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Internalizing Climate Change—Scientific Resource Management and the Climate Change Challenges

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ABSTRACT:

Current projections of climate change present a number of challenges to scientists and decision-makers. The projections predict a twenty-first-century climate in which many climate variables are likely to trend across broad geographical areas and at rates that are rapid by historical standards. The projections of change are likely to remain uncertain for many years to come, and complete surprises are possible. Responses to these changes will have to span large areas and many variables, and impacts will interact in complex ways. In the face of these challenges, we offer recommendations as to strategic approaches that the CALFED Science Program—which serves here as an important and illustrative example from among the many current scientific resource- and ecosystem-management programs—and the scientific and public-policy communities in central California, in general, may need to pursue. Recommended strategies include emphasis on long-term eco- and resource-system adaptability—rather than historical verisimilitude—in its restoration targets; major commitments to long-term monitoring of restoration and impacts; even more integration across scientific disciplines, observations, models, and across the study area; increased use of manipulative experiments; and recognition that climate-change issues must be addressed in all efforts undertaken by the program.

KEYWORDS:

Climate, climate change, adaptive management, adaptation, uncertainty

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INTRODUCTION

The recent increase in scientific and public concern about climate change has many agencies searching for ways to address the predicted changes in their planning and operations. In this article, some of the main characteristics of current projections of climate change are outlined, and near-term strategies for dealing with climate change in a large scientifically-based ecosystem and resource management program

are proposed. This article is intended to convey some important strategic considerations but does not purport to have final answers. Rather, the authors hope that this paper will spark discussion of the management challenges associated with climate change so that scientists working in support of major resource-management programs will re-think and, where necessary, re-focus observational, analytical, and management priorities soon.

The large ecosystem- and resource-management program that will provide the real-world focus of this discussion of climate-change accommodation strategies is the CALFED Bay-Delta Program in California. CALFED, a consortium of 25 state and federal member agencies (CALFED Bay Delta Program 2000), coordinates a large ecosystem-restoration and resource-planning effort, with a geographic focus on the San Francisco Bay-Sacramento/San Joaquin River Delta (Figure 1).

Because of the interconnectedness of the systems, CALFED also pursues efforts and restoration in the downstream San Francisco Bay and on its large upstream watershed (Figure 1). The Delta, in which populations for several key pelagic organisms are declining, is the nexus of California's state-scale water-supply delivery systems. Historical wetlands have been reduced by over 90%, and the present ecological and physical configuration of the Delta does not appear to be sustainable (Healey et al. 2008). CALFED was formed with the express goal of improving both ecological health and water management in the San Francisco Bay-Delta and its watershed. The program was envisioned as a 30-year attempt through inter-agency coordination and decision-making as well as adaptive-management approaches to improve deteriorating ecosystems, stressed water supplies, threatened water quality, and precarious levee systems in the Bay and Delta. CALFED's Science Program plays a central role in the overall program, developing, synthesizing, and supporting observations and investigations to provide sound foundations for the decision-makers who address these complex and conflicting physical, ecological, and social systems and problems.

Mount et al. (2006) have identified several primary drivers of future risk and adverse change in the Delta:

- land subsidence
- invasive species
- population growth and urbanization
- seismicity
- climate change with sea-level rise

Because of large uncertainties about the workings of the system and the future stresses it will face, science-based adaptive management is a central theme of the strategy laid out by the Record of Decision (ROD) that established the CALFED Bay-Delta Program (CALFED Bay Delta Program 2000). Adaptive management is defined in the ROD as:

> using and treating actions as partnerships between scientists and managers, designing those actions as experiments with a level of risk commensurate with the status of those species involved, and bringing science to bear in evaluating the feasibility of those experiments. New information and scientific interpretations will be developed through adaptive management as the programs progress, and will be used to confirm or modify problem definitions, conceptual models, research, and implementation actions. (p. 75)

As a result, the CALFED Science Program plays a central role in CALFED efforts.

In the following discussion, refinements are suggested for CALFED's adaptive-management strategies to accommodate the challenges and uncertainties associated with projected twenty-first-century climate changes. Taken together, these suggestions amount to a recommendation that the climate-change problem be internalized to become an integral part of the future envisioned by the CALFED Science Program and the Bay-Delta community at large, rather than externalized as a problem that can be addressed in isolation. Strategic responses to the projected climate

Figure 1. Location of the Sacramento-San Joaquin Rivers Delta in California and in relation to major geographic features.

changes, and to the uncertainties that continue to exist about those changes, include:

- emphasis on adaptability as a restoration goal
- commitment to even more long-term monitoring of restoration results than might otherwise be undertaken
- fundamental integration across scientific disciplines, observations, models, and across the study area
- focus on extreme events and manipulative experimentation
- recognition that climate-change issues cannot be separated or externalized from the rest of the problems addressed by the Science Program

While the CALFED Science Program offers a concrete context for the discussion here, all of these strategic responses have wider applicability.

CHALLENGES OF CLIMATE CHANGE

For the purposes of science-program planning, the climate changes and climate-change impacts that began in the late twentieth century and that are projected to accelerate in twenty-first-century California, present many challenges, several of which have not been discussed adequately.

1. The climate of twenty-first-century **California is expected to experience long-term human-induced changes** in response to greenhouse gases that have been added to the global climate system by human activities historically and in the near future. Several decades of warming and a variety of hydrologic and landscape responses have already occurred. These include increased fractions of precipitation falling as rain rather than snow (Knowles et al. 2006), less snowpack on many western mountain ranges (Mote 2003), earlier snow-fed stream-flows (Stewart et al. 2005), and earlier green-up (Cayan et al. 2001)—in large part due to emissions of greenhouse gases during the last half of the twentieth century (Cayan et al. 2001; National Research Council 2001; Intergovernmental Panel on Climate Change (IPCC) 2007; Barnett et al. 2008). The twenty-first-century climate is expected to continue to exhibit broad variations that have characterized California's climate in the past. But, along with those year-to-year variations, human-induced climate changes, mostly in the form of long-term trends, are projected to be larger and more sustained than those long-term fluctuations in the historical period, and comparable to—or larger than—natural climate excursions in the past several millennia (IPCC 2007; Malamud-Roam et al. 2007). These projected changes differ from most past and future climate variations in that they can already be anticipated, and in that they are human-caused. Short-term climate variations in the future may also be larger than those in the twentieth century, as evidenced by many paleoclimate reconstructions (Malamud-Roam et al. 2007), and potentially may be aggravated by the effects of global warming (e.g., Jain et al. 2005). Climate changes are projected to continue during the twenty-first century even if society acts to substantially reduce greenhouse-gas emissions in the near term (IPCC 2007). All in all, tomorrow's climate is not expected to be the same as our grandparents' climate, nor our grandchildren's climate the same as ours.

2. It is increasingly clear that society's emissions of greenhouse gases into the atmosphere are affecting the climate on a global scale (IPCC 2007). Other human activities that have been less studied but that may also be affecting global and regional climates include man's major modifications of surface-water flows and availability (in time and space) along as many as 78% of the major Northern Hemispheric rivers (Dynesius and Nilsson 1994), doubling of the global nitrogen cycle (Vitousek et al., 1997), widespread changes in land cover (WCFSD, 1999), appropriation of more than 50% of land-based net primary productivity (Vitousek et al., 1986), major increases in dust and aerosol contents of the atmosphere (Forster and Ramaswamy 2007), and so on. A wide range of climate variables is likely to be affected, so that climate **changes will be multivariate**. Over California, temperatures are very likely

to continue warming, but, along with that warming, sea level will continue to rise and precipitation amounts, forms, and timing may change along with any number of other lesser or at least less-well-understood climate variables (such as sunshine, humidity, severe storms, winds, waves, etc).

3. Projected climate changes arise mostly from global-scale processes and thus are expected to affect areas much larger than the Bay-Delta watershed area. Consequently, at CALFED's scale, **changes will be geographically pervasive**. There will be gradients and spatial patterns of change within the CALFED watershed; however, few if any areas can be expected to avoid changes. The changes are expected to be geographically so pervasive that avoidance would require some unlikely balancing between the global-to-regional changes and countervailing local changes. Thus, projected climate changes will not be limited to isolated problem areas within the region. Impacts of these pervasive changes will also be pervasive, although they may be very patchy and form mosaics of impacts across the landscape of central California as a result of geographic differences in the levels and forms of climate-change vulnerability.

4. Human-caused **climate changes are likely to be notable for their rapid progress** (e.g., Dettinger 2005). An indication of the projected rates of twenty-first-century climate change over Northern California is provided by the changes in probabilities of exceeding various annual-temperature increases in each decade of the twenty-first century (Figure 2). By the year 2030, an ensemble of 84 projections from 12 current climate models yields almost no years that are cool by historical standards, and, by mid-century, annual temperatures more than +2°C warmer than the historical norm are projected about half the time, compared to essentially never in the twentieth century. To put this warming into perspective, Figure 3 provides illustrations of how even +2°C of warming could result in as much as 25% more rain and less snow in parts of California, and increases in growing season lengths by as many as 2 months. Large, rapid, and long-lasting climate changes have affected the Bay-Delta and watershed system in the past, under natural conditions (Millar et al. 2006, Malamud-Roam et al. 2007). Warm epochs contrasting with cool epochs, and extended droughts contrasting with wet epochs, are all common in California's distant past. Presumably, many aspects of the coming climate changes could be accommodated by California's resources and ecosystems as though they were just another example of the climate variability that has always affected California. However, the general rapidity of the coming changes—and the extent to which we have weakened the state's ecosystems and have pushed engineered systems to near their limits—are likely to hinder the ability of many geomorphic, ecological, engineered, and even political systems to accommodate the climate changes without significant internal reorganization.

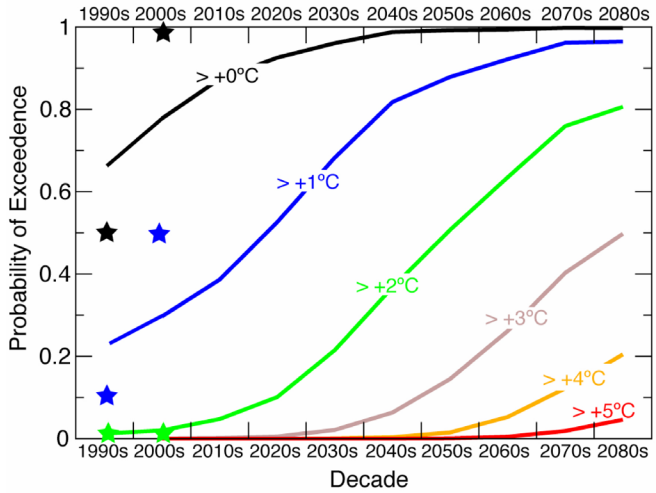

Figure 2. Frequency of projected exceedences of various levels of annual-temperature deviation (anomalies) from a 1950–1999 baseline average by decade in the twenty-first century, based on an ensemble of 84 climate projections based on 12 different climate models and several greenhouse-gas emissions scenarios, re-sampled and analyzed by the methods described by Dettinger (2005). Stars indicate the corresponding observed frequencies during the 1990s and during the first 8 years of the 2000s.

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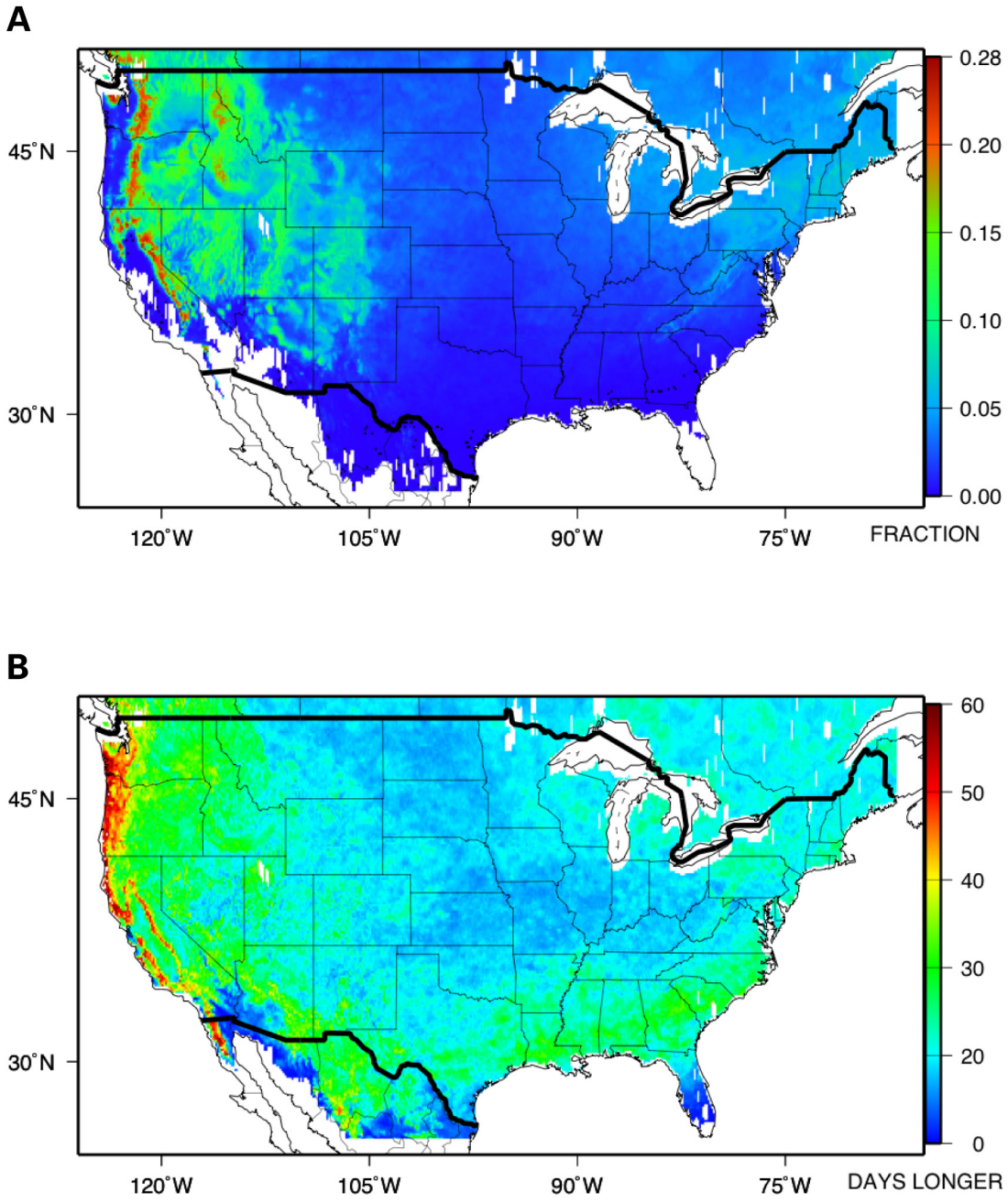

Figure 3. Influences of hypothetical +2°C uniform warming (imposed on historical records of daily temperature and precipitation) on (A) snow versus rain fractions of total precipitation, as the historical fraction of precipitation that fell on days in the temperature range -2°C to 0°C; (B) growing season lengths, with growing season defined as the longest period each year between an initial 3-day period with no temperatures less than 5°C and a last 3-day period with no such temperatures. Panel A is roughly the national version of Figure 1a in Bales et al. (2006), and both are based on the historical gridded meteorological series of Maurer et al. (2002).

5. The exact kinds and rates of change of climate and of the Bay-Delta and watershed systems that will result from accelerating greenhouse-gas emissions during the next 100 years remain uncertain (Dettinger 2005; Maurer and Duffy 2005). The **projected changes are likely to remain uncertain** even as they occur.

6. The climate changes and, especially, the impacts and responses that they will elicit from natural and engineered systems are likely to be **characterized by a bewildering web of interactions** among variables and systems (e.g., Burkett and Kusler 2000; Cloern et al. 2005). Even responses to accommodate the climate changes are likely to interact with, and affect, other objectives and responses in the highly-interconnected Bay-Delta watershed system (Healey et al. 2008).

7. An important aspect of the earth systems underlying future climate changes and climate-change effects is their capacity to produce climate-change **surprises** (Cox 2005; Burkett et al. 2005). Because of the complexity and interconnected processes in the global climate system and in the Bay-Delta ecosystems, climate changes and climate-change effects are not just uncertain in simple terms of error bars around some simple trend. They are also uncertain in the sense that truly unexpected things may happen. Abrupt, disproportionate changes and responses to gradually changing forces have arisen in both climate and ecosystems in the past. Similar surprises are just as possible in the future in response to increasing human influences.

STRATEGIC RESPONSES

Some strategic responses that are suggested by the seven challenges of climate change listed above are listed in Table 1 and discussed below:

Challenge 1: Human-Induced Climate Changes

Because California's twenty-first-century climate is expected to change progressively in response to external global changes rather than fluctuating randomly around some steady long-term average condition, no method, project, or restoration can be considered to be proven or validated for the long term based only on recent performance. Rather, systems that work well this decade may run afoul of the increasingly different climates in subsequent decades. As a consequence, **monitoring of the long-term status** of systems affected by restoration actions and research efforts should receive more consideration than has sometimes been the case. This means making commitments to long-term, multi-decade monitoring almost everywhere long-term restoration is being undertaken. This strategy will compete for—or require additions to—resources that otherwise might have been used for new work, but this seems to be an unavoidable corollary of the continued climate changes expected in the twenty-first century.

Important aspects of the progressively changing climate of the twenty-first century can be anticipated in broad terms. However, ecosystem and resource-system responses to even these anticipated changes are expected to be complex and difficult, presenting unfamiliar challenges to agency managers and decision-makers at all levels. This is not a set of issues that has been familiar to most participants until recently. Efforts by the CALFED Science Program to ensure **an adequate literacy and education of its community of agencies, legislators, and the public with respect to policy-relevant climate science** will make many of the strategic options suggested here easier to explain and implement.

Given the expected changes in twenty-first-century climate, a focus on **restoration that accommodates, adapts to, or remains resilient in the face of expected climate changes is more likely to succeed** than restoration targeted to historical states that worked under past or current climatic conditions. Attempts to recreate systems and conditions that functioned well in the historical past, or to preserve conditions that work well now, may not be suited to the climate of the near future. The corresponding climatic conditions are unlikely to survive the twenty-first century. Some of the projected climate changes (e.g., with respect to precipitation) may take a long time to exceed some of the large climatic excursions that

Table 1. Climate Change Challenges and Strategic Responses

Challenges	Strategic Responses
1. Human-induced climate changes have already begun, and are expected to continue	• Require long-term monitoring commitments from restoration and resource-management activities • Increase climate-science literacy and education • Prioritize ecosystem adaptability in restoration efforts • Evaluate opportunities for operational responses
2. Changes will be multi-variate	• Support multi-disciplinary science • Encourage multi-variate climate monitoring and modeling
3. Change will be geographically pervasive	• Ensure consistency of observational and analytical methods across the region • Focus on geographic connections • Expect California to be highly sensitive
4. Change will be rapid	• Identify maximum rates of adaptability • Undertake manipulative experiments • Consider artificial refugia and seed banking
5. Projections are, and will remain, uncertain	• Address more certain projections directly and less certain changes by increasing flexibility • Pursue risk-based decision-making • Support competing hypotheses • Explore contradictions • Develop and maintain multiple models of important subsystems • Reduce reliance on statistical models • Adopt standard terminologies for uncertainty
6. Effects will interact	• Integrate models • Coordinate across scientific disciplines • Focus on extreme events • Consider energy and greenhouse consequences
7. Surprises are likely	• Emphasize prediction nonetheless • Balance predictive vs. tracking strategies • Increase management flexibility • Expand diversity of response options

have been documented in paleorecords of California's past (Stine 1994), and that the Delta's ecosystems survived then. However, the Delta as currently configured and engineered is probably less flexible than during those past excursions (Healey et al. 2008). As a result, attempts to harden existing ecosystems against some of the more unavoidable responses to large-scale climatic changes may be ill-fated. Instead, CALFED needs to consider pursuing the objective of making ecosystems and resource systems more adaptable or resilient overall to the coming changes. By this, we mean that what may be more likely to succeed in the twenty-first century is focusing on restoring and then maintaining ecosystem services (rather than specific ecosystem configurations and species) as well as on increasing the opportunities for ecosystems to change and migrate successfully, in response to changing environmental conditions.

A related matter is perhaps the most pressing question confronting water-resource management components of CALFED: to what extent can improved resource management forestall or even reverse the need for construction of large additions to the State's water collection, storage, and conveyance capacities? The future climate is likely to require both managerial and structural responses. But, at present, the extent to which improved operations could contribute in both near and long terms has not been well explored. The extent to which large structural responses will be needed can only be evaluated once **potential contributions from management responses based on improved rules, tools, and information** have been thoroughly investigated.

Challenge 2: Multi-Variate Change

Many different aspects of California's climate are likely to change along with the projected warming. As a consequence, climate sensitivities of parts of the ecosystems and resource systems to a variety of climate variables might be disturbed by the climate changes of the twenty-first century. **Integrated, multi- and cross-disciplinary science approaches** to detect, adapt to, and mitigate for these varied changes will eventually be required. In the near term, until we understand more about how the various dimensions of climate change interact, and until we have a better sense of how ancillary climate variables—such as winds and cloudiness—will change, indexing changes to the primary climatic variables of temperatures and precipitation is a useful beginning. However, observed climate-change responses should be attributed to changes in those primary variables only with considerable caution.

With several different climate variables changing at the same time, climate-monitoring efforts in support of CALFED Science, by and large, should not be restricted to traditional temperature and precipitation gages. Rather, **monitoring of climate variables in addition to temperature and precipitation at more sites** in the CALFED watershed will be important to detect and attribute climate causes and effects. These other variables include solar and longwave radiation, winds, and humidity. Since its inception, CALFED has sponsored Indicator Workgroups that have labored to identify the most useful and widely-accepted indicators of ecological and resource outcomes from the Science Program. In the context of climate change, the stage upon which CALFED plays its role is expected to change. Thus, strong indicators of the driving forces are important. Where practical, it would be farsighted of CALFED to support monitoring of climatic variables that extend both above and below land and water surfaces to provide more complete depictions of the climatic conditions that are driving change in the Bay-Delta and watershed systems. More diverse climate monitoring will allow for more complete tracking of the coming climate changes, and will provide important inputs for more comprehensive models and assessments of climate influences on all aspects of the Bay-Delta and watershed systems.

Furthermore, **models of how these other climate variables induce changes in ecosystem character or function need to be developed**, exercised, and communicated to the larger CALFED community to stimulate consideration of potential ecosystem trajectories. Participants in the recent CALFED Delta Regional Ecosystem Restoration Implementation Plan (DRERIP) Ecosystem Element Conceptual Models effort are developing species life-history conceptual

models that are intended as a framework for assessing the influences of multiple stressors and management actions on the Delta's ecosystems (http://www.calwater.ca.gov/content/Documents/meetings/2006/Item_4.1_DRERIP_Status.pdf) DRERIP could provide a framework for determining which climate changes and variables would be most influential on Bay-Delta ecosystems.

Challenge 3: Geographical Pervasiveness of Change

The geographic pervasiveness of projected climate changes should motivate the CALFED Science Program to **require consistency of observational and analytical methods** across the Bay-Delta and watershed. Only with comparable observations of changes and responses across the region will it be possible to characterize the relative vulnerabilities to, and impacts of, climate change within the system. Given the wide range of drivers of adverse change at work in the Bay-Delta system—drivers which range from acute and local (i.e., local land-use decisions) to chronic and pervasive (as with climate change)—separating climate-change effects from other changes will become impossible unless at least some common methods and standards to monitor and track change and stasis are used throughout the Program.

In addition to consistency of monitoring, the broad geographic reach of climate change as a stressor on the Bay-Delta and watershed systems suggests that the CALFED Science Program should prioritize **integration of conceptual and computational models across at least the largest scales** in the Bay-Delta and watershed systems. CALFED'S DRERIP efforts to construct and link conceptual models of species life-histories should provide an important framework for such integration. Another large-scale model-integration project that CALFED supports is the U.S. Geological Survey's Computational Assessments of Scenarios of Change in the Delta Ecosystem (CASCaDE) Project, which links climate, watershed, Delta hydrodynamic, sediment, aquatic-ecosystems, contaminant, and fisheries models together to address selected scenarios of future Delta change (http://sfbay.wr.usgs.gov/watershed/index.html). The CALFED Science Program also supports investigations of state-scale water-resource system responses to various stressors, including climate change, using both the CALSIM II water-resources-management simulation model and the California Value Integrated Network (CALVIN) water economic-optimization model (following upon efforts by, for example, Brekke et al. 2004 and Tanaka et al. 2006, respectively) of the state and federal water-supply systems.

The links between various local responses to climate changes are likely to be as important as the local responses themselves. Links between responses to climate and responses to other external drivers of change are also likely to be important. The wide reach of coming climate changes suggests that influences exerted by forces outside the Bay-Delta watershed will become important. Thus, a particular **focus on broad geographic connections** is especially warranted. Along these lines, the CALFED Science Program has made systems-encompassing approaches for management of large-scale ecosystem restoration projects a priority (e.g., with DRERIP and CASCaDE), and has strongly focused on the connections between its component activities (Healey et al. 2008) rather than strictly on its individual components. Indeed, a focus on such links is a specific part of the position descriptions of some of its staff scientists.

Although the broadest spatial scales of the projected warming are larger than California, climate changes will also differ locally and, at least as importantly, resource and ecosystem sensitivities to the changes can be expected to vary within California and across the nation. Two simple estimates of sensitivities to warming are mapped in Figure 3 and show that, to first order, California and the other Pacific Coast states may respond to modest warming with some of the largest changes in mixes of rain versus snow, and lengths of growing seasons in the nation (indicated by the locations of the warmest colors on both maps). Similar patterns characterize sensitivities of a number of climate-change responses of particular concern in California, including snowpack duration and some flood risks (Bales et al. 2006). To the extent that the CALFED watershed area proves to be among the areas that are **most immediately sensitive to warming**, the CALFED Science Program may not be in a position to

wait for leadership or results from other regions and levels of government to develop the same urgency as may be felt in California.

Even though California is taking important steps toward leading human societies away from the kind of carbon-intensive technologies and economies that will cause dangerous climate changes at home and abroad (Franco et al. 2008), climate change will mostly be imposed on California as an uncontrolled external force. This relative lack of local control argues for a **focus on adaptations to, and especially adaptability to, climate-change impacts** within the Bay-Delta and watershed region, under the assumption that at least some additional future climate change has already been committed to with past emissions (IPCC 2007), with more change very likely to be added in the decades to come.

Challenge 4: Rapidity of Change

In the face of rapid climate changes, the CALFED Science Program may need to focus on the capacities of various program and ecosystem elements to absorb change and especially on **determining the *rates* at which the elements can absorb change**. In the past, CALFED objectives have more typically focused upon stabilizing this element or restoring that element, but efforts to harden Bay-Delta systems may run afoul of the rapid, externally-imposed stresses threatened by global climate change.

Because the projected changes are expected to be rapid, CALFED may find that a **greater-than-expected reliance on manipulative experiments** is needed. Given significant and continuing uncertainties in climate change projections, interpreting changes and responses is likely to play an important role in how CALFED and resource managers respond. However, because the coming changes are projected to be rapid relative to the capacity of many of the natural and engineered systems to respond, strategies that wait until changes are underway before they identify vulnerabilities and develop accommodation strategies may yield results that are too little, too late. Manipulative experiments to determine how well various biological and engineered systems will fare under artificially-arranged previews of climate change, before the actual changes arrive, may provide important head-starts to develop the scientific basis for decision-making. The need for manipulative experiments is well within the scope of CALFED's adaptive-management strategy, but the rapidity of expected climate changes may require that that strategy be pushed beyond the range that might otherwise have been anticipated. Examples of manipulative experiments could include transplanting ecosystem elements into climatic settings that are more like the climates they will soon face, construction of artificially "askew" landscapes and vegetation communities, and experimental reservoir releases that anticipate stream-flow changes projected for coming decades. Where such manipulations prove infeasible, an emphasis on ecosystem responses to past climate (and sea-level) extremes are a plausible second best, given the relatively novel pace and character of the coming changes.

Some restoration efforts, along with ecological manipulations, may succeed in the face of rapid climate change, but some may fail. Thus, CALFED already may need to consider **establishing artificial refugia and seed banking** for the preservation of critical species and communities that may be lost unexpectedly in the rush of climate changes projected for the twenty-first century and beyond. Refuge populations of salmon (e.g., http://www.delta.dfg.ca.gov/AFRp/documents/restplan_final.html) and delta smelt have been established in the past (e.g., UC Davis's Delta Smelt Culture Facility; Rettinghouse 2005) and can provide examples of how such approaches might be used more widely.

Challenge 5: Uncertainty

The coming climate changes and effects are likely to be characterized by significant and lasting uncertainties well into the twenty-first century. Denial or underplaying of these uncertainties is no more a sound basis for developing management responses than is denial or underplaying of the impacts themselves. Climate-change projections range from some aspects that are increasingly certain to those that are less certain. For example, temperatures are strongly expected to continue their rise; warming will likely

accelerate along with—and eventually faster than—society's growing greenhouse-gas emissions (Hayhoe et al. 2004). Along with warming, sea-level rise will continue and very likely accelerate (Cayan et al. 2008). Other aspects of current projections are much more uncertain: northern California precipitation may increase or decrease (Dettinger 2005), winds over the Delta may change to an essentially unspecified degree, and so on. Given such wide ranges of uncertainties, a reasonable response is to **address vulnerabilities to the more confidently-predicted changes, such as warming, head on**, while also **increasing the capacity for flexible responses and adaptations to more uncertain aspects such as precipitation**. Decisions and accommodations related to climate change will continue to entail significant uncertainties, and, thus, responses to climate-change projections will be best formulated as **risk analyses**. That is, given that the details of climate change will remain uncertain, decisions must be made by explicitly weighing the diminishing odds that predicted impacts will not develop against the costs if they do. At present, even the most conservative projections of twenty-first century warming threaten to cause significant and even potentially dangerous changes in the state's resource and ecosystems (e.g., Dettinger et al. 2004; Hayhoe et al. 2004).

In view of the large uncertainties, scientific approaches to resource management should **support competing hypotheses and competing interpretations** of observations and projections. To the extent possible, those scientific and observational strategies that are most likely to uncover and accommodate the unexpected should be encouraged. Among such strategies are the active pursuit and nurturing of multiple and competing interpretations until the less likely hypotheses and interpretations are supplanted or invalidated. Multi-model approaches are likely to cover a wider range of possibilities than would a single model, however advanced or detailed. Contradictions among observations, models, and findings are thus important opportunities that should be identified and explored, and apparently-conflicting explanatory models should best be considered as a collective rather than mutually-exclusive depiction of the uncertain real world. These strategies would increase the expense and efforts that a program such as CALFED Science would incur, but would provide some assurance that designs will not be fitted to the wrong future. Again, this is a natural part of the give-and-take of adaptive management (http://www.resilience.org) to which CALFED has strongly committed, but uncertain climate changes provide yet another motivation for following through with this approach. A prematurely too-certain approach to interpreting or anticipating the fundamental changes ahead is likely to suffer from our inexperience with the new conditions. Solutions that are optimal for the wrong future may turn out to be inflexible or inadequate when the true future emerges.

One aspect of the future that is fairly certain is that many of the lessons learned from the historical period will be stretched to and beyond their applicable limits. Relations between variables and processes that are well-established from the historical era may fail to work under future climate conditions. In particular, the climate changes may stress many historically-reliable statistical relations beyond their limits. **Developing physically-based models and predictors**, rooted in physical and biological "first principles" and well-described processes, rather than on statistical relations, should be a high priority. Similarly, to the extent possible, monitoring should focus directly upon key variables and processes, eschewing easier observations that have been useful because of historical statistical links to the key variables in the past. An example of these considerations comes from the statistical forecasts of April–July water supplies made by the California Department of Water Resources each year, forecasts that are in many ways remarkably accurate but which rely on historical correlations between April snowpack and warm-season runoff. In a warming world, the historical relations that dictate that most of the water that runs off in the warm season is still measured in the region's snowpacks on April 1 each year will weaken as the snowpacks deteriorate. Current statistical forecasts may lose their accuracy more so than more physically-complete models that directly simulate snowpack evolution and soil-moisture considerations in response to weather inputs.

The Intergovernmental Panel on Climate Change (IPCC) has struggled during its past two (5-year) scientific assessments with how best to express climate-change uncertainties. One result has been adoption of a standard terminology to describe various levels of uncertainty. For example, the IPCC has internally agreed that all of its elements will define "very likely" to mean "having a 90% likelihood of correctness" and "extremely likely" as "having a 99% confidence level." This particular terminology may not meet CALFED's needs for communicating uncertainties because of this terminology's strong tendency to reject many true statements in order to minimize the number of false statements allowed, and because, in its simplest form, it can mask important issues of the time-scales over which risks accrue (Mount and Twiss, 2005). Thus, it might be wise for the Science Program to establish **standard guidance for determining and expressing levels of certainty and uncertainty** to be applied throughout the Program, sooner rather than later. Such standards make communications clearer from the start, and also provide targets for design of experiments and analyses, e.g., "how many samples or years of observation will it take to reach the very likely 90% confidence level?" To carry such standards even further, Quinn (2007) recently contrasted the ways that scientists express certainties in normal speech with how lay people use the same terms, noting, for example, that the phrase "scientists believe that ..." is often an expression of broad consensus and considerable certainty among scientists, whereas, for laypeople, "beliefs" more often describe opinions that draw more on faith than on direct evidence. Thus, along with standard terminologies for levels of uncertainty, the CALFED Science Program may want to promulgate guidance as to how various levels of scientific belief, hypothesis, theory, and laws can best be related to the public.

Challenge 6: Interactions

Interactions among the varied aspects of climate change can amplify and hasten their individual impacts. Complex and complexly-interacting systems often respond to stimuli faster than can any individual component, with the classic example being a school of fish that responds to threats faster on average than the individual fish. The rates and magnitudes of climate-change effects in both the natural and human systems are likely to exceed the sum of the direct impacts on individual components and sectors. Thus it is important that predictions of climate-change effects and responses in the Bay-Delta and watershed be based on **conceptual models that are integrated across as many scales and components** as possible.

The wide range of interactions that may be expected to characterize climate-change impacts means that, unless studies and observations from the various sectors and settings of the CALFED Science Program are inter-comparable, interpreting and identifying the interacting effects across scales and systems will prove impossible. In the end, though, climate changes will affect the entire region simultaneously; there will be no neatly-separated climate changes to be isolated and evaluated one by one. At the highest levels of the CALFED Program, adaptive management can only be a scientific and successful process if the results arriving at the top are expressed in common currencies, across geographical areas, across disciplines, and across objectives. The complex interactions amongst climate-change effects eventually are likely to affect most of the CALFED Program efforts and successes, and **will make multi-disciplinary and cross-discipline consistency among the Program elements and observations more critical**.

One set of interactions likely to determine rates and magnitudes of system responses to climate changes is the relationship between changing climate averages and the ongoing variability of the natural climate system. Many of the most immediate and largest effects of long-term climate change may arise when they amplify the impact of extreme events that themselves may not be caused directly by climate change. For example, the most immediately dangerous impacts of sea-level rise are likely to occur in locations where a slow sea-level rise encourages more frequent short-term inundations of areas during storm surges and floods (Cayan et al. 2008). For another example, storms that otherwise might not have caused floods will be more likely to do so under warmer conditions

(e.g., Dettinger et al. 2004). Thus, **improved understanding and prediction of short-term extreme events** is likely to be an important component of science-based responses to long-term climate change.

Other interactions are the relations between water-resource management, ecosystem restoration, energy, and emissions of greenhouse gases to the atmosphere. California's water-supply systems are important generators of electricity, but also are important users of electricity. Notably, the State Water Project is the largest single user of electricity in the state, and a net user of electricity (Cohen et al. 2004). The major surface-water storage options that CALFED has considered thus far would also be net consumers of energy (Cohen et al. 2004). Thus, large-scale water-supply decisions generally have significant implications for the state's energy systems. In addition to energy demands and costs, decisions about the future of California's water systems will presumably have implications for the state's greenhouse-gas emissions. Similarly, large-scale ecosystem restorations of the sort undertaken by CALFED also will have **implications for the state's energy demands and greenhouse-gas emissions**. Because the severity of projected climate changes depends upon the amounts of greenhouse gases emitted (Hayhoe et al. 2004), and because California is roughly the ninth-largest emitter of greenhouse gases globally (Climate Action Team 2005), controlling these emissions may become politically and economically more important in the future. The impacts of CALFED management and restoration activities on emissions and sequestration of greenhouse gases will likely contribute to the eventual costs and benefits of many of its decisions.

Challenge 7: Surprises

The potential for climate-change surprises and surprising impacts poses very difficult challenges for the CALFED Science Program. As counter-intuitive as it might seem, a reasonable response is to place **increased emphasis on forecastability** in CALFED's adaptive-management strategies. First, unless the best predictions of climate and impacts are made and continually tested, recognition of surprises will take a long time, even as the surprises emerge. Second, the surprises in climate change will most likely be like "punctuated equilibria" in evolutionary systems (Gould 1977) so that, most of the time, standard predictions that incorporate the more gradual changes will work reasonably well. These predictable times may be separated by brief but potentially destructive interludes of surprise. Thus, the expectation should be that modern (and improving) climate-model projections and the attendant projections of climate-change impacts will work most of the time. As the CALFED community strives to accommodate competing visions of the Bay-Delta system, gains to be obtained from projections can still be valuable on operational time-scales. Third, on longer planning time-scales, if we have learned nothing else from society's release of greenhouse gases into the atmosphere during the past century, we should know that without proper attention to forecasts based on the best available scientific resources, every climate change will be experienced as a surprise.

Nonetheless, the prospect of climate and climate-driven surprises—arising from complexities in the systems involved—also suggests that too much reliance on predictions alone will be a mistake. Climate-change surprises will be a distinct possibility in the foreseeable future. For managers facing the prospect of surprise, **a balance between "predict-and-plan" strategies and "track-and-accommodate" strategies will be needed**. As changes accumulate and impacts accrue, some can be anticipated (e.g., the most directly warming-induced effects) and adaptations should be planned. Such challenges may be anticipated, and groundwork for accommodations put in place, before the worst effects occur. Other challenges will need to be accommodated as they happen, with little opportunity for much forethought either because they are surprises or because their details could not be predicted accurately. Successful "track-and-accommodate" strategies depend on strong multi-variate monitoring commitments to glean whatever early warnings are possible.

Because surprises may threaten long-term planning, an important objective of CALFED implementing-agency plans should be to **build the capacity for management and restoration flexibility by expanding the range and diversity of responses** available to future

managers by either structural or operational (economic, legal or regulatory) means. To achieve this, rigid goals that can block the recognition of surprises or opportunities should be avoided. Instead, cross cutting and simply-stated and simply-evaluated goals would better promote coherence and more diverse and responsive adaptation than would overly-specific and definitive rules and milestones. CALFED's success may ultimately be judged on the basis of how much capacity for adaptation to surprises it was able to institute.

Finding the correct mix of these several approaches and objectives—employing better predictions, better tracking, and greater diversity of management options—is yet another possible goal for the adaptive-management approaches to be applied at the highest levels of CALFED. We do not know the correct mix, and will only discover it by experimentation.

CONCLUSION

Overall, climate change presents a wide range of challenges that may be addressed best by "internalizing" the issue, rather than by treating it as a new and separate problem. Climate change threatens to change the landscape upon which restoration and management decisions will succeed or fail, even as those decisions are being made and implemented. Rather than thinking about it as a separate problem, we would do well to recognize that the climate of the foreseeable future will be a constantly-changing framework upon which all of our other ecosystem and resource problems will be draped (Milly et al. 2008). If we attempt to cordon off the climate-change issue as a separate problem, we are likely to miscast the contexts of and solutions to many of the other problems we face. If under-estimated and treated as an isolated issue, climate change could overturn quickly and decisively some of CALFED's more pressing objectives and successes. Instead, the challenges presented by current climate-change projections require broad strategic responses and re-emphasis of some of the core Science Program strategies: all the lessons of adaptive management become the more important under an uncertainly-changing climate. One key challenge may be the recognition that current climate-change projections recommend that at least one core objective of the CALFED Program be re-thought: should ecosystem restoration in a changing climate be primarily about recreating or enforcing some desired conditions or functions, or should its primary target be building capacity for ecosystem and resource-system adaptability to an as-yet-uncertain and potentially difficult future? Although California's climate has varied often in the long-term past, its landscapes and ecosystems have not been confronted with the combination of local and global human-induced changes that will be imposed on it in the twenty-first century and beyond. Adaptability will have everything to do with recovery and survival of the ecosystems and water-resource systems that are at the heart of the CALFED Bay-Delta Program.

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