Technical Memorandum: Delta Risk Management Strategy (DRMS) Phase 1

Topical Area:

Climate Change

Draft 2

Prepared by:
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Prepared for:
California Department of Water Resources (DWR)

June 15, 2007

URS

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Subject: Delta Risk Management Strategy
Phase 1 Draft 2 Technical Memorandum –- Climate Change

Dear Mr. Svetich,

Please find herewith a draft copy of the subject technical memorandum. Members of the Steering Committee's Technical Advisory Committee and agency staff have reviewed the draft technical memorandum, and this second draft addresses their comments.

This document was prepared by Professor Philip B. Duffy (University of California, Merced). The DRMS Climate Team is indebted to our colleagues for providing crucial guidance and model results. Dan Cayan, Mike Dettinger, Ruby Leung, Ed Maurer, and Mary Tyree all provided information that has been critical to the progress of this project. We very much appreciate their cooperation and support. This technical memorandum was reviewed by Drs. Said Salah-Mars (URS) and Marty McCann (JBA). Internal peer review was provided in accordance with URS' quality assurance program, as outlined in the (DRMS) project management plan.

Sincerely,

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Topical Area: Climate Change

Preamble

The Delta Risk Management Strategy (DRMS) project was authorized by DWR to perform a risk analysis of the Delta and Suisun Marsh (Phase 1) and to develop a set of improvement strategies to manage those risks (Phase 2) in response to Assembly Bill 1200 (Laird, Chaptered, September 2005). The Technical Memorandum (TM), is one of 12 TMs (2 topics are presented in one TM: hydrodynamics and water management) prepared for topical areas for Phase 1 of the DRMS project. The topical areas covered in the Phase 1 Risk Analysis include:

1. Geomorphology of the Delta and Suisun Marsh
2. Subsidence of the Delta and Suisun Marsh
3. Seismic Hazards of the Delta and Suisun Marsh
4. Global Warming Effects in the Delta and Suisun Marsh
5. Flood Hazard of the Delta and Suisun Marsh
6. Wind Wave Action of the Delta and Suisun Marsh
7. Levee Vulnerability of the Delta and Suisun Marsh
8. Emergency Response and Repair of the Delta and Suisun Marsh Levees
9. Hydrodynamics of the Delta and Suisun Marsh
10. Water Management and Operation of the Delta and Suisun Marsh
11. Ecological Impacts of the Delta and Suisun Marsh
12. Impact to Infrastructure of the Delta and Suisun Marsh
13. Economic Impacts of the Delta and Suisun Marsh

Note that the Hydrodynamics and Water Quality topical area was combined with the Water Management and Operations topical area because they needed to be considered together in developing the model of levee breach water impacts for the risk analysis. The resulting team is the Water Analysis Module (WAM) Team and this TM is the Water Analysis Module TM.

The work product described in these TMs will be used to develop the integrated risk analysis of the Delta and Suisun Marsh. The results of the integrated risk analysis will be presented in a technical report referred to as:

14. Risk Analysis – Report

The first draft of this report was made available to the DRMS Steering Committee in April 2007.

Assembly Bill 1200 amends Section 139.2 of the Water Code, to read, "The department shall evaluate the potential impacts on water supplies derived from the Sacramento-San Joaquin Delta based on 50-, 100-, and 200-year projections for each of the following possible impacts on the delta:

1. Subsidence.
2. Earthquakes.
3. Floods.
4. Changes in precipitation, temperature, and ocean levels.
5. A combination of the impacts specified in paragraphs (1) to (4) inclusive."

In addition, Section 139.4 was amended to read: (a) The Department and the Department of Fish and Game shall determine the principal options for the delta. (b) The Department shall evaluate and comparatively rate each option determined in subdivision (a) for its ability to do the following:

1. Prevent the disruption of water supplies derived from the Sacramento-San Joaquin Delta.
2. Improve the quality of drinking water supplies derived from the delta.
3. Reduce the amount of salts contained in delta water and delivered to, and often retained in, our agricultural areas.
4. Maintain Delta water quality for Delta users.
5. Assist in preserving Delta lands.
6. Protect water rights of the "area of origin" and protect the environments of the Sacramento- San Joaquin river systems.
7. Protect highways, utility facilities, and other infrastructure located within the delta.
8. Preserve, protect, and improve Delta levees.…"

In meeting the requirements of AB 1200, the DRMS project is divided into two parts. Phase 1 involves the development and implementation of a risk analysis to evaluate the impacts to the Delta of various stressing events. In Phase 2 of the project, risk reduction and risk management strategies for long-term management of the Delta will be developed.

Definitions and Assumptions

During the Phase 1 study, the DRMS project team developed various predictive models of future stressing events and their consequences. These events and their consequences have been estimated using engineering and scientific tools readily available or based on a broad and current consensus among practitioners. Such events include the likely occurrence of future earthquakes of varying magnitude in the region, future rates of subsidence given continued farming practices, the likely magnitude and frequency of storm events, the potential effects of global warming (sea level rise, climate change, and temperature change) and their effects on the environment. Using the current state of knowledge, estimates of the likelihood of these events occurring can be made for the 50-, 100-, and 200-year projections with some confidence.

While estimating the likelihood of stressing events can generally be done using current technologies, estimating the consequences of these stressing events at future times is somewhat more difficult. Obviously, over the next 50, 100, and 200 years, the Delta will undergo changes that will affect what impact the stressing events will have. To assess those consequences, some assumptions about the future "look" of the Delta must be established.

To address the challenge of predicting impacts under changing conditions, DRMS adopted the approach of evaluating impacts absent changes in the Delta as a baseline.

This approach is referred to as the “business-as-usual” (BAU) scenario. Defining a business-as-usual Delta is required, since one of the objectives of this work is to estimate whether ‘business-as-usual’ is sustainable for the foreseeable future. Obviously changes from this baseline condition can occur; however, as a basis of comparison for risks and risk reduction measures, the BAU scenario serves as a consistent standard rather than as a “prediction of the future” and relies on existing agreements, policies, and practices to the extent possible.

In some cases, there are instances where procedures and policies may not exist to define standard emergency response procedure during a major (unprecedented) stressing event in the Delta or restoration guidelines after such a major event. In these cases, prioritization of action will be based on: (1) existing and expected future response resources, and (2) highest value recovery/restoration given available resources.

This study relies solely on available data. Because of the limited time to complete this work, no investigation or research were to be conducted to supplement the state of knowledge.

Perspective

The analysis results presented in this technical memorandum do not represent the full estimate of risk for the topic presented herein. The subject and results are expressed whenever possible in probabilistic terms to characterize the uncertainties and the random nature of the parameters that control the subject under consideration. The results are the expression of either the probable outcome of the hazards (earthquake, floods, climate change, subsidence, wind waves, and sunny day failures) or the conditional probability of the subject outcome (levee failures, emergency response, water management, hydrodynamic response of the Delta and Suisun Marsh, ecosystem response, and economic impacts) given the stressing events.

A full characterization of risk is presented in the Risk Analysis Report. In that report, the integration of the probable initiating events, the conditional probable response of the Delta levee system, and the expected probable consequences are integrated in the risk analysis module to develop a complete assessment of risk to the Delta and Suisun Marsh.

Consequently, the subject areas of the technical memoranda should be viewed as pieces contributing to the total risk, and their outcomes represent the input to the risk analysis module.

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List of Acronyms and Abbreviations

AR4	Fourth Assessment Report of IPCC (same as FAR)
CDF	Cumulative distribution function
CIMIS	California Irrigation Management Information System
cm/yr	centimeter(s) per year
CSM	Climate System Model
DRMS	Delta Risk Management Strategy
ENSO	El Niño/Southern Oscillation
FAR	Fourth Assessment Report (of IPCC; same as AR4)
GCM	Global Climate Model
GFDL	Geophysical Fluid Dynamics Laboratory
IPCC	Intergovernmental Panel on Climate Change
km	kilometer(s)
km^3/yr	cubic kilometer(s) per year
mm/yr	millimeter(s) per year
NCAR	National Center for Atmospheric Research
PCM	Parallel Climate Model
PCMDI	Program for Climate Model Diagnosis and Intercomparison
PDF	probability density function
PNNL	Pacific Northwest National Laboratory
SRES	Special Report on Emissions Scenarios
TAR	Third Assessment Report (of IPCC)

Topical Area: Climate Change

1. Problem Statement

1.1 Recent and Future Climate Change in California

Climate change is occurring now in California. Recent temperature trends in California have been shown to be too rapid to be explained solely by "natural internal variability;" i.e., sources of variability internal to the climate system; i.e., oscillations of the nonlinear ocean-atmosphere-sea ice-land surface system (Bonfils et al. 2006). This implies that some external factor(s) are contributing to observed warming trends. Although these factors could in principle be of natural origin (specifically solar variability or volcanic eruptions), the greater likelihood is that human activities are the dominant contributor. The primary mechanism of warming is likely increased atmospheric greenhouse gases. The radiative effects of these well-mixed gases occur everywhere, though climate responses vary from region to region depending on the strength of feedback mechanisms. Other human-related factors influencing California's climate include urban and agricultural aerosols (which tend to reduce temperatures and suppress precipitation [Rosenfeld 2000]), urbanization (which tends to increase temperatures, and irrigation (which reduces daytime temperatures in summer [Lobell et al. 2006a, 2006b; Lobell and Bonfils 2006; Bonfils et al. 2006b]). Although the influence of these latter factors can be strong, they primarily act locally and may have minimal effect on large-scale climate.

Increasing temperatures in California have resulted in a shift in precipitation from snow to rain, which in turn has altered the seasonal timing of river flows toward increased flows in winter and reduced flows in spring and summer (Roos 1991; Knowles and Cayan 2002; Stewart et al. 2005). A shift in the seasonal timing of flows on California rivers is a predicted consequence of increased atmospheric greenhouse gases (e.g., Gleick 1987; Maurer and Duffy 2005). This shift results from warming, which increases the fraction of precipitation as rain, and thus increases rainy-season (winter) runoff and river flows, and reduces late-season runoff and river flows (which result primarily from snow-melt). Earlier melting of snow also contributes to this shift. Because it results from warming, it is a robust prediction even though different climate models do not agree on the magnitude or sign of predicted changes in precipitation (Maurer and Duffy 2005).

Changes in river flow timing of the sort predicted to result from warming have been observed on major rivers in California. (Roos 1991, also Stewart et al. 2005). This consistency between model results and observations lends credibility to the predictions. Nonetheless, recent analyses Maurer et al. (2007) indicate that observed changes in river flow timing have not yet exceeded those possible from natural climate variability. Thus, observed changes in river flow timing are consistent with predicted effects of increased greenhouse gases, but also with natural variability. It may seem surprising that trends in temperature are outside the bounds of natural variability (Bonfils et al. 2006), while trends in river flow timing, which are caused by trends in temperature, are not. The reason is that river flow timing, like other hydrological quantities, is subject to very large year -to-year variations.

Warming has also resulted in earlier onset of spring (e.g., earlier snowmelt) in much of the U.S. West, including California (Cayan et al. 2001). Except at the highest elevations in the Southern Sierra, snow water content has decreased (Mote 2003; Mote et al. 2005).

As climate change continues, California will experience:

- Additional warming (Figure 1), including more frequent and severe extreme heat events)
- Further reductions in snowfall and in snow on the ground (Figure 2), and earlier snow melt
- Continued trends toward earlier in-the-year river flows
- Uncertain changes in monthly, seasonal, and annual precipitation amounts (Figure 1)
- Likely increases in maximum daily precipitation amounts
- Rising sea levels
- Possible increased flood risk in winter, and reduced risk in the late season.

Superposed on these decadal-timescale trends will be climate variability on all time scales. This means that, like past climates, future climates will have relatively cool periods. In addition, the character of climate variability itself may change. In particular, more frequent extreme precipitation events are robustly predicted, and result from a sound fundamental result: the increased moisture-holding capacity of a warmer atmosphere. An increase in extreme daily precipitation events, together with the general increase in winter-season river flows, seem likely to result in increased flood potential in that season.

1.2 Effects of Climate Change on the Delta and Levees

Climate change will affect California's levees through altered river flows on daily and seasonal timescales (affecting water levels), increased sea level (affecting water levels), and changes in wind speeds and directions in the Delta (affecting wind/wave action). Less obvious effects include a possible acceleration of the subsidence of Delta islands in response to higher soil temperatures. Although projected changes in precipitation are highly uncertain, the impacts mentioned above are to a large degree independent of small changes in seasonal-mean precipitation.

Water levels in the Delta depend on sea level and river inputs, including short-timescale fluctuations. Increased flood frequency is a predicted consequence of increased atmospheric greenhouse gases ("global warming") in California (Detttinger et al. 2004; Hayhoe et al. 2004; Maurer et al., 2005) and elsewhere (e.g., Whetton et al. 1993; Trenberth 1999; Thumerer et al. 2000). Consistent with this, the frequency of major floods was observed to increased worldwide during the 20th century (Milly et al. 2002).

Mechanisms whereby increased atmospheric greenhouse gases lead to elevated flood risk include sea level rise, more intense daily precipitation events, and shifts in the seasonal timing of river flows. All of these may be occurring now or may occur in the future in California, and could contribute to increased flood risk and levee failure in the Delta. The highest observed water levels in the Delta have resulted to a large extent from short-term increases in river flows, rather than sea level variations (Cayan et al. 2006a).

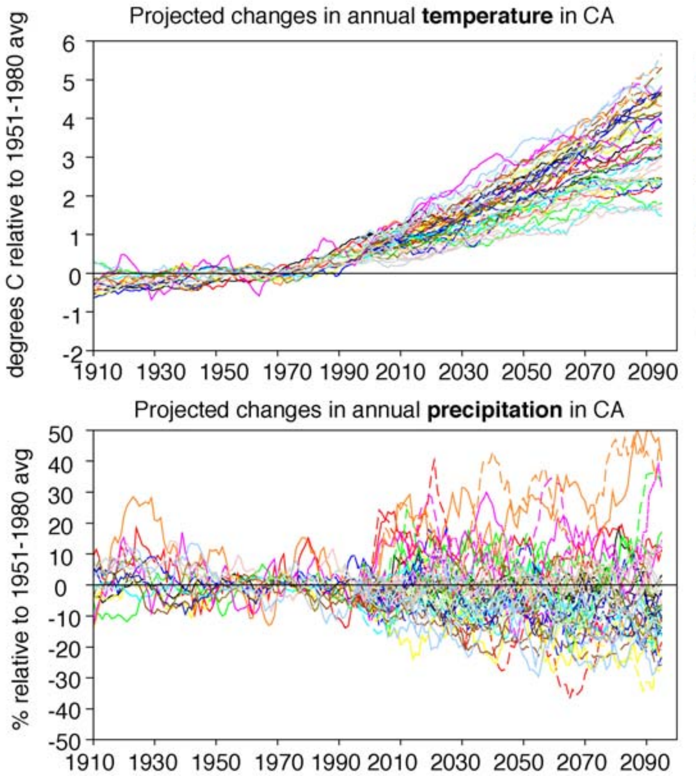

Figure 1
Simulations of Historical and Future Statewide
Mean Temperatures (top) and Precipitation (bottom) for California

Note: Results are from simulations performed with 15 different global climate models and submitted to the data archive of the Intergovernmental Panel on Climate Change Fourth Assessment Report, located at Lawrence Livermore National Laboratory. The models are state-of-the-art coupled ocean-atmosphere-sea ice models developed and run by international research groups. Documentation on the models is available at http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php. For temperature (top), the vertical axis is absolute change relative to mean value in the reference period (1960-1980). For precipitation (bottom), the vertical axis is percent change. With each model, three different greenhouse gas emissions scenarios were simulated. Thus, the spread of results represents uncertainties in both future greenhouse gas emissions and in how the climate system will respond to those emissions. For precipitation, the sign of future changes is unknown. Source: Celine Bonfils, U.C. Merced.

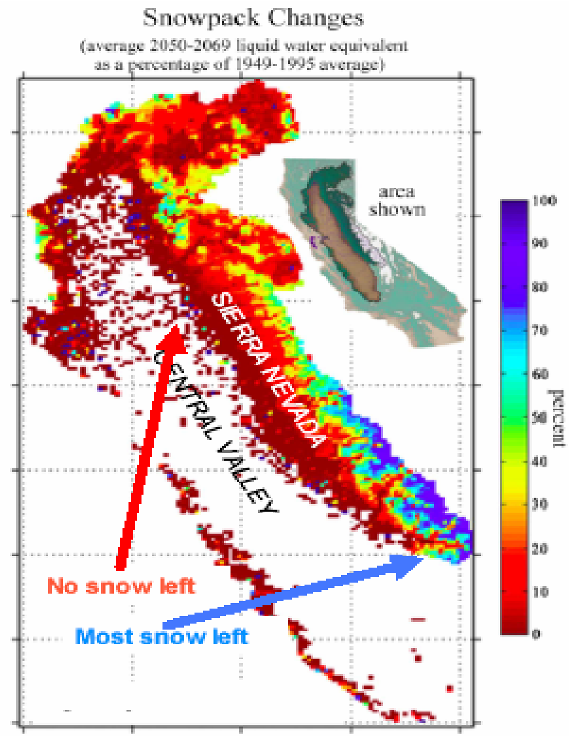

Figure 2 Projected Reduction in California Snow Pack

Note: Projected snow in 2050–2069 as a fraction of that present during 1949-1995. At lower elevations, most or all snow is projected to disappear; these areas appear reddish. At the highest elevations in the Southern Sierra, nearly all snow remains (blue). This is a typical result based on one model (the DOE/NCA PCM model; http://www.cgd.ucar.edu/pcm/); other models would give qualitatively similar but quantitatively different results.

Source: Knowles and Cayan 2002.

2. Technical Approach

The primary purpose of the climate change topical area in the Delta Risk Management Strategy (DRMS) project is to provide the climate change information and projections needed in the other topical areas (wind/wave, flood hazard, subsidence, hydrodynamic modeling, and risk analysis). The following projections are being provided: sea-level rise (on timescales down to hourly), daily river flow rates, in-Delta wind velocities, and statewide temperatures and precipitation. The last two quantities will be used to assess the sensitivity of statewide water demand to climate change.

The overarching philosophy of the DRMS project is to use existing (“off-the-shelf”) results. This is dictated by immutable schedule and budget constraints. As discussed in Section 4 (“Limitations”), this approach introduces some inconsistencies, in that the models and assumptions used to produce projections of one climate quantity may be somewhat inconsistent with those used to project other climate quantities. As a result, what is presented falls short of being a coherent picture of future climate and its impacts on California. Furthermore, our results reflect weaknesses in the present state of the science, including uncertainties in future precipitation trends, and limitations in the estimation of future flood risk. A more desirable technical approach would be to produce self-consistent projections of all needed climate quantities using one set of assumptions and one set of climate and hydrology models. This would involve a substantially larger budget, and much more time, than was available to DRMS. Notwithstanding these constraints, all results adopted here have been published in the peer-reviewed literature and were obtained using state-of-the-art methods and models.

3. Phase 1 Technical Results

3.1 Sea-Level Rise

3.1.1 Introduction

Sea level rise has multiple impacts, some of which are felt well beyond coastal regions. Below the possible important impacts of sea level rise are reviewed. Titus et al. (1984) and others give more thorough discussions.

The most obvious impact is increased risk of coastal flooding. As global sea level increases, areas that were once beyond the range of storm surges (temporarily elevated sea levels resulting from a combination of reduced barometric pressure and high winds) are subject to periodic floods. In addition, penetration of coastal floods further inland can result in greatly increased rates of erosion. Other areas that were previously exposed some or all of the time become permanently inundated as a result of sea level rise. Flooding and inundation have disproportionate societal impacts because coastal regions are nearly always more densely settled than inland regions. Sea level rise can also increase inland flood risk, because higher water tables can result in slower draining of stormwaters.

Rising sea level tends to increase salinity in inland waterways, such as the Delta, that have significant tidal inflows. Because most of the water used in the state passes through the Delta, managed outflows will have to be increased in order to repel intruding seawater and maintain water quality standards; this action, while preserving water quality, will reduce the quantity of water available to meet planned deliveries. Similarly, rising sea level tends to increase salinity of groundwater in coastal regions; this can have significant impacts if this water is used for domestic consumption or irrigation.

In some important areas, including the Mississippi Delta and the Sacramento-San Joaquin Delta, some of the effects of sea level rise are compounded by rates of subsidence that can exceed rates of sea level rise. Local vertical motion of land (e.g., subsidence or isostatic rebound) also complicates the process of determining sea level changes from tide gauge measurements.

In addition to the physical impacts mentioned above, sea level rise also has significant environmental and ecosystem impacts. For example, wetland ecosystems, in many cases already threatened by development, are further stressed by flooding, erosion, and increased salinity. Salt intrusion can affect species that need a freshwater environment, as well as species such as oysters that require minimum salinity levels.

For the Sacramento-San Joaquin Delta, mean sea level determines a baseline water level, to which contributions from river inflows and short-term sea-level fluctuations are added.

This applies to the entire frequency distribution of water levels (Figure 3). In addition, as noted above, salinities increase with increasing sea level, requiring greater outflows (flushing) to maintain acceptable salt concentrations.

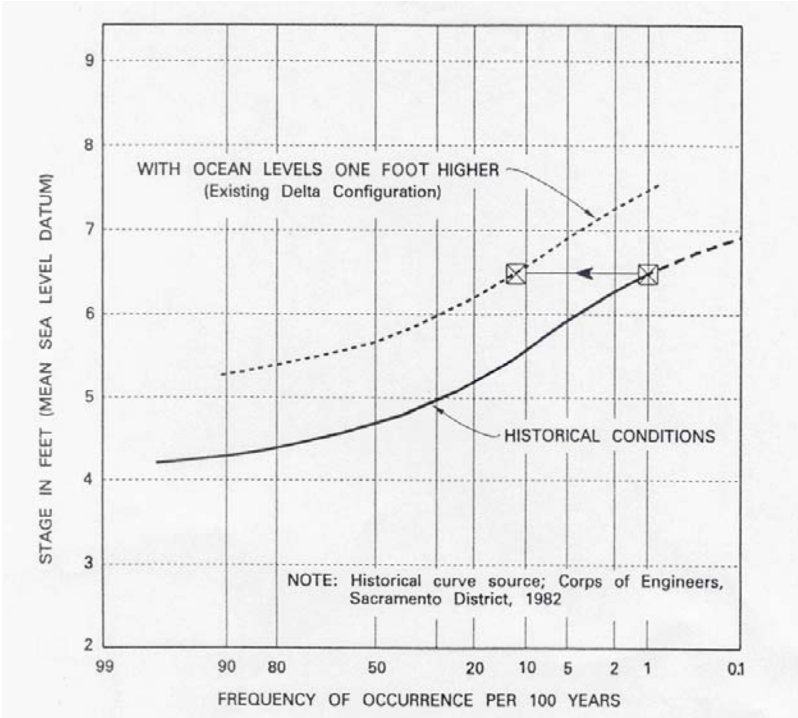

Figure 3 “Stage/frequency curve” at Antioch, California.

Note: The solid line shows the historical frequency of occurrence of water levels measured at Antioch. The dashed curve shows hypothetical frequencies assuming a 1-foot increase in mean (long-term time-averaged) sea level.

Source: Maury Roos (DWR).

3.1.2 Sea Level Rise During the Twentieth Century

Long-term changes in sea level result from (1) thermal expansion or contraction of sea water due to changes in ocean temperature (the “steric” component); (2) changes in ocean mass due to exchanges of water with continental glaciers, ice sheets, ground water, or the atmosphere (the “eustatic” component). Apparent changes in sea level also result from vertical motion of land (e.g., subsidence or isostatic rebound) at locations of tide gauges, and long-term changes in the geometry of ocean basins. The advent of satellite altimetry has lessened the impact of land motions on ability to measure sea level.

In addition to long-term changes, short-term variations in sea levels result from astronomical tides, variations in atmospheric pressure, variations in the local density of sea water due to short-term climate fluctuations (such as ENSO), and changing winds.

Observations of sea level rise during the 20th century are discussed with some thoroughness in the IPCC TAR and IPCC FAR. A few salient results are mentioned here.

Based on consideration of a range of sources, the IPCC TAR estimated a mean rate for sea-level rise of 1.0 to 2.0 mm/yr for 1910–1990. A more recent review by Church et al.

(2004) determined a global rise of 1.8 ± 0.3 mm yr^{-1} during 1950–2000. The IPCC FAR cites a similar range of 1.8 ± 0.5 mm yr^{-1}, for 1961–2003. Measurements made since 1990 using satellite altimetry show a much more rapid increase of 3.1 ± 0.8 mm yr^{-1} over 1993–2005 (Leuliette et al. 2004). Based on this and other sources, the IPCC FAR cites a value of 3.1 ± 0.7 mm yr^{-1} over 1993–2003. While these estimates clearly show higher values for later epochs, it is not clear to what extent this recent acceleration reflects a response to anthropogenic forcing, as opposed to decadal-timescale climate variability.

For the 20th century as a whole, thermal expansion is thought to have caused half or more of global sea level rise (IPCC FAR; Rahmstorf 2006). As discussed in detail below, observations made using a variety of approaches show small but apparently increasing contribution from melting of Greenland. Munk (2002), however, argues that the estimated steric and eustatic components of 20th century sea level rise sum to significantly less than the total observed sea level change (18 cm). Similarly, the IPCC FAR shows that estimates of the different components of sea level rise during 1961-2003 sum to a value that is less than observed total sea level rise, although the two values are barely within combined uncertainties. This paradox may be explained in part by rebound from the Krakatoa volcanic eruption of 1816. As shown by Gleckler et al. (2006) the cooling effect of this eruption actually depressed sea levels; recovery lasted well into the 20th century.

3.1.3 Projections of Future Sea Level

Changes in sea level on timescales of up to 100 years are projected using different methods to estimate different components of sea level rise. Contributions from thermal expansion are simulated using global climate models directly. These models simulate uptake by and transport of heat within the ocean, and calculate sea level using approximations to the nonlinear equation of state for seawater. Contributions from melting of glaciers and ice sheets (excluding Greenland and Antarctica) are not simulated by climate models, but can be estimated using empirical relationships, together with spatially downscaled climate projections from global climate models (e.g., Zuo and Oerlemans, 1997; Oerlemans and Reichert 2000; Oerlemans 2001). Alternatively, a “degree-day method” (in which ablation is proportional to time above the freezing point) has been employed (e.g., De Woul and Hock 2005). Melting of large land ice sheets (Greenland and Antarctica) is simulated using ice-sheet models, driven by meteorological input from global climate models. As discussed below, however, most ice sheet models do not adequately treat ice-dynamical processes, particularly those related to lubrication of the bottom of ice sheets by meltwater. This process can result in much more rapid disintegration of land ice sheets (and correspondingly rapid sea level rise) than would occur via *in situ* melting of the ice.

Sea level projections developed here for the DRMS project are based on results from several sources. Cayan et al. (2006a) made detailed and careful projections of future sea levels in California. These projections include both short-term fluctuations due to weather, climate variations, and astronomical tides and long-term trends due to climate change. Dan Cayan and Mary Tyree of the University of California, San Diego, have provided these sea-level projections to DRMS in digital form.

An important limitation of Cayan et al. (2006a) is the authors do not explicitly project long-term future sea level trends. Instead, they make projections using multiple scenarios (10, 30, 50, 70, and 90 centimeters per year [cm/yr]) for long-term trends without assigning probabilities to the different scenarios. It is left to the user to decide which long-term trend to adopt. For this reason and others, we adopt the results of Cayan et al. (2006a) for short-term (hourly/daily) sea level fluctuations, but use a different approach for projections of long-term sea level trends.

A starting point for projections of 21st century sea level is the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (FAR; *Summary for Policymakers* released on February 2, 2007.) For comparison, we also cite projections from the previous IPCC report, the Third Assessment Report (TAR; available at http://www.grida.no/climate/ipcc_tar/ and published by the Cambridge University Press). Both reports were contributed to by dozens of leading scientists from around the world, and were subject to both thorough scientific peer review and additional governmental review. They are regarded as authoritative summaries of scientific knowledge at the time of their preparation.

The IPCC TAR projects total increases in global sea level between 1990 and 2100 ranging from 9 cm to 88 cm, with a central (not maximum-likelihood) value of 48 cm (Figure 4). This includes a negligible contribution (1 to 3 cm) from melting of Greenland. The quoted range reflects uncertainties due to use of different models (i.e., imperfect understanding of climate responses), as well as different SRES scenarios (i.e., imperfect knowledge of the future rate of increase of atmospheric greenhouse gases, and other factors perturbing climate). The range due to different scenarios, however, is very small: ± 1 cm at 2040, ± ~2 cm at 2040, and ± 9 cm at 2100. The TAR makes no projections beyond 2100.

The IPCC FAR projects increases in global sea level for 2090-2099 relative to 1980-1999 of 28 ± 10 cm to 43 ± 17 cm, depending on which emissions scenario is considered. As shown in Table 1, the midpoint of the range of projections for each emissions scenario is about 10% lower in the FAR than the TAR; i.e., projections of sea-level rise have *decreased*. Furthermore, uncertainty ranges for individual scenarios are much lower in the FAR than the TAR; i.e., uncertainties in projected sea level rise are also claimed to have decreased.

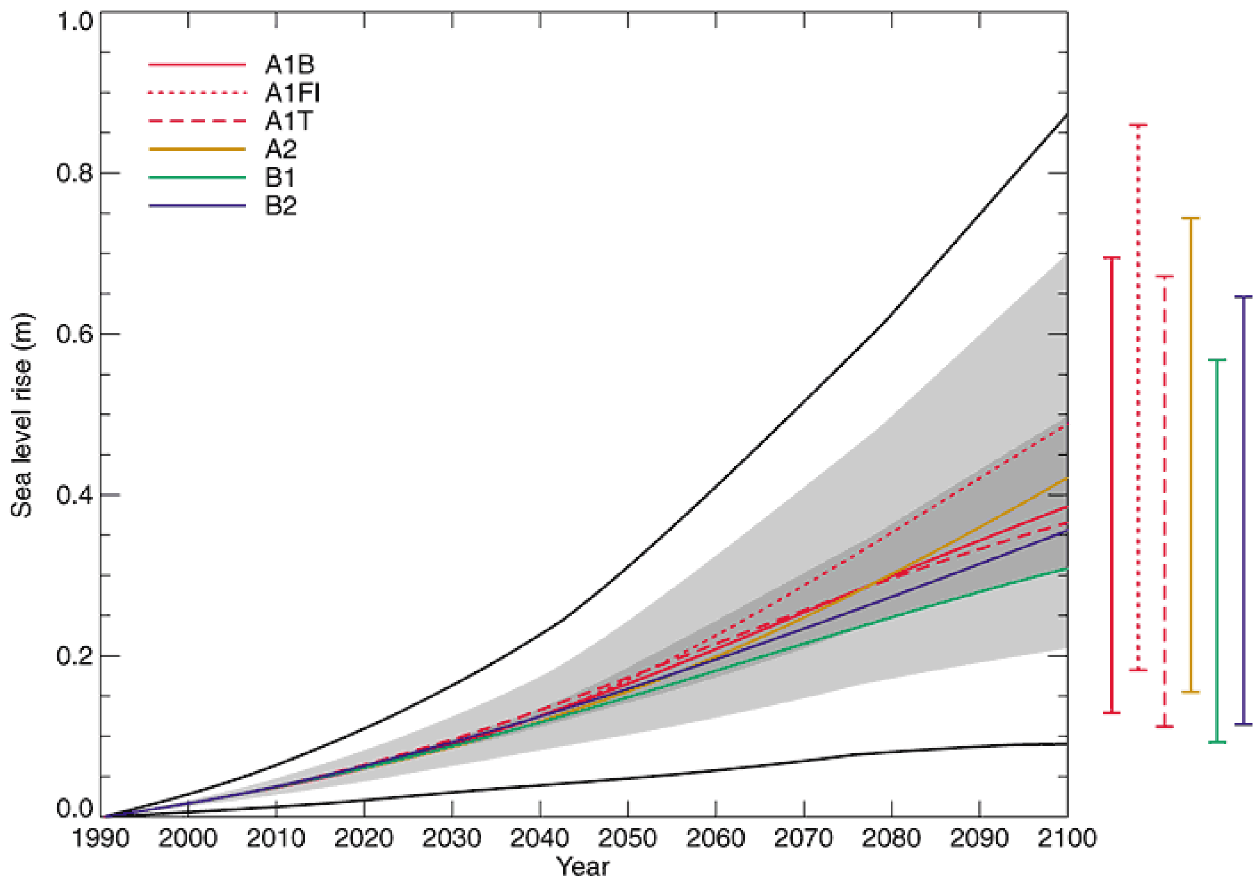

Figure 4 Global average sea level rise 1990 to 2100 for the SRES scenarios, from the IPCC TAR.

Note: Results are shown corresponding to 7 different climate models and multiple greenhouse gas emissions scenarios. Thermal expansion and land ice contributions were calculated using a simple climate model calibrated separately for each of seven comprehensive climate models, and contributions from changes in permafrost, the effect of sediment deposition and the long-term adjustment of the ice sheets to past climate change were added. Each colored curve shows the result for one of six commonly-used SRES scenarios, averaged over all 7 climate models. The region in dark shading shows, for the average of all 7 climate models, the range for all 35 SRES scenarios (i.e., shows the scenario component of uncertainty). The region in light shading shows the range of all AOGCMs for all 35 scenarios (i.e., the sum of scenario uncertainty and uncertainty with respect to choice of climate model). The region delimited by the outermost lines shows the range of all AOGCMs and scenarios including uncertainty in land-ice changes, permafrost changes and sediment deposition. Note that this range does not allow for uncertainty relating to ice-dynamical changes in the West Antarctic ice sheet. The vertical bars show the range in 2100 of all AOGCMs for the six illustrative scenarios.

Source: Figure is from IPCC TAR; caption modified from IPCC TAR.

Table 1 Projections of Global Mean Sea Level Rise (in cm) Between 1990 and 2050 (rows 2 – 6) or 2100 (rows 7 – 11)

	Emissions scenario	IPCC TAR	IPCC FAR	Rahmstorf (2006)
2050	all scenarios	18 ± 13^		31 ± 11*
	A1f1	18 ± 27$	19+ ± 8%	35 ± 4#
	A2	15 ± 27$		
	A1B	16 ± 27$	16@ ± 6	
	B1	14 ± 27$	13+ ± 6%	25 ± 3#
2100	all scenarios	48.5 ± 39.5^		95 ± 54*
	A1f1	48 +38, -30	43 ± 17	102 ± 11#
	A2	42	37 ± 14	
	A1B	38 +31 -25	35 ± 13	
	B1	31	28 ± 10	68 ± 7#

Notes: Results are shown for 4 emissions scenarios (A1f1, A2, A1B, and B1) as well as for all scenarios. For results pertaining to individual scenarios, error bars represent uncertainty in the climate system response (details in notes below). For "all scenarios" results, error bars represent this uncertainty convolved with scenario uncertainty. The column labeled IPCC TAR gives results form the IPCC Third assessment Report, and similarly for IPCC FAR. The column labeled Rahmstorf (2006) gives results obtained using the methodology described in the cited paper; that approach is summarized in the text.

^ This uncertainty reflects scenario uncertainty combined with response uncertainty, as measured by a range of results from seven climate models.

* This uncertainty reflects scenario uncertainty combined with statistical uncertainty in the constant of proportionality (a) in Equation 1.

This uncertainty reflects only statistical uncertainty in the constant of proportionality (a) in Eqn. 1.

$ This uncertainty reflects the range of results from 7 climate models, together with uncertainty in land-ice changes, permafrost changes and sediment deposition.

@ These projections based on only "those models whose results for thermal expansion and glacier melt during 1961–2003 fall within the observational ranges." Values for these quantities given the FAR pertain to a starting date of 2000; I added 3 cm to obtain values relative to 1990.

+ This value obtained by adding (in the case of A1F1 scenario) or subtracting (B1 scenario) half of "scenario spread" to value for A1B scenario given in FAR.

% Uncertainties obtained by scaling from values given for A1B scenario by assuming uncertainty is a fixed fraction of projected sea level rise.

Several lines of reasoning, however, suggest the IPCC projections and the stated uncertainties in those projections are both too low. First, linear extrapolation of historical rates of sea level rise yield values higher than the low-end IPCC FAR projections. The rate of 3.1 mm yr^{-1} observed during the 1990s (Leuliette et al., 2004) implies around 34 cm of sea level rise between 1990 and 2100 (an interval widely used in discussions of sea level rise, and adopted here). Even if one discounts this relatively rapid rate as an artifact of decadal-timescale climate variability or observational error (the latter is considered unlikely by the FAR), measured rates cited above for the latter half of the 20^{th} century (1.8 ± 0.3 mm yr^{-1} and 1.8 ± 0.5 mm yr^{-1}) imply 20 cm of sea level rise between 1990 and 2100. Thus, the low-end IPCC TAR value (9 cm between 1990 and 2100) would require a significant *de*celeration of sea level rise. In light of increasing (indeed accelerating) concentrations of greenhouse gases in the atmosphere, and evidence cited below for the onset of melting of Greenland, this seems exceedingly unlikely. Based on this reasoning, a low-end value of less than around 20 cm by 2100 seems unsupportable.

A second and related issue is that models used to project future sea level generally underpredict historical sea level rise during the 20th century (Rahmstorff 2006; IPCC FAR). In light of the findings cited above, it might seem logical to attribute this to underestimation of the rate of melting of land ice sheets. However the Greenland ice sheet, at least, was apparently near balance (neither growing nor shrinking significantly) as recently as the 1990s (H. J. Zwally et al. 2005; Munk 2002); thus another explanation seems to be required. As noted below, this dilemma may be explained at least in part by the Krakatoa volcanic eruption of 1816. As shown by Gleckler et al. (2006), this event initially depressed sea levels; recovery (i.e., a period of anomalously low sea level but rapid sea level rise) lasted well into the 20th century. Without knowing why models underpredict historical sea level rise, one cannot say if this implies that they will also underpredict future sea levels, but it is certainly a possibility.

Third, subsequent analysis indicates that the glacier-melt component may be much greater than estimated in the IPCC TAR. Dyurgerov and Meier (2002) estimate this component at 20 – 46 cm, versus 1 – 23 cm estimated in the TAR.

Finally, and possibly most importantly, projections in the FAR explicitly exclude significant contributions from dynamical ice loss from Greenland. Recent publications suggest that this is a poor assumption, implying that both future sea level increases, and uncertainties in projected increases, may be much larger than stated in the FAR. Overpeck et al. (2006) and Otto-Bliesner et al. (2006) argue that sea levels during the last interglacial (130 to 127 thousand years before present) were several meters higher than today, due to extensive melting of land ice sheets. This raises the possibility that future sea level rise might be significantly more rapid than widely expected, due to unexpected melting of major land ice sheets.

Indeed, recently-gathered evidence suggests that significant melting of Greenland is starting to occur. The rate of melting of Greenland ice has been estimated from airborne laser and satellite-based altimetry, as well as space-based synthetic aperture radar interferometry. In addition, new measurements are available from the NASA/DLR Gravity Recovery and Climate Experiment (GRACE) satellite, which measures small changes in Earth’s gravitational field. A recent review (Cazenave 2006) shows a net loss of ice mass from Greenland and West Antarctica, and a smaller net gain in East Antarctica. Results from Greenland, although unanimous in showing melting, have a wide range: observations made since 2002 yield melting rates ranging from 50 to 250 Gton/yr. (Veliconga and Wahr 2005, 2006a, 2006b; Chen et al., 2006a, 2006b; Ramillien et al. 2007). These correspond to rates of sea level rise of roughly 0.15 to 0.75 mm/yr. Comparison to measurements made in the 1990s show an apparent acceleration of mass loss (Cazenave 2006; Alley et al. 2005). This is confirmed by a rapid increase in seismic activity from large-scale motions of ice (“ice quakes”; Ekstrom et al. 2006),

The first two, at least, of the above issues are addressed by the work of Rahmstorf (2006). Motivated by a desire to estimate future sea levels without depending on flawed models, he projected future sea level rise using an empirical relationship between observed rates of sea level rise and temperature relative to a preindustrial threshold value:

$$dH/dt = a(T - T_0) \qquad (1)$$

where H is the global-mean sea level, t is time, T is the global-mean temperature and T_0 its previous equilibrium value. This relationship and the values of the parameters *a* and T_0 are established based on observations performed during the 20th century; thus Equation (1) reflects all factors contributing to sea level rise during that period. The linear relationship between temperature increment and rate of sea level rise should be valid during an equilibration period—which should last centuries—when sea level is adjusting to recent changes in temperature. Using this approach, Rahmstorf projects sea level increases of 50 to 140 cm (i.e., 95 ± 45 cm) during the 21st century. This range reflects scenario uncertainty (i.e., differing projected rates of future temperature increase in different IPCC SRES scenarios), as well as statistical uncertainty in the relationship expressed by Equation (1).

Although much higher than the IPCC FAR and TAR projections (his low-end estimate slightly exceeds the central value of the TAR; his midpoint estimate is more than twice any of the IPCC values), the projections of Rahmstorf nonetheless may underestimate the future rate of sea level rise. The reason is that Equation (1) does not reflect significant contributions from melting of major land ice sheets (Greenland or Antarctica), since these are believed to have been near equilibrium during the 20th century, when the observations were made that form the basis of Equation 1. For example, Munk (2002) concludes that melting of land ice sheets contributed less than 0.5 mm yr^{-1} to sea level rise during the 20th century. Rahmstorf points out that Equation 1 could in principle *over*estimate the glacial melt component, since some glaciers might disappear completely before 2100 (in which case their contribution to sea level rise would cease). Nonetheless, the "upside" potential from melting of Greenland seems likely to be greater than the "downside" potential from overestimation of glacier melting. So in the final analysis the projections of Rahmstorf seem more likely to be too low than too high.

3.1.4 Discussion and Recommendations

Regarding future long-term changes in mean sea level, perceived uncertainty is almost certainly greater now than several years ago, despite claims to the contrary in the IPCC FAR. The primary cause of this increased uncertainty is the realization that significant melting of Greenland during the 21st century cannot be ruled out, and, indeed, may be likely. At the same time, however, quantitative projections of the progress of this melting do not exist and are beyond the state of the science. (This is an example of improved understanding leading to larger perceived uncertainties, at least initially). The progress of melting of Greenland (and other large land ice sheets) is exceedingly difficult to predict, because the ice-dynamical processes involved are highly nonlinear, have not been observed in detail, are poorly understood, and are not treated by today's ice-sheet models (Rahmstorf 2006). Even if only thermodynamic processes—which are relatively well-understood—are considered, the progress of melting is difficult to predict because it is strongly influenced by competing feedbacks. Even negative contributions to sea level rise (i.e., increases in ice-sheet mass) cannot be completely ruled out, although this possibility now seems highly unlikely.

Furthermore, the work of Rahmstorf (2006) suggests the other (i.e., thermal expansion and glacier-melt) components of future sea level rise are probably significantly more uncertain than acknowledged in the IPCC TAR or FAR.

Based on the above considerations, it is recommended the DRMS project consider the following mean sea level rise values for 2050 (Table 2):

1. 11 cm (a direct extrapolation of the observed increased during the 20th century)

2. 20 cm (the low-end value of Rahmstorf, and close to the mid-range value of the IPCC TAR).

3. 30 cm (close to the mid-range value of Rahmstorf, and to the high-end of the IPCC TAR)

4. 41 cm (the high-end value of Rahmstorf.

For 2050, it is recommended the following values be used:

1. 20 cm (a direct extrapolation of the observed increased during the entire 20th century)

2. 50 cm (the low-end value of Rahmstorf, and very close to the central value from the IPCC TAR).

3. 90 cm (close to both the high-end value of the IPCC TAR, and the mid-range value of Rahmstorf)

4. 140 cm (the high-end value of Rahmstorf).

The state of the science does not allow quantitative estimates of the probabilities of these different projections. Although values lower than the lowest projections seem very unlikely, it seems possible to exceed the highest projections, given the rapidly-evolving state of the science.

Table 2 Recommended Values for Global Sea Level Rise, Relative to 1990 Value, in cm

Date	Source/Rationale	Sea Level increment
2100	Rahmstorf high	140
	Rahmstorf mid, IPCC TAR high	90
	Rhamstorf low, IPCCC TAR mid	50
	linear extrapolation	20
2050	Rahmstorf high	41
	Rahmstorf mid, IPCC TAR high	30
	Rhamstorf low, IPCCC TAR mid	20
	linear extrapolation	11

3.1.5 Short-Timescale Variations in Sea Level

Risk of overtopping and other forms of levee failure will be elevated when short-term increases in sea level combine with long-term sea level rise to produce unusually high water levels. As noted above, the DRMS project has obtained projections of future sea level—including both slow trends and short-term variations—at San Francisco (Cayan et al. 2006b) (Figure 5). (Due to the chaotic nature of the atmosphere, weather variations simulated by climate models should be correct statistically, but the timing of specific events will not be correct.) What is needed, however, are projections of future sea levels in the Delta. While the long-term trends will be the same in the two locations, short-term sea-level variations are generally damped in inland waterways and estuaries such as the Delta. This is a result of friction and geometrical factors. Consistent with this general pattern, the amplitude of sea-level variations in the Delta is significantly less than at that San Francisco (Figure 6; in the results shown here, water levels are referenced to mean sea level at San Francisco in 2000; this is roughly 91.1 cm above NAVD88). Thus, the DRMS project needs an approach for projecting future variations in sea levels in the Delta, given projected variations at San Francisco (Figure 5).

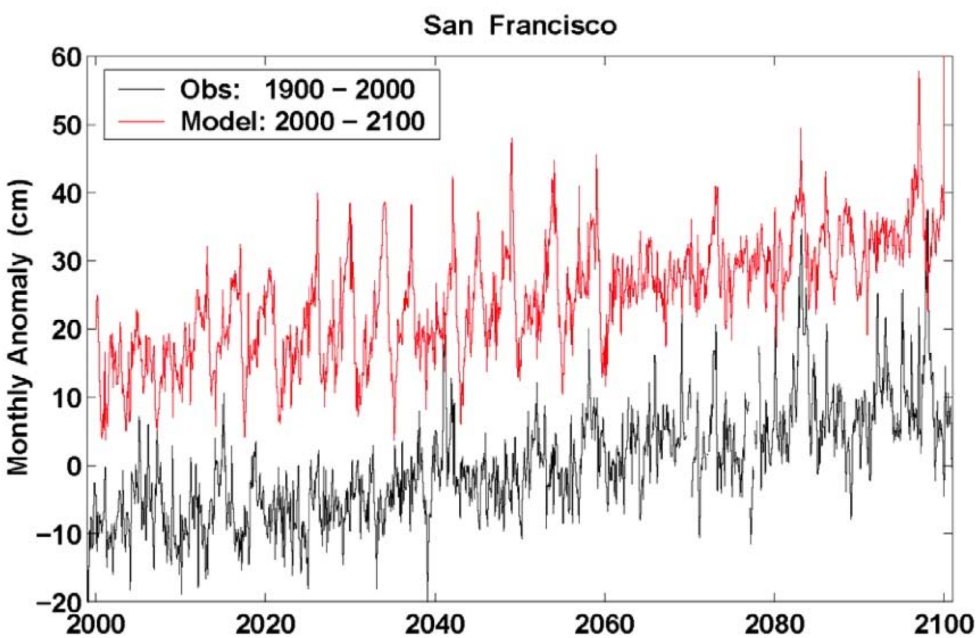

Figure 5 Projected (Red) and Historical (Black) Sea Level Anomalies (Differences from Historical Mean) for San Francisco

Note: The projected long-term trend is assumed in this figure to be 20 centimeters per century. The projected short-timescale variations are based on the weather and climate fluctuations simulated by the Geophysical Fluid Dynamics Laboratory (GFDL) climate model, assuming the IPCC Special Report on Emissions Scenarios (SRES) "A2" scenario for future greenhouse gas emissions. Variations due to astronomical tides are also included.

Power spectra of observed hourly sea levels at San Francisco and Mallard Island (i.e., of the two time series in Figure 6) both show peaks at periods of 12 hours and 24 hours, produced by tides (Figure 7). At San Francisco, however, the 12-hour peak has more energy than the peak at 24 hours, whereas the reverse is true at Mallard Island. This

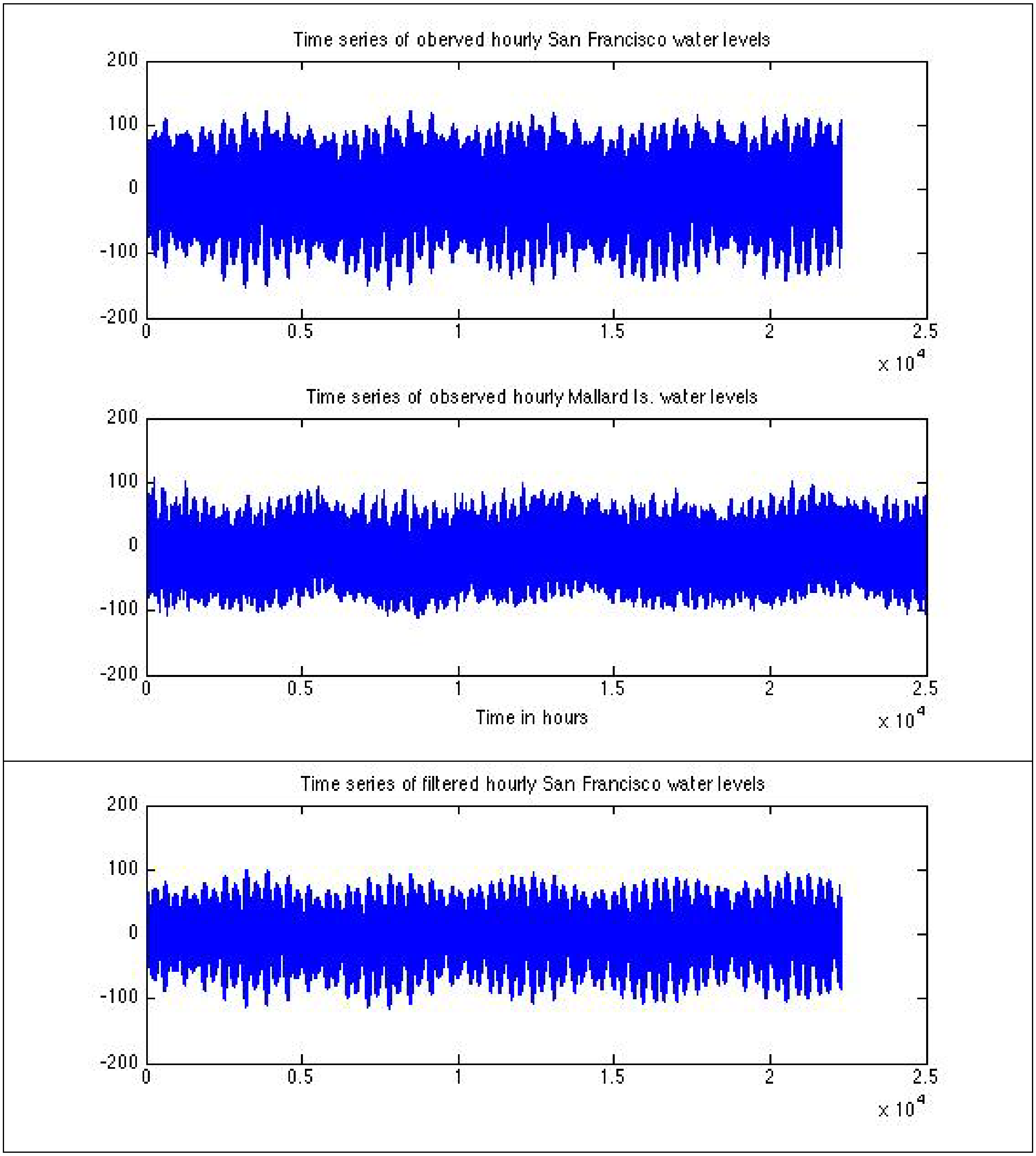

Figure 6 Time series of observed hourly sea levels at San Francisco (top) and Mallard Island (middle).

The smaller amplitude of variations at Mallard Island results from damping of tidal and other high-frequency variations. The bottom panel shows sea levels at San Francisco after digital filtering.

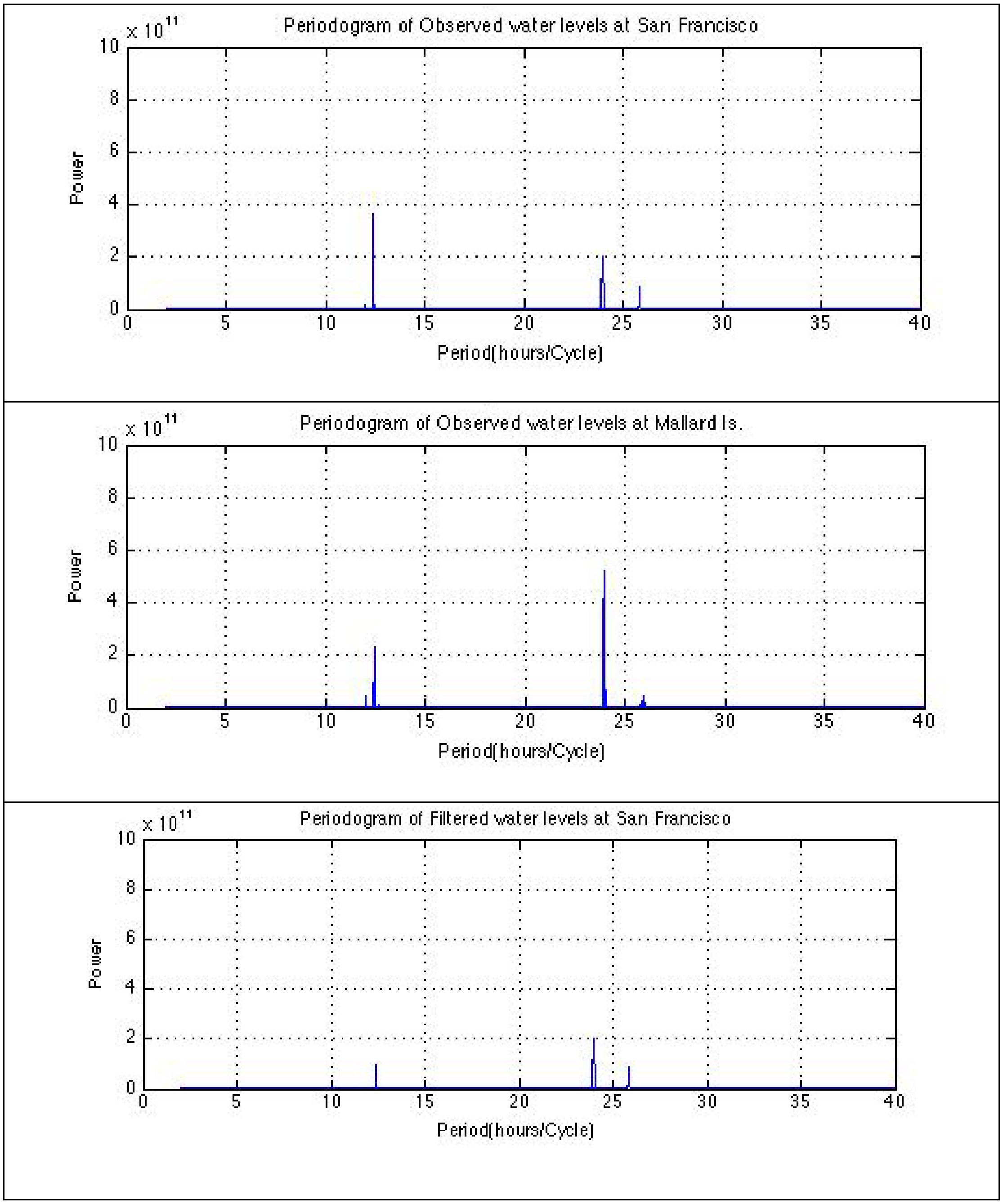

Figure 7 Power spectra of observed hourly sea levels at San Francisco (top) and Mallard Island (middle), as well as filtered sea levels at San Francisco (bottom).

Notes: At San Francisco, the spectral peak at a 12 hour period is almost twice as strong as that at 24 hours in the unfiltered results (top). At Mallard Island, the 12-hourly variations are highly damped, resulting in less energy at this period than at 24 hours (middle). The filtered San Francisco hourly values also have this property (bottom). This shows that the filtering is successfully replicating the observed damping of 12-hourly tidal variations at Mallard Island.

indicates preferential damping of the 12-hourly variations at the inland location. This means that future sea level variations inland cannot be assumed to be the same as those projected for San Francisco.

Next I describe a procedure for mathematically mimicking this damping. This procedure is evaluated by applying it to observed sea levels at and Francisco, and showing that the resulting filtered sea levels resemble those observed at Mallard Island. Having completed this evaluation, the procedure is applied to projected sea levels at San Francisco to produce estimates of projected sea levels at Mallard Island.

To mimic the effects of inland damping of high-frequency sea level variation, I designed a digital low-pass filter that preferentially damps the higher-frequency variations. The specific properties of the filter were selected empirically, to optimize agreement between filtered San Francisco sea levels and observed sea levels at Mallard Island. During this optimization process I experimented with both Butterworth filters and Chebyshev Type 1 filters, varying the order and cutoff frequency. A 13^{th}-order Butterworth filter was found to perform best.

As noted above, this filter was evaluated by applying it to predicted sea levels at San Francisco; ideally, the resulting filtered sea levels would have identical statistical properties to those observed at Mallard Island. In practice, some differences are noted, although the filter does mimic many of the effects of inland damping.

The time series of filtered sea levels (Figure 6, bottom panel) resembles that of observed sea levels at Mallard Island (Figure 6 middle panel) in that the overall amplitude of variations, as well as the quasi-periodic oscillation at a period of roughly 500 hours, are similar. The power spectrum of filtered San Francisco sea levels (Figure 7, bottom) resembles the Mallard Island power spectrum in that power at 12 hours is about half that at 24 hours.

The most relevant quantity for evaluation of the filtering procedure is the Cumulative Density Function (CDF) of filtered sea levels. This directly predicts the likelihood of exceeding any specified sea level threshold, which is the information needed for the DRMS project. The CDF of the filtered San Francisco sea levels quite closely resembles that of observed sea levels at Mallard Island (Figure 8), meaning that the filtering procedure is successfully transforming values measured at San Francisco to equivalent (according to this measure) values at Mallard Island.

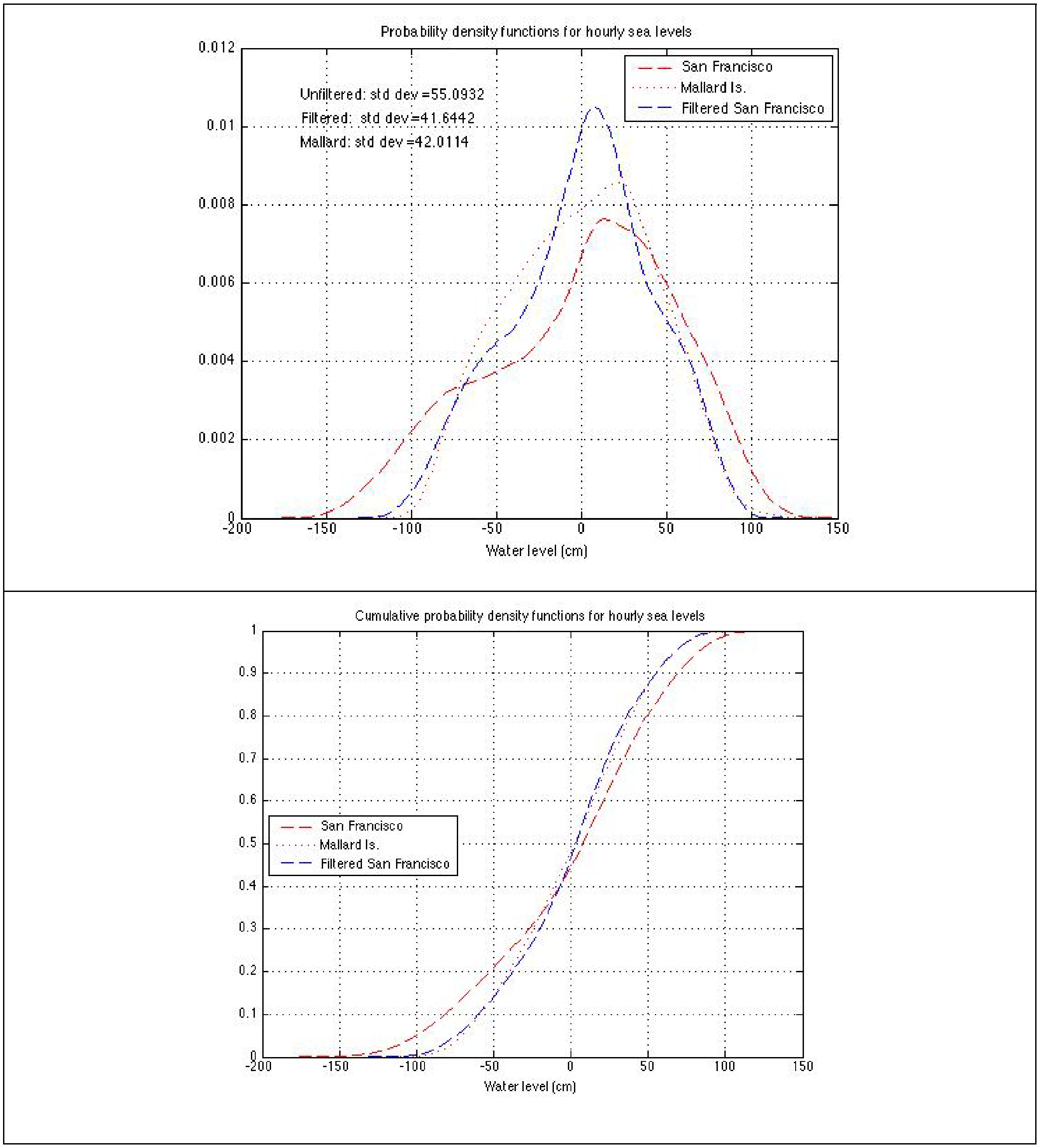

Figure 8 Probability Density Functions (PDFs) (top) of observed hourly sea levels at San Francisco and Mallard Island.

Notes: For San Francisco, results are shown before and after application of the low-pass filter. Bottom panel shows the same results displayed in the form of Cumulative Distribution Functions (CDFs). These results show that filtering the San Francisco data results in a distribution of sea level values that is very similar to that at Mallard Island. This validates the use of this filter on future-climate predicted sea levels at San Francisco, to produce estimated values at Mallard Island.

Having demonstrated that application of a low-pass filter can replicate relevant aspects of inland tidal damping, we next applied the filter to time series of predicted sea levels at San Francisco. This resulted in time series of predicted sea levels at Mallard Island.

To produce results for other locations in the Delta, a similar procedure could be used. In general, different filter parameters would be needed at other locations. A time series of observed sea levels at these locations would be needed to allow determination of these filter parameters.

3.2 River Flow Rates

As noted by Cayan et al. (2006a), variations in river flow rates, as opposed to sea level variations, are the dominant contributor to short-timescale water level variations in most areas of the Delta. Short-term water level variations depend on hourly-timescale precipitation, runoff, and stream flow as well as reservoir operations practices. Although multiple projections of monthly-timescale river flows in California have been published (e.g., Maurer and Duffy 2005), daily-timescale river flows are more difficult to simulate, and only one comprehensive set of simulations has been published, by Prof. Edwin Maurer of Santa Clara University, in Cayan et al. 2006b. These results have been made available to DRMS through the courtesy of Prof. Maurer. The methodology used to produce these simulations is discussed in Wood et al. (2002) and Cayan et al. (2006b) and is reviewed briefly next. As noted above, peak flood flows should be calculated using an hourly timescale, so even daily-timescale flows are less than ideal for this purpose.

Maurer calculated daily-mean unimpaired river flows for 20 major rivers in California. These rivers are those needed as inputs to the Calsim II water operations model, and include the major inflows feeding the Delta. These flows were calculated using the Variable Infiltration Capacity (VIC) surface hydrology model, using meteorological input from simulations of the 21st century performed for the upcoming IPCC 4th Assessment Report, and archived at Lawrence Livermore National Laboratory (http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php). To aid in quantifying uncertainties, river flows were calculated based on output from 22 quasi-independent climate models.

The VIC model treats the surface energy budget, snow on the ground, soil moisture, runoff, and river flows, and related processes. It is driven by meteorological input (precipitation, near-surface temperatures, and downwelling solar radiation), obtained in this case from simulations of the 21st century performed with global climate models (GCMs), and using scenarios for future greenhouse gas emissions.

VIC and other surface hydrology models require daily-mean meteorological input. Daily-timescale results of GCMs, however, are not always reliable. In particular, GCMS have a tendency to predict too many rainy days and not enough rain per rainy day (Mearns et al. 1995, Duffy et al. 2003, Sun et al. 2005); this would result in a tendency to underestimate flood risk. We therefore drive VIC with daily mean precipitation values estimated from monthly-mean GCM results using statistical relationships derived from observations. This “temporal downscaling” process assumes that the relationship between monthly precipitation amounts and daily precipitation amounts will be fixed as climate changes. In essence, this procedure assumes that the number of rainy days per month will remain fixed under climate change, and that any change in monthly precipitation amounts will come in the form of changes in precipitation intensity (precipitation amounts on days when significant precipitation occurs).

In addition to the temporal downscaling described above, GCM results are spatially downscaled and bias corrected as described below, before being passed to VIC. To adapt GCM output for hydrological study we will apply a bias correction technique originally developed by Wood et al. (2002) for using global model forecast output for long-range streamflow forecasting, later adapted for use in studies examining the hydrologic impacts of climate change (Hayhoe et al. 2004; Maurer and Duffy 2005; Van Rheenan et al. 2004). This is an empirical statistical technique that maps precipitation and temperature probabilities (at a monthly scale) during a historical period (such as 1950-1999) from the GCM to the concurrent historical record. The historical observational data set for this effort is the gridded National Climatic Data Center Cooperative Observer station data developed as described in Maurer et al. (2002), and aggregated up to a 2° latitude-longitude spatial resolution. The quantiles for monthly GCM simulated precipitation and temperature are then mapped to the same quantiles for the observationally based CDF. For temperature the linear trend will be removed prior to this bias correction and replaced afterward, to avoid increasing sampling at the tails of the CDF as temperatures rise. In this way the probability distribution of observations will reproduced by the bias corrected climate model data for the overlapping climatological period, while both the mean and variability of future climate can evolve according to GCM projections. For spatially interpolating the monthly bias-corrected precipitation and temperature, we applied the method of Wood et al. (2002; 2004), which for each month interpolates the bias corrected GCM anomalies, expressed as a ratio (for P) and shift (for T) relative to the climatological period at each 2° GCM grid cell to the centers of 1/8 degree hydrologic model grid cells over California. These factors are then applied to the 1/8 degree gridded precipitation and T, the resolution of the final product.

The method used to obtain daily-timescale meteorology is an important limitation of this approach. Although our approach is defensible, other approaches can be imagined that might produce significantly different results.

Monthly-mean projected flows based upon this approach show the now-expected result of increased flows in winter, and reduced flows in spring and summer; this trend continues as the century progresses (Figure 9). In addition, these trends in monthly-mean flows are robust (e.g., Figure 10), meaning that they are not sensitive to which greenhouse gas emissions scenario is simulated or which model is used to perform the simulation. This robustness arises because the basic result—increased flows in winter and early spring and reduced flows in late spring and summer—occurs as a result of warming. Specifically, a shift from rain to snow together with earlier snowmelt, both consequences of warming, are responsible for these trends.

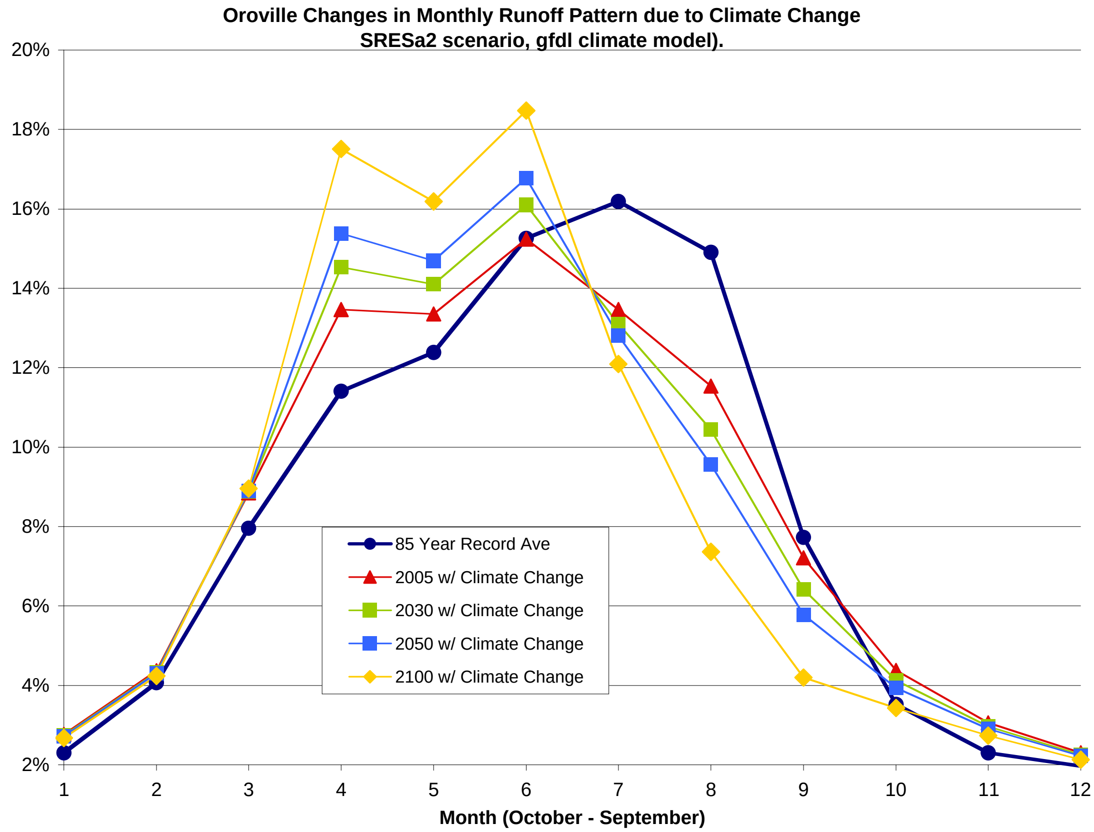

Figure 9 Projected Monthly-Mean Flows at Oroville

Note: Flows were simulated using the VIC surface hydrology model (as described in the text), with future-climate meteorology obtained from the Geophysical Fluid Dynamics Laboratory (GFDL) climate model, which was run using the IPCC SRES "A2" greenhouse gas emissions scenario. Raw simulated flows were adjusted as described in the Water Analysis Module (WAM) Technical Memorandum.

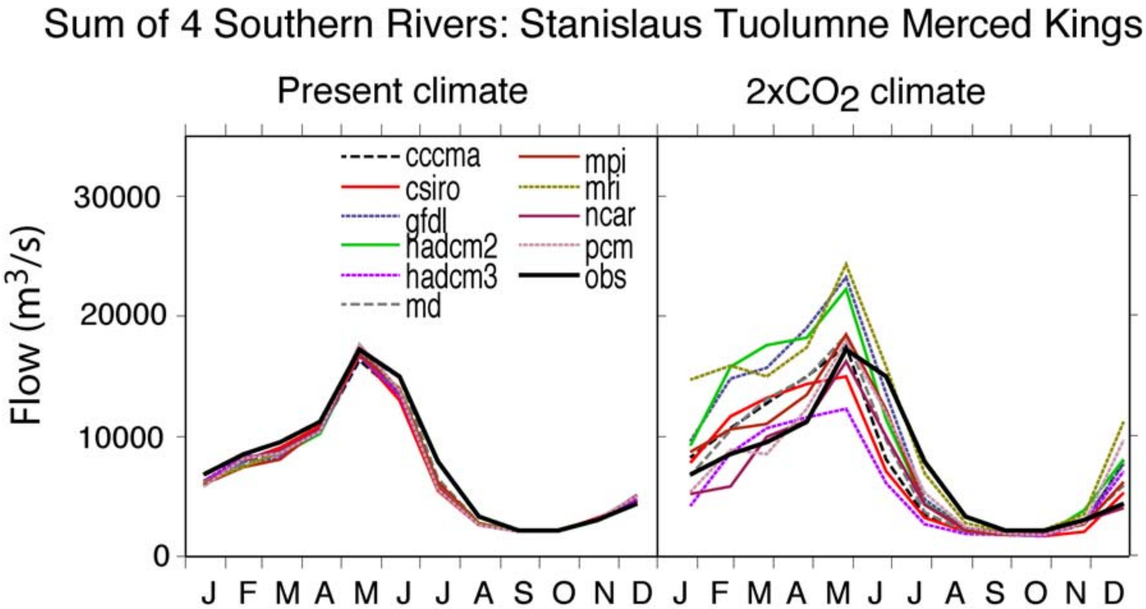

Figure 10 Simulated Monthly-Timescale Flows on 4 rivers in Southern California

Note: Simulated and observed monthly mean flows on 4 rivers in southern California. Left: present climate; right: doubled-CO_2 climate. Black curve is observed present-climate flow. Colored curves are show flows simulated using the VIC surface hydrology model, with meteorological input obtained from climate simulations submitted to the IPCC AR4 archive at Lawrence Livermore National Laboratory; different colored curves represent results based on different climate models. Simulated present-climate flows are consistent across multiple climate models, and agree well with observed flows, because meteorological data is subject to a bias correction before being supplied to the surface hydrology model that calculates flows (as described in the text). From Maurer and Duffy (2005).

3.3 Wind Velocities in the Delta

In-Delta wind velocities determine wind/wave action, which can be a significant factor in the erosion of levees. Accurate simulation of any climate quantity on the scale of the Delta is challenging for typical global climate models, in which the minimum resolved scale is 100 to 200 kilometers (km) or larger. In the case of winds, the flows in the Delta region are driven by large-scale pressure gradients, which typically result from strong temperature gradients between the coast and the Central Valley. Global climate models should be able to simulate these large-scale gradients. However, local flows are influenced by small-scale topographic and meteorological features that will not be resolved by typical global-scale climate models. These considerations suggest that a sensible approach to simulating winds in the Delta is to use a fine-resolution limited-domain climate model nested within a coarser-resolution global-scale model. The global model should capture the large-scale driving gradients, and the finer-resolution nested model should simulate the smaller-scale features and flows.

We have implemented this approach by obtaining simulated present-climate winds from two global/nested model combinations. The first model is the RegCM3 limited-domain climate model nested within the NCAR Climate System Model (CSM) global ocean-atmosphere-sea ice climate model. RegCM3 uses a grid spacing of 40 km (i.e., the model resolution is 40 km). The RegCM3 model was run by M. Snyder et al. at the University of California, Santa Cruz, who is a member of the DRMS team. The second model is the Pacific Northwest National Laboratory (PNNL) version of the MM5 limited-domain model, nested within the NCAR PCM global climate model. In this case, the nested model uses a 36-km grid spacing. These results were kindly provided by R. Leung of the PNNL.

We evaluated the ability of the RegCM3 model to reproduce observed wind speeds and directions in the Delta. Because these are long-term climate simulations, they should reproduce the statistical properties (e.g., means and standard deviations) of observed winds; however, model results for specific days will not reproduce observed results on that day. Evaluation of the RegCM3 results suggests the model does quite well at reproducing wind directions; however, simulated wind speeds are significantly higher than observed wind speeds (Figure 11). Furthermore, the predicted response of in-Delta winds to increased atmospheric greenhouse gases is very small (Figure 12) – much smaller than the biases just mentioned. These results suggest that even state of the art nested models are probably incapable of making trustworthy projections of wind speed responses on the small spatial scales of interest here.

Notwithstanding the limitations of models, a simple argument can be made that points to increases in in-Delta wind speeds as climate change progresses: for the foreseeable future, the climate system will be out of equilibrium, as a result of increasing radiative forcing due to the buildup of greenhouse gases in the atmosphere. This will tend to increase the existing temperature gradient between the Central Valley and adjacent ocean regions. Since this gradient is the driver for the generally westerly flows that predominate in the Central Valley (see e.g., Figure 11), these flows can be expected to increase in strength.

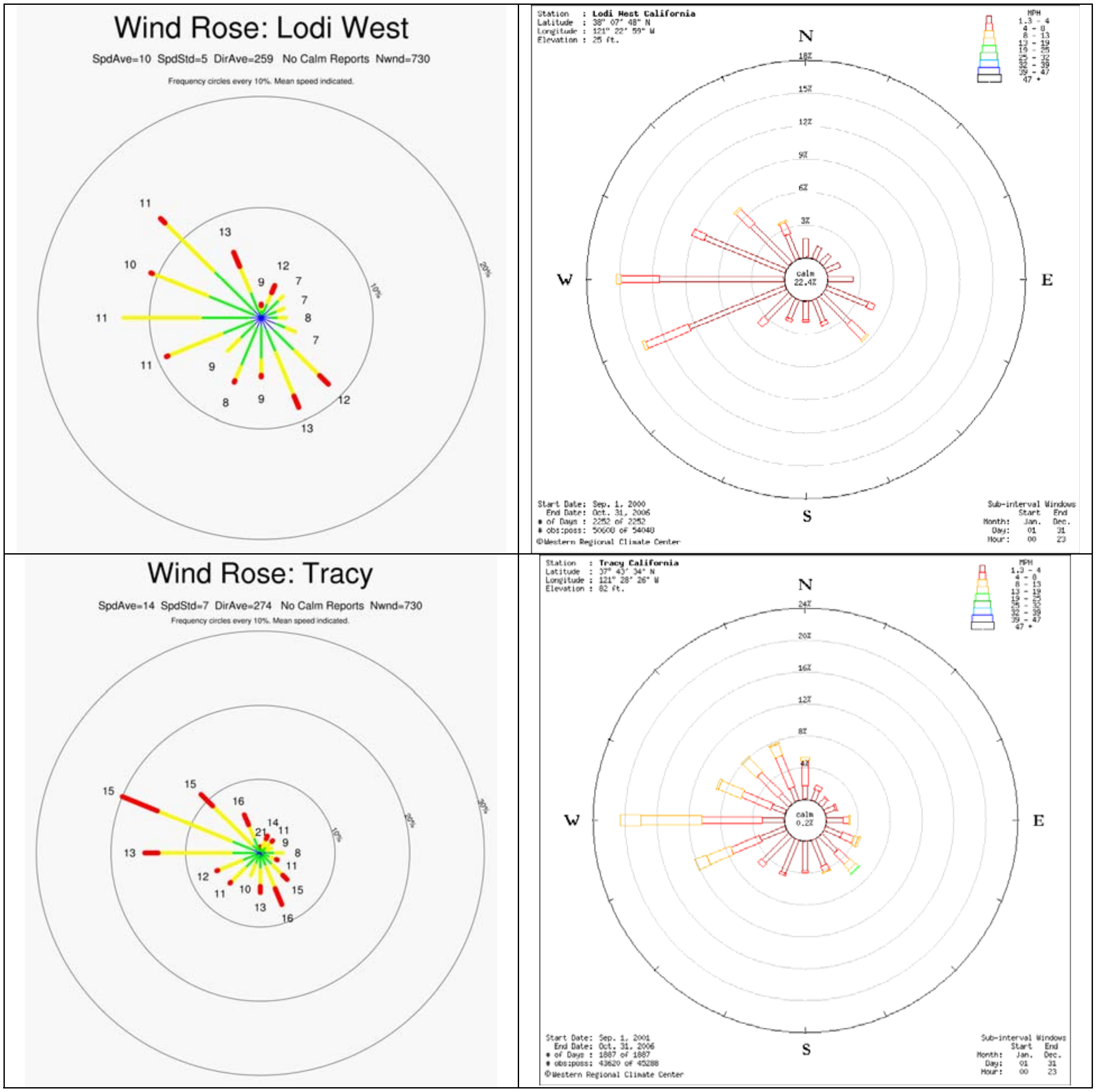

Figure 11 Simulated and Observed Wind Speeds and Direction in Two Locations in the Delta

Note: Lengths of "spokes" indicate the relative frequency of occurrence of wind from that compass point. Left: results from a present-climate simulation performed at the University of California, Santa Cruz, using the RegCM3 nested regional climate model. The numbers at the end of each spoke denote the mean speed of winds from that direction. Right: observations from the California Irrigation Management Information System (CIMIS) network.

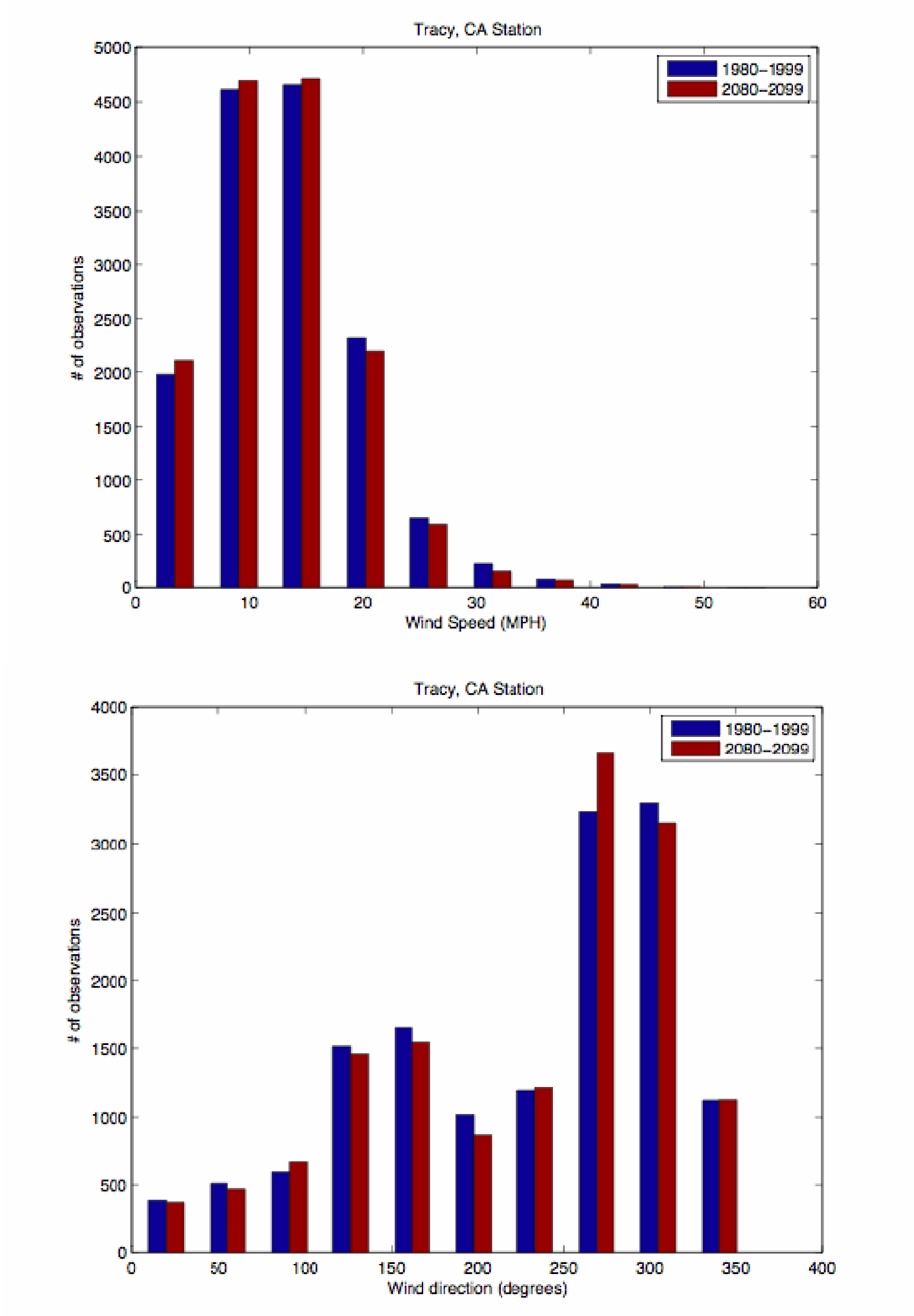

Figure 12 Simulated Wind Speeds and Direction in Tracy, for present and future climates

Note: Histograms of simulated wind speeds (left) and directions (right) in Tracy. Results are shown for the present climate (blue) and a hypothetical doubled-CO_2 climate (red).

3.4 Statewide Projections of Temperature and Precipitation

3.4.1 Methodology

DRMS requires temperature and precipitation information as inputs to projections of future statewide water demand.

To meet this need, we have obtained probabilistic projections of future temperatures and precipitation from M. Dettinger of the U.S. Geological Survey and the University of California, San Diego. These projections were made using the methodology described in Dettinger (2004a, 2004b, 2005, 2006); however, the specific projections used here were performed specifically for DRMS. The differences relative to already-published projections are that the time intervals considered are earlier (2040 through 2059 and 2080 through 2099) and the projections are given as results relative to values in 2000.

These probabilistic projections reflect uncertainties from three sources: varying scenarios for future greenhouse gas emissions, scientific uncertainty regarding the climate response to specified perturbing influences (mainly increased atmospheric greenhouse gas concentrations), and climate system initial conditions. The first component of uncertainty is represented by including results based on three greenhouse gas emissions scenarios: the IPCC SRES A1b, A2, and B1 scenarios. The second component of uncertainty is represented by using results from multiple, independent global climate models. We used results from thirteen models that contributed simulations to the IPCC AR4 report simulation database at the Program for Climate Model Diagnosis and Intercomparison (PCMDI) (http://www-pcmdi.llnl.gov/ipcc/ about_ipcc.php), which is based at Lawrence Livermore National Laboratory. The third uncertainty component (initial conditions) was represented by analyzing multiple simulations from individual models differing only in the initial state of the ocean-atmosphere-sea ice system. (Because of the chaotic nature of this system, varying initial conditions can result in significantly different future-climate "trajectories.") In developing probabilistic projections, all models—not all simulations—were given equal weight. Thus, for models that contributed larger initial condition ensembles, each simulation had a proportionately lower weight. In all, 84 simulations were analyzed. Based on these 84 simulations, probabilistic projections were developed using a mathematical "resampling" technique described in the references named above. This technique produces large numbers of synthetic projections that share key statistical properties with the relatively small number of model results available. The use of this approach results in mathematically "smoother" (more continuous) projections than would otherwise be obtained.

For California, projections of future temperature and precipitation can be considered independently, because analysis of future-climate simulations from multiple models shows that projected temperature changes are not correlated with projected precipitation changes (Figure 13).

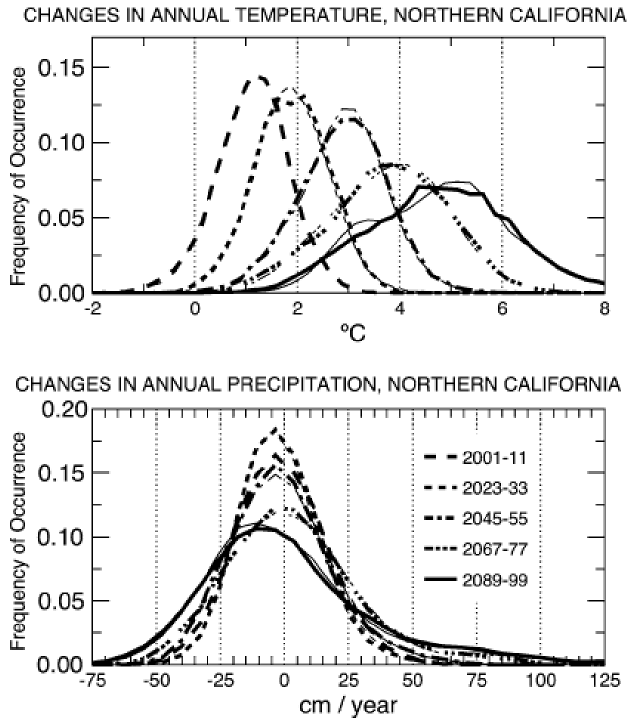

Figure 13 Probabilistic Projections of Changes in Spatial Mean Temperature and Precipitation for Northern California

Note: Projected changes in temperature and precipitation for Northern California. Each curve represents a probabilistic estimate for a specific time period. Uncertainties reflect varying results from six different global climate models, each driven by three different greenhouse gas emissions scenarios; for some combinations of models and scenarios, multiple estimates of atmospheric initial conditions contribute additional uncertainty.
Source: Dettinger 2006.

3.4.2 Discussion

There is consensus among today's climate models that California's future will be warmer. This reflects the effects of increasing atmospheric greenhouse gases, primarily CO_2. Most likely estimated warming by mid-century is roughly 3 degrees C. Uncertainties are greater for later time periods, because of increased "scenario uncertainty" (uncertainty in future atmospheric greenhouse gas concentrations and other climate "forcings"), as well as increased uncertainty in the climate system's response to those forcings. For precipitation, the models express a slight preference for a drier future, however uncertainties are large enough to include wetter futures as well. How can a warmer climate be drier? In a warmer world, increased evaporation will produce an accelerated hydrological cycle, including increased global-mean precipitation. Regional changes, however, including those in California, can be of either sign, because changes in atmospheric circulation can lead to altered patterns of precipitation.

Despite qualitative uncertainties about changes in precipitation, some impacts on California's hydrological cycle can be robustly predicted. The prediction of increased river flows in winter, and reduced flows in late spring and summer, is at least qualitatively robust, since these phenomena result from consequences of warming: a shift in the form of precipitation from rain to snow, and earlier melting of snow. The expected shift in the seasonal timing of river flows has implications for water availability that may be very significant for some water districts (e.g., Zhu et al. 2005). Consequences for flood risk have not been studied nearly as thoroughly as those for water supply, but it seems hard to avoid the conclusion that increased monthly-mean river flow rates in winter, together with more intense daily precipitation events, will result in increased potential for winter flooding. Similarly, late season flood risk may be reduced.

4. Limitations

As noted above, the principal limitations of climate change work result from the need to use “off-the-shelf” results; this was dictated by schedule and budget constraints. One consequence of this approach is that projections of different climate quantities were produced independently, i.e., they obtained from different sources and were therefore in some cases produced using different models and assumptions. For example, our probabilistic projections of statewide temperature and precipitation are based on results from 22 different climate models and three different greenhouse gas emissions scenarios. River flow projections are based on only 2 of these 22 models and two of the three emissions scenarios.

A more serious problem is the daily-timescale variations in sea level and in-river flows; although both were produced using defensible methodologies, were produced independently, and are thus uncorrelated. In actuality, weather variations result in fluctuations in sea level and in-river flow rates that are correlated in time; these correlated variations can combine to produce extreme water levels in the Delta. Our methodology does not capture these correlations, as daily-timescale variations in river flows were simulated independently of daily-timescale variations in sea level. As a result, our results will tend to result in underestimates of flood risk.

As the remarks immediately above imply, a more ideal approach would have been to base all results needed here (sea level rise, changes in temperature, precipitation, wind speeds, and river flows) on one set of models and on a common set of emissions scenarios. This would, first, produce results (PDFs of projected changes) for different climate quantities based on common and consistent assumptions. More fundamentally, it would allow us to link specific projected changes in one climate quantity to projected changes in others. For example, in the present approach regional-scale temperature change and sea level rise are projected using different models (in fact different types of models); this might, at best, provide a PDF of projected temperature change and an independent PDF of sea level rise. We have a intuitive notion that more warming will correspond to more rapid sea level rise and vice-versa, but no way to quantitatively associate specific amounts of warming with specific projections of sea level rise. A unified approach in which regional-scale warming and sea level rise were both calculated using the same assumptions and models would enable us essentially to construct a mapping between the temperature change PDF and the sea level rise PDF (for example). This ability could have important implications for estimating risk to the levees. For example, if scenarios with more warming and more rapid sea level rise tend to have less precipitation than other scenarios (which is a possibility), this would mean that any increased risk from sea level rise in these scenarios might by offset at least in part by reduced risk from river floods. In other words, it may be that no one scenario results in both maximum sea level rise and maximum precipitation increases; hence maximum risk might be less than would be estimated without this knowledge. The present approach does not allow us to know this; a more unified approach would.

To implement a unified approach, one would select a set of several greenhouse gas emissions scenarios (e.g., A2, B1, etc.) spanning the range of futures one would like to consider. Next, one would select a set of global climate models and obtain projections from all of them for each emissions scenario. All else being equal, a larger set of models is preferable, because this would more completely sample the range of plausible outcomes. This much could be done immediately. Ideally, these global-domain projections would be downscaled to finer spatial resolution using a nested dynamical climate model. This, however, would require high temporal frequency (3-hourly or 6-hourly) output from the global models, which is not generally available. A second choice would be to use statistical downscaling, which can be based upon daily or even monthly global model output and is computationally much less demanding. Downscaled projections from a limited range of global climate models will soon be produced for North America by the NARCCAP project; a similar set of downscaled projections, at finer spatial resolution and with a domain of California, is planned by the California Energy Commission (CEC) Public Interest Energy Research (PIER) Program.

Downscaled global model output, whether obtained dynamically or statistically, would be used directly to produce projections of future changes in regional-scale temperature, precipitation, and wind speeds. Uncertainty quantification would be performed by obtaining results based on multiple emissions scenarios and multiple global climate models. River flow rates would be calculated by using downscaled global model output to drive a surface hydrology model of the sort used to produce the river flow rates discussed elsewhere in this document. Again, uncertainty quantification would be based on obtaining results based on multiple emissions scenarios and multiple global climate models. Further exploration of uncertainties could be performed by using multiple surface hydrology models.

Even given additional time and resources, sea level rise would still be the most difficult quantity to estimate. The thermal expansion component of mean sea level rise can be estimated relatively straightforwardly from the output of global climate models. The components due to melting of glaciers and land ice sheets are more difficult, requiring specialized knowledge and models. As discussed above, in the case of land ice sheets, it is not clear that present understanding is adequate to produce even probabilistic estimates. Short-term variations in sea level (due astronomical tides and weather variability) can be estimated using the methodology of Cayan et al. (2006a), or similar.

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