. A valid question is that if such actions are so desirable, why have they not been implemented already? The fact that they have not may indicate institutional or economic obstacles, split incentives, or other barriers to their implementation that must be overcome.

There are certain decisions that require a longer planning horizon (>30 years) and actions the specifically address climate change to avoid severe impacts. Examples include constructing barriers to protect coastal infrastructure from rising sea levels (where that infrastructure is not already threatened), considering sea level rise (and its implications for erosion and storm surge) when investing in new long-lived infrastructure (power plants, transportation infrastructure, etc.), improving water storage capacity to adapt to decreasing precipitation and earlier snowpack runoff by constructing additional reservoirs, or investing in habitat conservation for threatened or endangered species. In these cases, considering the full range of climate projections over the next century is important.

In the long-term, adaptation must also be coordinated with mitigation actions that will be implemented concurrently, as the success of each will depend on the other. Emissions reduction choices will determine the severity of future climate change and its impacts, and thus the degree of adaptation required in the future. At the same time, adaptation has limits, and improved understanding of those limits will better inform mitigation targets. Moreover, specific actions may be beneficial for meeting both adaptation and mitigation goals, or may involve tradeoffs between the two. For example, recharging groundwater, a strategy for increasing freshwater storage, may be more energy intensive than current storage strategies, potentially inhibiting the achievement of mitigation goals.

The uncertainty in future projections, which grows the further into the future projections are made, poses two challenges. The first is that, as discussed above, different models produce different projections of climate change (magnitudes of temperature increase, changes in precipitation, regional patterns, etc.) for the same scenario for greenhouse gas emissions. The second is that the trajectory of future greenhouse gas emissions is uncertain. One can examine ensembles of models to look for common trends (e.g., reduction in overall precipitation in CA as was described above) even when there is uncertainty in the magnitude of those trends to prioritize “low regrets” actions. As in the case above, the fact that six models project a reduction in overall rainfall under both a higher and lower emissions scenario provides greater confidence for prioritizing actions to prepare for a dryer climate in California in the future.

Model projections are often not this consistent, however, and there will be limits to the “certainty” that climate model projections can provide. Different models run under the same emissions scenario can produce very different results. Even in the example given above the magnitude of drying varies considerably (Cayan et al. 2009). Further scientific research can help to narrow this spread, but given the complexity of the system, it is unrealistic to expect that such uncertainty will be eliminated completely. Results also differ across emissions scenario, with higher emissions scenarios generating more severe impacts. This is a different kind of uncertainty—it is impossible to predict the future path of greenhouse gas emissions with certainty. One path forward is more formal assessment of expert opinion regarding the relative likelihoods (also called “Bayesian,” or subjective probability) of different scenarios for future emissions and therefore climate impacts, but such weighting will always be based on “educated guesses.”

Finally, more work can be done to make existing projections of climate change available in a form that decisionmakers can use. This special issue as a whole is such an attempt (see also, Mastrandrea et al., 2010). Decision-makers want understandable information about climate change risks. In particular, planners and managers seek climate information that can support adaptation-related decision-making, provide straightforward estimates of uncertainty, and serve the needs of decision-makers in specific sectors. Such knowledge is ideally co-produced through sustained stakeholder-scientist interactions. If the goal is to turn scientific analysis into policy action, then stakeholders and scientists must connect at all stages of the process: problem-detection, design of adaptation and mitigation plans, and implementation.

Acknowledgements M.D. Mastrandrea acknowledges partial support from the Climate Decision Making Center (created through a cooperative agreement between the National Science Foundation (SES-0345798) and Carnegie Mellon University). We would also like to thank Louise Bedsworth, Ellen Hanak, and anonymous reviewers for their helpful comments during the preparation of this article.

References

Bindoff NL, Willebrand J, Artale V, Cazenave A, Gregory J, Gulev S, Hanawa K, Le Quéré C, Levitus S, Nojiri Y, Shum CK, Talley LD, Unnikrishnan A (2007) Observations: oceanic climate change and sea level. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

California Climate Change Center (2006) Our changing climate: Assessing the risks to California. Sacramento, California

California Department of Finance (2007) Population projections for California and its counties 2000–2050. Sacramento, California

California Energy Commission (1989) The impacts of global warming on California. Interim Report, Sacramento, California, August

California Natural Resources Agency (2009) 2009 California climate adaptation strategy, pp 200

Cayan DR, Maurer E, Dettinger M, Tyree M, Hayhoe K (2008a) Climate change scenarios for the California region. Clim Chang 87(Suppl 1):S21–S42

Cayan DR, Bromirski PD, Hayhoe K, Tyree M, Dettinger MD, Flick RE (2008b) Climate change projections of sea level extremes along the California coast. Clim Chang 87(Suppl 1):S57–S73

Cayan DR, Tyree M, Dettinger MD, Hidalgo H, Das T, Maurer E, Bromirski PD, Graham N, Flick RE (2009) Climate change scenarios and sea level rise estimates for California - 2008 Climate Change Scenarios Assessment - Final Report. California Energy Commission, PIER Report CEC-500-2009-014-F

Climate Action Team (2009) Climate action team biennial report to the governor and legislature. Sacramento, California

Hayhoe K et al (2004) Emissions pathways, climate change, and impacts on California. Proc Natl Acad Sci 101:12422–12427

Hidalgo, HG, Dettinger, MD, Cayan, DR (2008) Downscaling with constructed analogues: Daily precipitation and temperature fields over the United States. California Energy Commission, PIER Project Report CEC-500-2007-123

Kapnick S, Hall A (2009) Observed changes in the Sierra Nevada Snow Pack: Potential Causes and Concerns. PIER Technical Report CEC-500-2009-016-F

Knowles N, Cayan DR (2002) Potential effects of global warming on the Sacramento/San Joaquin watershed and the San Francisco estuary. Geophys Res Let 29:1891–1895

Mastrandrea, MD, Tebaldi, C, Snyder, CP, Schneider, SH (2009) Current and future impacts of extreme events in California. California Energy Commission, PIER Technical Report CEC-500-2009-026-D

Mastrandrea MD, Heller NE, Root TL, Schneider SH (2010) Bridging the gap: linking climate-impacts research with adaptation planning and management. Clim Chang 100:87–101

Meehl G et al (2005) How much more global warming and sea level rise? Science 307:1769–1772

Meehl GA, Stocker TF, Collins WD, Friedlingstein P, Gaye AT, Gregory JM, Kitoh A, Knutti R, Murphy JM, Noda A, Raper SCB, Watterson IG, Weaver AJ, Zhao Z-C (2007) Global climate projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate Change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Milly PCD, Betancourt J, Falkenmark M, Hirsch RM, Kundzewicz ZW, Lettenmaier DP, Stouffer RJ (2008) Stationarity is dead: whither water management? Science 319:573–574

Rahmstorf S (2007) A semi-empirical approach to projecting future sea-level rise. Science 315:368–370

Schneider SH et al (2007) Assessing key vulnerabilities and the risk from climate change. In: Parry M et al (eds) Climate Change 2007: Impacts, adaptation, and vulnerability—Contribution of Working Group II to the Intergovernmental Panel on Climate Change Fourth Assessment Report. Cambridge University Press, Cambridge, pp 779–810

Smith, JB, Vogel, JM, Cromwell, JE (2009) An architecture for government action on adaptation to climate change. Clim Change 95:53–61

Wigley TML (2005) The climate change commitment. Science 307:1766–1769

Wilkinson R (2002) The potential consequences of climate variability and change for California. The California Regional Assessment. USGCRP http://www.usgcrp.gov/usgcrp/nacc/california.htm

Willows R, Connell R (eds) (2003) Climate adaptation: Risk, uncertainty and decision-making. UKCIP Technical Report. United Kingdom Climate Impacts Program, Oxford

Wood AW, Leung LR, Sridhar V, Lettenmaier DP (2004) Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs. Clim Chang 62:189–216