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Climate Change and the Delta

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ABSTRACT

Anthropogenic climate change amounts to a rapidly approaching, “new” stressor in the Sacramento–San Joaquin Delta system. In response to California’s extreme natural hydroclimatic variability, complex water-management systems have been developed, even as the Delta’s natural ecosystems have been largely devastated. Climate change is projected to challenge these management and ecological systems in different ways that are characterized by different levels of uncertainty. For example, there is high certainty that climate will warm by about 2°C more (than late-20th-century averages) by mid-century and about 4°C by end of century, if greenhouse-gas emissions continue their current rates of acceleration. Future precipitation changes are much less certain, with as many climate models projecting wetter conditions as drier. However, the same projections agree that precipitation will be more intense when storms do arrive, even as more dry days will separate storms. Warmer temperatures will likely enhance evaporative demands and raise water temperatures. Consequently, climate change is projected to yield both more extreme flood risks and greater drought risks. Sea level rise (SLR) during the 20th century was about 22 cm, and is projected to increase by at least 3-fold this century. SLR together with land subsidence threatens the Delta with greater vulnerabilities to inundation and salinity intrusion. Effects on the Delta ecosystem that are traceable to warming include SLR, reduced snowpack, earlier snowmelt and larger storm-driven streamflows, warmer and longer summers, warmer summer water temperatures, and water-quality changes. These changes and their uncertainties will challenge the operations of water projects and uses throughout the Delta’s watershed and delivery areas. Although the effects of climate change on Delta ecosystems may be profound, the end results are difficult to predict, except that native species will fare worse than invaders. Successful preparation for the coming changes will require greater integration of monitoring, modeling, and decision making across time, variables, and space than has been historically normal.

KEY WORDS

Climate change, climate variability, sea level rise, water resources, ecosystems, Sacramento–San Joaquin Delta

INTRODUCTION

The Sacramento–San Joaquin Delta (the Delta) is a hub where many flows, natural and artificial (water, nutrients, sediments, energy, and economics), converge and interact in California. And although the Delta has been in this same pivotal position throughout California's history and prehistory, climate change is one stressor among the many that ensure that the Delta of the future will not be the same as the Delta we know today. Nonetheless, the Delta is at the foot of one of the largest, most complex water-management systems in the world, with hundreds of reservoir operations, canals, and diversions; a predictable if imperfect water-rights system; and vast swaths of managed lands above and contributing to it. That massive upstream machinery can be a source of some optimism in the face of climate change, as can the system's long history of mostly-successful management of the wildest hydroclimatic regime in the country (Dettinger et al. 2011). If we work to understand the challenges and specifics of what climate change will bring, if we begin incorporating this understanding into decisions made today and tomorrow, and if we work to find the most effective adaptations and responses using our many natural and man-made assets, the Delta should be better off overall than many landscapes that will be facing climate-change challenges from much less robust starting points.

That is, the Delta is not a system that needs to wait passively for whatever challenges climate change brings. Looking forward, three particularly pressing scientific questions are:

- To what extent does the Delta system have built-in resiliency to future climate changes?
- Will (or when will) climate change push the system beyond its built-in resiliencies, whether physical, biological, or socio-economic?
- How will we know, and can we anticipate, when that resiliency has been exhausted?

To answer these questions usefully will require a deeper understanding of the changes to come, and of the natural variations that the Delta has experienced historically and that have been managed by society. This review summarizes the current state of climate-change science as it applies to the restoration and sustainability of the Delta environment, facilities, and ecosystems, as a part of the 2016 State of Bay–Delta Science collection and report. These issues have been near the forefront of much intellectual activity concerning California's water supplies and ecosystems, and often specifically the Delta's ecosystems and water resources, with some major and recent studies of the potential effects of, and adaptations to, climate change in the Delta are listed in Table 1.

The challenges that climate change will pose to the Delta and Delta management can only be understood in the context of California's already challenging natural climate and hydrologic variations. Thus, we begin this review with a brief synopsis of the state's hydroclimatic variability in its natural state, and follow that with an overview of recent projections of 21st century climate change. We will then discuss sea level rise, droughts and floods, followed by climate-change challenges to the co-equal goals of water-resources reliability and ecosystems restoration and sustainability. We conclude with a discussion of key gaps in knowledge regarding climate change and its likely effects, and future science and monitoring directions to close these gaps.

HISTORICAL CLIMATE VARIABILITY

The climate of the Delta and its watershed is characterized by mildly cool, wet winters under prevailing westerly winds, followed by hot, dry summers. This seasonal pattern is shared by the Mediterranean region as well as parts of Chile, South Africa, and southern Australia. This climate regime yields strong seasonal variations in freshwater inflows to the Delta, which in turn are the source of much of the Delta's physical and biological character. In addition to winter floods, spring snowmelts, and summer low flows, the Delta is also influenced, at its seaward end, by tidal inflows and outflows governed by natural daily, monthly, and seasonal processes. The coastal ocean also affects the San Francisco Estuary (the estuary) ecosystem and climate with its regular seasonal pattern of strong spring and early summer upwelling of cool, nutrient-rich waters.

Table 1 Selected recent planning efforts that consider climate change and the Delta

STUDY NAME AND REFERENCE	YEAR	KEY TOPICS
CASCaDE: Computational Assessments of Scenarios of Change for the Delta Ecosystem U.S. Geological Survey *http://cascade.wr.usgs.gov/*	Ongoing	Ecosystems Sea level rise
Sea Level Rise Policy Guidance California Coastal Commission *https://documents.coastal.ca.gov/assets/slr/guidance/August2015/0a_ExecSumm_Adopted_Sea_Level_Rise_Policy_Guidance.pdf*	Ongoing	Sea level rise
Water Fix and EcoRestore (formerly the Bay–Delta Conservation Plan California Dept. of Water Resources and U.S. Bureau of Reclamation *http://www.californiawaterfix.com/* *https://s3.amazonaws.com/californiawater/pdfs/ECO_FS_Overview.pdf* *http://baydeltaconservationplan.com/Home.aspx*	Ongoing	Water supply Ecosystems
Central Valley Flood Protection Plan's Basin Wide Feasibility Study California Dept. of Water Resources *http://www.water.ca.gov/cvfmp/bwfs/*	Ongoing	Flood control Ecosystems
Delta Levee Investment Strategy Delta Stewardship Council *http://deltacouncil.ca.gov/delta-levees-investment-strategy*	Ongoing	Levees
Safeguarding California: Reducing Climate Risk California Natural Resources Agency *http://resources.ca.gov/docs/climate/Final_Safeguarding_CA_Plan_July_31_2014.pdf*	2014	Agriculture Ecosystems Water, etc.
West-Wide Climate Change Risk Assessments: Sacramento and San Joaquin Basins U.S. Bureau of Reclamation *http://www.usbr.gov/WaterSMART/wcra/*	2014	Water supply Water quality Groundwater
California Water Plan Update 2013 California Dept. of Water Resources *http://www.waterplan.water.ca.gov/cwpu2013/final/index.cfm* *http://www.waterplan.water.ca.gov/docs/cwpu2013/Final/Vol2_DeltaRR.pdf*	2013–2014	Water supply Water quality Flood management
Sea-Level Rise for the Coasts of California, Oregon, and Washington National Academy of Sciences *http://www.nap.edu/catalog/13389/sea-level-rise-for-the-coasts-of-california-oregon-and-washington*	2012	Sea level rise
Sustainable Water and Environmental Management in the California Bay-Delta National Academy of Sciences *http://www.nap.edu/catalog/13394/sustainable-water-and-environmental-management-in-the-california-bay-delta*	2012	Ecosystems Water
Delta Risk Management Strategy California Department of Water Resources *http://www.water.ca.gov/floodsafe/fessro/levees/drms/* *http://www.water.ca.gov/floodsafe/fessro/levees/drms/docs/Climate_Change_TM.pdf* *http://www.water.ca.gov/floodsafe/fessro/levees/drms/docs/Water_Analysis_Module_TM.pdf* (see Appendices F and H)	2011	Levees Flow Water level Water quality
Delta Vision *http://deltavision.ca.gov/index.shtml*	2008	Ecosystems Water

On time-scales ranging from seasons to decades, the Delta's natural (air) temperature variability is buffered somewhat (relative to much of North America) by California's proximity to the vast Pacific Ocean heat sink (Dettinger et al. 1995). The catchment's seasonal range of temperatures is generally less than seasonal swings in the continental interior, and its year-to-year temperature fluctuations are also less pronounced (in absolute terms) than other parts of the country. Nonetheless the catchment does experience brutal heat waves that can result in warm surface waters, dangerous increases in fire risks in the Delta's upland watersheds, and significant swings in water demand by natural and, especially, human water users.

In contrast to the Delta's comparatively buffered temperature regime, its precipitation and storm regimes are more variable and extreme than almost any other region in the country on storm-by-storm (Ralph and Dettinger 2012) and annual or longer scales (Figure 1; Dettinger et al. 2011). California's most extreme storms have been a focus of much

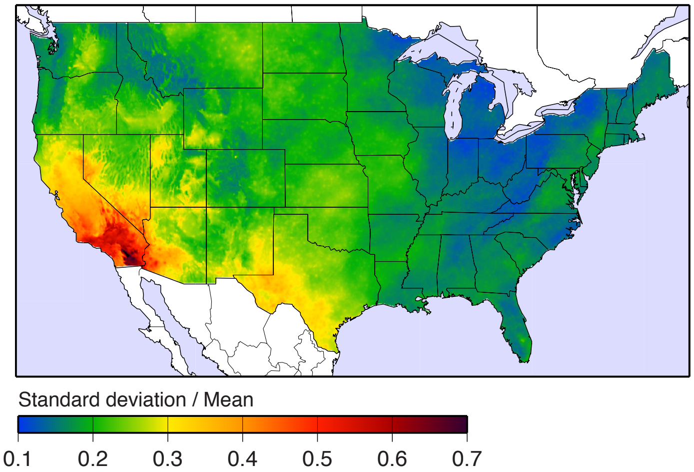
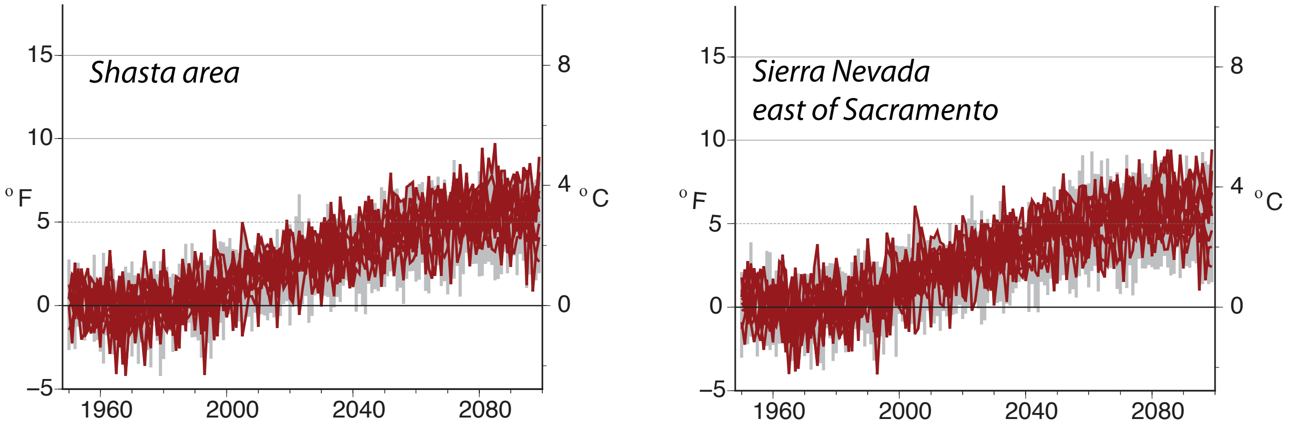


Figure 1 Coefficients of variation (standard deviation divided by mean) of water–year precipitation totals across the conterminous Unite States, 1945–2015

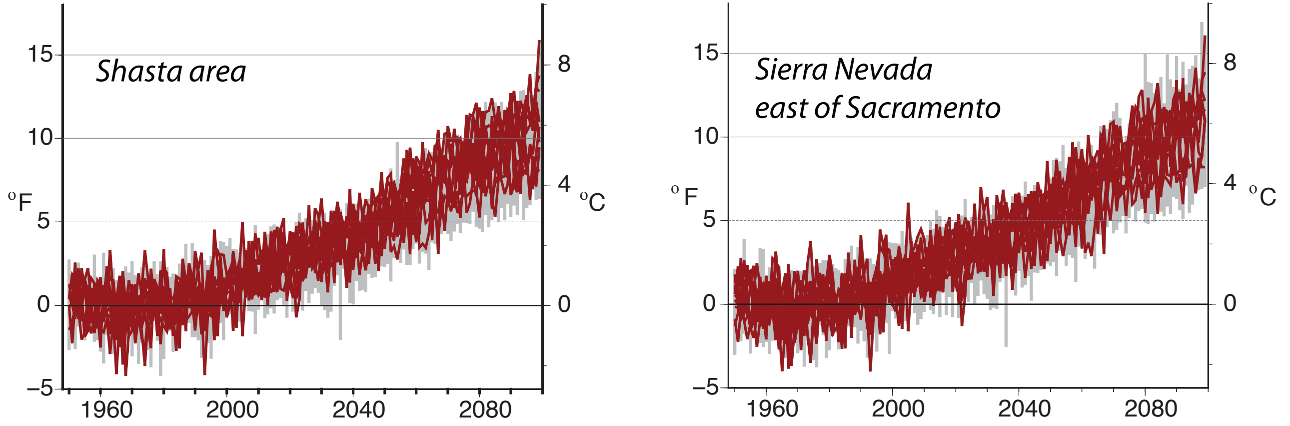
recent research, which has shown that these storms have historically been the result of landfalling atmospheric rivers (ARs). ARs are naturally occurring, transitory, long (> 2,000 km), narrow (~ 500 km) streams of intense water-vapor transport through the lower atmosphere (< 2 km above sea level). ARs gather and transport moisture over the North Pacific Ocean, connecting moisture sources from the tropics and extratropics to the West Coast (Ralph and Dettinger 2011). When these ARs encounter California's mountain ranges, they are uplifted and cooled, and produce heavy rain and snow (Guan et al. 2010). The most intense ARs drop massive amounts of precipitation on the state. Among the largest storms in California's history—storms that dropped more than 400 mm of precipitation within 3 days—92% have been ARs (Ralph and Dettinger 2012).

ARs are the dominant cause of the largest historical floods that have flowed through the Delta: over 80% of major floods (and levee breaks) since 1950 have been driven by ARs (Florsheim and Dettinger 2015). The Delta has experienced extremely large floods, including the New Year's 1997 floods of recent memory and the winter 1862 flood (Figure 2), which may have exceeded the "record breaking" 1997 outflows by as much as 25% (Moftakhari et al. 2013). The 1997 flood and, very likely, the 1862 flood were caused by periods with more-or-less continual arrivals of warm AR storms on the central California coast and Sierra Nevada of warm AR storms (e.g., Dettinger and Ingram 2013). A notable characteristic of the Delta's historical flood regime is that, although in most years high flows occur during the spring snowmelt season, the largest floods have nearly always occurred during winter months as a result of heavy and warm winter storms that yield rapid runoff and flooding of river channels and the Delta (e.g., Florsheim and Dettinger 2015).

At seasonal to multi-year time-scales, these large storms are also a key determinant of the Delta's average flows and, especially, its large hydroclimatic variability. ARs bring the Sierra Nevada about 40% of its average precipitation and resulting streamflows (Guan et al. 2010; Dettinger et al. 2011). The arrivals, or not, of large storms—including, prominently, ARs—explain about 92% of the year-to-year and decade-to-decade variance of water-year precipitation (Dettinger and Cayan 2014; Dettinger 2016), including all the catchment's major droughts during the historical period. Large AR storms also play an important role in ending sustained droughts in the historical period, ending about 40% of Delta droughts since 1950 (Dettinger 2013a). Although these large storms are increasingly being forecasted as much as a week or slightly more in advance (Wick et al. 2013; Lavers et al. 2016), their year-to-year variations remain poorly understood and forecasted. Taken together, the central roles that ARs play in California's floods and its droughts strongly suggest their importance to understanding and managing hydrologic variability in the Delta on time scales from days to decades. ARs were first recognized only in 1998 (Zhu and Newell 1998) and so our scientific understanding of these features is quite new and still emerging. Their central roles in California's hydroclimate have motivated wide ranging research to improve our ability to track, model and forecast ARs (Ralph and Dettinger 2011), including a major new storm-centered monitoring network led by the California Department of Water Resources (CDWR) and the National Oceanic and Atmospheric Administration (NOAA) (White et al. 2013); AR-focused modeling and forecasting efforts (Wick et al. 2013; Hughes et al. 2014); and, in recent winters, reconnaissance flights to visit and better



A **Assuming Lower Future Greenhouse-Gas Concentrations (RCP4.5 scenario)**



B **Assuming Higher Future Greenhouse-Gas Concentrations (RCP8.5 scenario)**

Figure 2 Projected annual changes in air temperature, relative to 1961–1990 averages, in 10 selected global climate models (bright curves, 5-year moving averaged) and in 31 models (grey, unsmoothed), under low **(A)** and high **(B)** future greenhouse-gas emissions. (Source: CDWR Climate Change Technical Advisory Group 2015).

characterize ARs several days before their arrival in California (Ralph et al. 2016).

On these longer time-scales, some limited ability to forecast California's temperature and precipitation derives from observations and forecasts of the state of the climate over the Pacific Ocean. Most attention in the past 2 decades has focused on the state of the El Niño–Southern Oscillation (ENSO) process in the tropical Pacific (Allan et al. 1996), which is the primary source of climate forecast "skill" (accuracy) almost anywhere in the world. El Niño events reorganize atmospheric circulations in the tropics in ways that divert and change the normal transports of heat and momentum (and, to an extent, moisture) out of the tropics towards extra-tropical regions, including the North Pacific and, ultimately, western North America. Thus, each time an El Niño (a period with anomalously warm sea-surface temperatures across much of the central to eastern equatorial Pacific) begins to form, there is much speculation about how it will affect winter precipitation over California. Unfortunately, across central to northern California, El Niño years have not yielded consistent precipitation outcomes at seasonal scales (e.g., Redmond and Koch 1991) and in terms of extreme precipitation or streamflow events (Cayan and Webb 1992; Cayan et al. 1999). That is, about as many past El Niño years have yielded dry weather as have yielded wet weather, although there is some evidence that the warmest El Niño years tilt the odds more decidedly towards wet conditions all along the West Coast, including in the Delta's catchment (e.g., Hoell et al 2015). ENSO variability is mostly active in time-scales from 3 to 7 years, but interacts with the Pacific Basin beyond the tropics on longer time-scales, most notably in the form of the Pacific Decadal Oscillation (PDO; Mantua et al. 1997), which has historically influenced North American precipitation patterns for periods lasting for 25 years and more. The PDO, like ENSO, has historically led to stronger-than-normal contrasts in the amounts of precipitation falling in the southwestern U.S. compared to the northwestern U.S. but, also as with ENSO, the PDO's precipitation patterns tend to leave the Delta's catchment with little precipitation certainty from year to year. Nonetheless, although these important global climate modes do not offer much predictability for Delta hydroclimate, they are almost certainly major contributors to the large range of precipitation amounts that the catchment receives from year to year. Arguably, an important but understudied part of the multi-year variation of precipitation over the Delta's catchment occurs on time scales that are between the 3- to 7-year ENSO characteristic and the 25- to 70-year PDO scales; however, this decadal (14- to 15-year) variation is not well understood and, although significant during most of the 20th century, has come and gone in longer term tree-ring records (Meko et al. 2014; St. George and Ault 2011).

In the Delta's widely varying precipitation regime, drought is a fact of life. The catchment has experienced severe short droughts (such as 1976–77) and less severe but more sustained droughts (such as the 1920s and 1930, or 1987–92) in the historical period. Tree-ring reconstructions of droughts in northern California have documented numerous droughts during the past 2000 years, including strong evidence of much longer and more severe droughts in the past (e.g., Meko et al. 2014; Ault et al. 2014). Precipitation deficits in the current drought (2012–present) have been extreme, although not record-breaking in water-year precipitation aggregates. On longer time scales, though, precipitation deficits during this current drought have been record breaking (e.g., in 14-month, 3-year, and 4-year totals) and have been characterized by very wet episodes bracketing the persistent dryness. For example, January 2013 through February 2014 was the driest such "season" since 1895, comprising a string of extremely dry months beginning immediately after strong AR storms in December 2012, and closing with the arrival of major AR storms in March 2014. This scenario is of special concern because it mimics, to an extent, the way that climate-change projections for the Delta are characterized by occasional very wet conditions separated by longer, drier droughts (see Dettinger 2016, and the next section, "Climate Change").

Even more concerning has been that current drought conditions have been much aggravated by the record-breaking warm conditions that prevailed in 2014 and 2015 (Dettinger and Cayan 2014; Griffin and Anchukaitis 2014). Warmer conditions during droughts exacerbate precipitation deficits with drier soils yielding less runoff, as well as and longer periods with much reduced freshwater inflows, more wildfire risk, and warmer streams. Increasingly, warm droughts are also a consensus projection for our future climate (see "Climate Change").

As a consequence of the large storms and long droughts that California has experienced naturally, the Delta has historically faced great floods and great droughts. These extremes have shaped the land and California's infrastructure, politics, economy, and society (e.g., Kelley 1988) in ways that we will need to mobilize and exploit in order to address the new challenges of climate change.

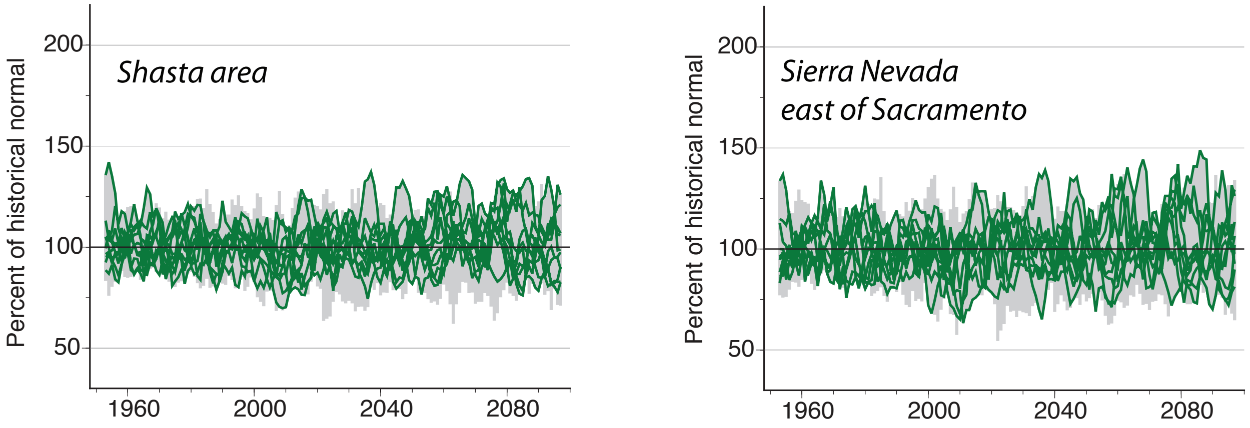
CLIMATE CHANGE

In the next several sections, we summarize the current state of science for several aspects of climate change as it will influence the Delta. Most work to date has begun with consideration of long-term projected changes in temperatures and precipitation, and this section focuses on projected trends in these variables. Confidence is high in the continuation of warming trends, if greenhouse-gas concentrations continue to increase, and so long as global warming continues, sea levels are likewise expected to rise. Thus, we consider sea level rise in the next section. Recent climate change research around the Delta has increasingly focused on the projected future of hydroclimatic extremes, such as major storms, floods, and droughts. The state of science for hydroclimatic extremes in the Delta will comprise the third section that follows ("Droughts and Floods: Climate Extremes"), before we discuss in subsequent sections the water management ("Water Resources Effects") and ecological implications ("Fisheries, Habitats, and Ecosystem Effects") of findings to date.

California has warmed by over 1°C since the late 19th century (Hoerling et al. 2013), and all modern climate models indicate that Earth's climate will continue to warm as greenhouse gases accumulate in the atmosphere as a result of fossil fuel combustion and other anthropogenic effects. By 2025, the California Delta and its watershed is projected to warm above late 20th century levels by another 1°C; by 2055, between 2°C and 2.5°C; and by 2085, between 3.5°C and 4°C (Figure 3, depending on how much global greenhouse-gas emissions continue to increase; Cayan et al. [2008b]). This warming scales nearly linearly with cumulative carbon emissions into the atmosphere, so if a lower emissions pathway were achieved globally, through aggressive and rapid transitions to economies less reliant on fossil fuels, the warming would be significantly less (Maurer 2007; Tebaldi and Arblaster 2014).

Within the Delta's catchment, local differences are certain to arise. For example, warming is likely to be amplified the farther from the coast one moves, and higher altitudes may warm faster than lower altitudes (Wang et al. 2014). The resulting amplification of warming inland across the Delta's watershed may cause enhanced sea breezes with cooler coastal air that penetrates further inland, an effect that has already been detected in California (Lebassi et al. 2009). This effect may also be affected by (and affect)

A **Assuming Lower Future Greenhouse-Gas Concentrations (RCP4.5 scenario)**



B **Assuming Higher Future Greenhouse-Gas Concentrations (RCP8.5 scenario)**

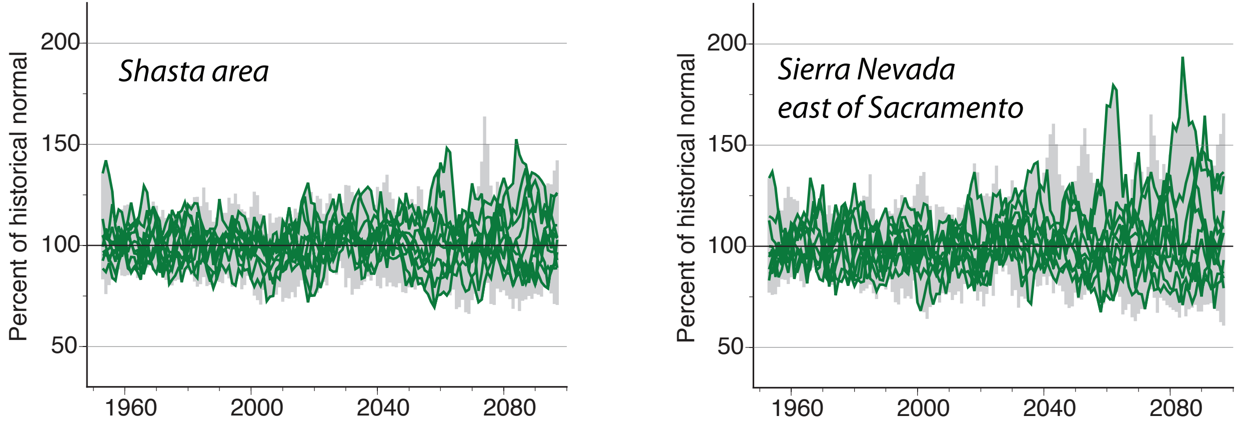


Figure 3 Projected annual changes in precipitation, relative to 1961–1990 averages, in 10 selected global climate models (bright curves, 5-year moving averaged) and in 31 models (grey, unsmoothed), under low **(A)** and high **(B)** future greenhouse-gas emissions. (Source: CDWR Climate Change Technical Advisory Group 2015).

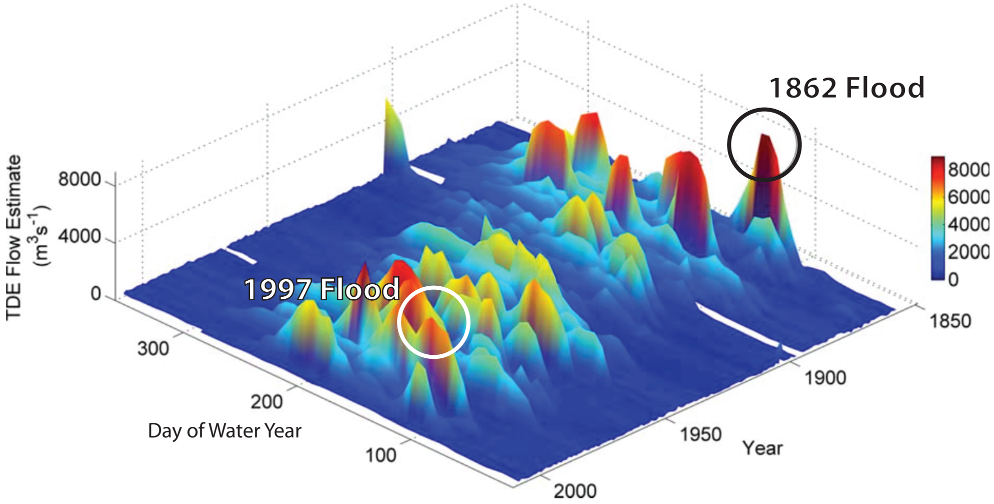


Figure 4 Freshwater outflows from the San Francisco Estuary, as tidal-discharge estimates (TDE) based on tidal gages in San Francisco Bay at the Presidio, as a function of years in the past and time of year, illustrating the high flood flows in winter 1862 and many subsequent occasions. (Modified from Moftakhari et al. 2013.)

changes in coastal upwelling of deep sea waters (Snyder et al. 2003).

Future changes in precipitation are much less certain than warming and some other changes like sea level rise and surface air humidities (Cayan et al. 2008b). Among global climate models, about half project increasing annual precipitation for the Delta's catchment and half project decreasing precipitation (Figure 4). Within this uncertainty about annual totals, more than half of the models project precipitation increases in winter months and declines in the spring and fall seasons (Pierce et al. 2013b). Also, most projections indicate that by the middle of the 21st century there will be fewer days with precipitation, but increases in the intensity of the largest storms (Pierce et al. 2013a; Polade et al. 2014; Dettinger 2016). To date, no strong consensus has emerged among modern projections about to the future prevalence of El Niño or PDO events (Vecchi and Wittenberg 2010), although the range of future ENSO fluctuations may increase (Cai et al. 2015). Thus, even the meager guidance about northern California precipitation that knowledge of future El Niño and PDO behavior would provide is not yet available to inform plans for future precipitation variations over the Delta watershed.

Winter snowfall and spring snow accumulation in the western United States have declined in recent decades, largely in response to warmer temperatures (Knowles et al. 2006; Mote et al. 2006; Kapnick and Hall 2012). Attendant changes in the timing of snow-fed streamflow have already been detected (Fritze et al. 2011). Springtime snowpack will decline significantly in the Sierra Nevada as climate warms, quite likely by at least half of present-day water contents by 2100 (Knowles and Cayan 2002; Maurer et al. 2007; Cayan et al 2008b; Pierce and Cayan 2013). As a result, by 2100, arrivals of snowmelt-fed inflows to the Delta will be delayed by a month or more. As snow retreats in a warming climate, the exposed land surface absorbs greater solar radiation, which produces a positive feedback that can accelerate local warming and snow retreat, an effect not well represented in most current projections (Pavelsky et al. 2011). The effect implies that the rate of snow loss and melt may be even more rapid than has been projected so far.

The details of these influences of warming (and precipitation change) on snowpack and snow-fed streamflows in the Delta watershed are strongly modulated by the complex topography of the state's mountain ranges. Because global climate models (GCMs) yield climate projections on coarse spatial grids, with resolutions ranging from about 100 to 200 km, a process called "downscaling" is applied to re-introduce spatial details of climate differences and variability that drive most of the watersheds, rivers, and systems of California water. The spatial resolutions of GCMs are improving, but the level of spatial detail they will provide is likely to be 50 kilometers or coarser through the next decade.

Two methods have been used in most downscaling efforts to date (CCTAG 2015): Dynamical downscaling simulates local-to-regional weather responses to coarse GCM outputs. These full-physics (or dynamic) models represent the physics of weather and climate as best we understand them at high resolutions and thus provide a full suite of climate variables (beyond “simply” temperatures and precipitation). But they also have limitations, including their own biases, uncertainties about observations to which the models are calibrated, and high computational storage requirements. The primary alternative has been statistical downscaling whereby historical weather patterns in response to various large-scale climatic conditions are interpolated into the GCM outputs by various statistical means. Statistical downscaling has the advantage that downscaled products are less computationally burdensome to develop and thus can be produced from large numbers of climate-change projections. That said, all statistical downscaling hinges on some assumption of “stationarity”—that relationships of historical large-scale to finer-scale variations will apply in the future. The statistical methods inevitably depend on the quality of historical observation data used to develop the statistical relationships.

At present, statistical-downscaled products are most widely used and are probably acceptable to meet immediate needs, as well as being consistent with several iterations of climate assessments in California in the past dozen years. Nonetheless, in years to come, either new statistical methods, new hybrids that apply combinations of both dynamic and statistical tools, or, eventually, dynamical downscaling will be needed to address the full range of issues that may threaten the Delta.

Returning to the issue of how warming will likely affect riverine inflows to the Delta, as winter storms warm and become rainier (less snow), and snowpacks melt earlier, a greater fraction of runoff generated will pass through the Delta earlier in the year. As a result, summer salinity in the upper San Francisco Bay and Delta is projected to increase (Knowles and Cayan 2004; Cloern et al. 2011). The combination of changes in temperature and precipitation, resulting in a much reduced snow regime and occasional more intense storms, is also projected to increase the frequency and magnitude of floods in the river systems that feed the Delta. By the end of the 21st century, this was found to produce robust increases in floods with return periods from 2 to 50 years for both the northern and southern Sierra Nevada, regardless of whether the climate projections considered were for overall wetter or drier conditions (Das et al. 2013).

Changes have been detected in other aspects of surface climate, including a reduction in wind speed (Vautard et al. 2010), though the driving cause is not primarily large-scale warming. Projections of large-scale wind changes over the Delta have not been much explored and remain quite uncertain, even among projections by a single climate model (Dettinger 2013b), although, as noted previously, Delta breezes may intensify. Though total atmospheric moisture content is projected to increase, warmer surface-air temperatures offset that effect to produce declines in relative humidity by as much as 14% for California (Pierce et al. 2013c). This decline would result in greater potential for evapotranspiration from soil and vegetation, intensifying hydrologic droughts. However, as CO_2 concentrations in the atmosphere increase, plants tend to use water more efficiently (called a “direct CO_2 fertilization effect”), which could offset some of the greater atmospheric evapotranspiration potential; but as temperatures rise, growing seasons will also tend to lengthen, which in turn will contribute to increases in total evapotranspiration (Lee et al. 2011). The net effect of these several countervailing influences on overall evapotranspiration and vegetation water demands remains a topic that needs more research, but the U.S. Bureau of Reclamation has concluded that overall agricultural-water demands in the Central Valley will increase (USBR 2015).

On the whole, uncertainties about many of these projections are smaller than they were 2 decades ago. But, perhaps as importantly, projections today do not differ markedly from projections in the past several Intergovernmental Panel on Climate

Change assessment cycles. That is, modern climate projections seem to have largely converged toward the values that we currently report. Nonetheless, our ability to predict the future climate over the Bay–Delta's catchment is limited by several sources of uncertainty (Hawkins and Sutton 2009, 2011): (1) uncertainties concerning the rates at which greenhouse gases will be emitted into the atmosphere in the future; (2) uncertainties concerning climate-system responses to the changing greenhouse gas concentrations (essentially climate-model uncertainties and differences); and (3) the limits of long-lead predictability of natural variations of the climate system; for example, the fluctuations of ENSO and the PDO. Natural variability (#3) plays a declining role in terms of projected temperature (and temperature-driven) changes on time-scales beyond about 2 decades. The second source of uncertainty dominates uncertainties by mid-century, and by the end of the 21st century (and beyond) the first uncertainty dominates. Precipitation projections for California, by contrast, vary largely from natural variability throughout the 21st century, but with gradually increasing uncertainty deriving from the second source later in the century.

Delta systems, both natural and human-developed, are susceptible to the effects of climate change to varying extents and on differing time-scales. Effects are likely to include altered water supplies, increased flood and levee-stability risks, and important challenges to the sustainability of species and the Delta ecosystem as we know it (Cloern et al. 2011). Decisions about adaptation should accept and, indeed, expect uncertainties in projections (Mastrandrea and Luers 2012). The first source of uncertainty can be partially accommodated by considering both ends of the emissions-pathways spectrum, although as a practical matter, it is worth noting that projected climate changes early in the 21st century tend to be similar regardless of the emissions pathway assumed, but then the changes associated with different emissions pathways differ increasingly after mid-century. Because we cannot determine which of the climate models provides the most accurate projections of the future, standard practice is to consider the statistics (and especially the extent of consensus) of projections from collections or ensembles of different models, in hopes that the outcomes upon which the models agree most are the outcomes least subject to the second type of uncertainty. Attempting to characterize likely climate change effects using too few model projections runs the risk of accidentally over-emphasizing specific natural wetter or drier fluctuations in the various (few) projections, under-representing the full range and consistencies among plausible futures. In the past decade, the numbers of climate models and climate change projections available for these ensemble analyses has increased and, with them, confidence has improved in many aspects and statistics regarding likely climate changes and effects. Furthermore, detailed outputs from historical simulations by the 30 or more climate models now in use are more readily available than they were a decade ago, so that the models that perform worst in historical simulations (and their projections) can be culled from the ensembles before they contaminate assessments of likely climate change effects (CCTAG 2015). Because climate models are not synchronized (for example, as to when El Niño events occur), using an ensemble of century-long projections also reflects the evolving role of natural climate variability more clearly (e.g., Dettinger et al. 2004).

The greater confidence regarding projections of warming and the larger uncertainties concerning how precipitation will change suggest that adaptations which accommodate warming (and its consequences) might be acted on more confidently (deterministically) than adaptations directed at future precipitation changes. The greater uncertainties around precipitation change do not argue for less attention to—nor for less urgency about—adaptations to possible precipitation changes. Rather, they imply that adaptations to changing precipitation and water supplies should focus on increasing the range of possible water futures that the Delta systems—engineered and natural—can accommodate sustainably.

SEA LEVEL RISE

Water levels in the Delta are not much higher than coastal sea level, and thus will be affected by sea level rise (SLR). Astronomical tides are attenuated as they propagate landward through the north bay and into the Delta, but are still readily detectable.

The Delta and its surrounding borders are low lying, making Delta landscapes and hydrodynamics vulnerable to water level increases and extremes.

During the 20th century, sea levels along the California coast rose about 20 cm (Cayan et al. 2008a; NRC 2012). Because of global warming, SLR is projected to continue, and very likely will accelerate during the 21st century (NRC 2012). Satellite altimetry has indicated that global SLR rates increased during the last 2 decades—from about 2 mm yr^{-1} to about 3 mm yr^{-1} (Hay et al. 2015). The rate of SLR along the California coast followed global rates closely during the 20th century. However, there is considerable variability on shorter time-scales. For example, the West Coast has experienced little SLR during the last few decades, while the western Pacific has exhibited SLR at three or more times the global rate (Bromirski et al. 2011) because of wind and pressure differences across the Pacific Ocean. Projections of the amplitude of 21st century SLR remain fairly uncertain, largely reflecting uncertainties about temperature changes and ice-cap loss rates, but most end-of-century estimates are between 0.2 m and 1.7 m of additional rise from the end of the 20th century, with outliers mostly projecting potentially even more rise (Pfeffer et al. 2008; NRC 2012; Hansen et al. 2016; DeConto and Pollard 2016).

Within the Delta, subsidence of Delta islands increases risks from SLR (Mount and Twiss 2005; Brooks et al. 2012). Increased water levels in the Bay/Delta are projected to change the tidal regime in the estuary (Holleman and Stacey 2014). Depending on how the estuary's shorelines change in coming decades—e.g., with hardened seawalls and levees vs. restored wetlands—the tidal regime could become more amplified or more dissipated, yielding wider tidal ranges, with even local shoreline changes affecting tidal ranges in parts of the estuary both near and far. Many problems associated with SLR will be amplified or hastened when large storms coincide with high astronomical tides (Cayan et al. 2008a). Strong storm winds and wind waves compound the effects of flooding along the Delta's land-water boundaries. Storm-generated freshwater flood flows may dwarf the high sea levels; flood stages in the Delta's upper reaches stand several feet above normal levels. The resulting high waters increase the risk that Delta lands and surroundings will be inundated and levees breached.

Although short-term water-level extremes are of early and pressing concern, even the most gradual expressions of SLR will eventually transport more ocean salinity into the Bay–Delta (Knowles and Cayan 2004; Cloern et al 2011). Increased salinities will affect brackish and freshwater habitats and, unless managed very skillfully, threaten water supplies (more in "Water Resources Effects").

DROUGHTS AND FLOODS (CLIMATE EXTREMES)

As temperatures rise, the character of California's climatic and hydroclimatic extremes is almost unanimously projected to change. Some events are extreme because of their size relative to historical climate distributions while other events are extreme because they comprise never before seen combinations of events. Both types of extremes will likely increase in frequency and magnitude, ultimately crossing thresholds that require reassessment and adaptation of management and restoration strategies. Understanding the underlying processes is key to understanding how to adapt to these "new" events. The current drought (2012–present) highlights these considerations: Over the past 4 years, temperatures have reached new highs, and snowpack has declined to record lows while precipitation deficits have been challenging but not record-breaking. Thus, this drought has provided both record-breaking extremes (in isolation) and a historically new set of hydrologic challenges for water management. In the Delta, new water-quality challenges and greater vulnerability to salinity intrusion have resulted. Outcomes such as these are expected to become more frequent in the coming decades.

At the other extreme, central California's largest floods have historically been driven by winter storms with heavy rains that reach higher up into the mountain watersheds than most. When these storms and floods have coincided with extreme winter tides, storm surges and high wind waves, they have formed a dual threat (high river flows and water levels) for Delta levee failures and flooding within the Delta. Warmer storms yield higher flood

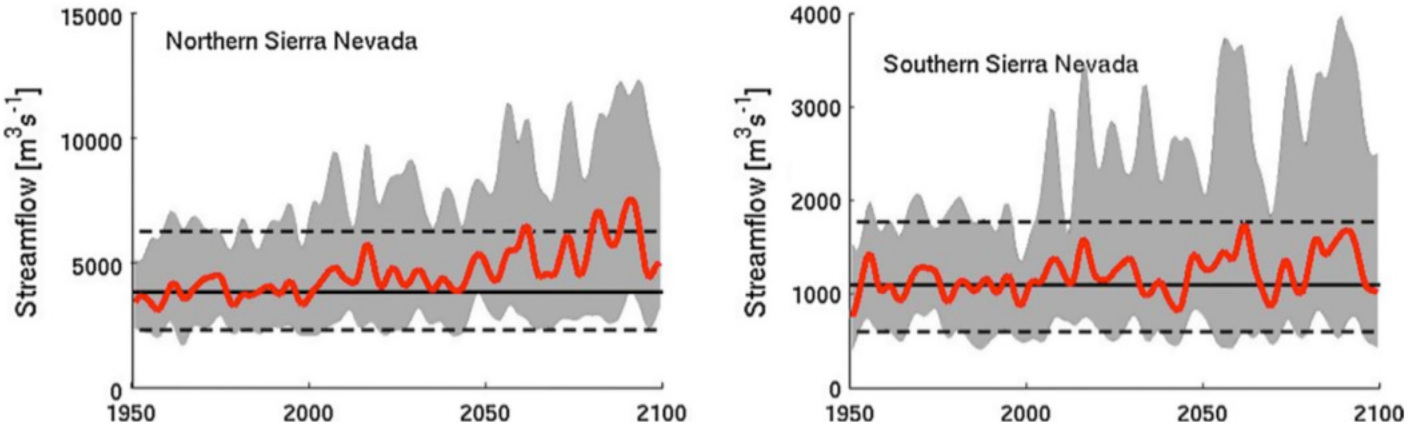


Figure 5 VIC simulated 3-days annual maximum streamflows as driven by downscaled meteorologies from 16 global climate models. The median (red line) and 25th and 75th percentiles (gray shading) are shown from the simulated streamflows distribution among the 16 models. Black horizontal lines represent median (solid black line), 25th and 75th percentiles (dotted black lines) computed over the climate model simulated historical time period 1951–1999. Results are smoothed using low pass filter shown from high emission scenario (SRES A2); from Das et al. (2013).

flows because more of the watershed receives rainfall, and contributing runoff that immediately runs off, rather than snow, which accumulates in snowpacks. Warmer temperatures also can support greater atmospheric moisture influxes that may lead to higher precipitation rates and, thus, higher flows. At the same time, a large majority of climate models project that the numbers and (less so) intensities of ARs making landfall in California will increase significantly in the 21st century if greenhouse-gas emissions continue to increase (Dettinger 2011; Warner et al. 2015; Gao et al. 2016). Together these changes are projected to result in larger peak flows and flood risks in the warming future (Figure 5).

In current climate-change projections, both droughts and floods increase as the climate warms, with storms becoming more intense, and intervening periods drier, longer, and warmer. Although changes in these extremes have not been detected with any confidence to date, these projections offer a vision of the future in which more severe droughts tempt us to store more (increasingly, cool-season) runoff even as more severe floods motivate us to release more water in pursuit of greater flood-mitigation capacity behind our primary dams. Unique new management balances between flood-control and water-supply management imperatives will likely be needed. Water year 1997 might provide an inkling of the problems involved. Following the record-breaking floods of New Year's 1997, the late winter and spring of 1997 was one of the driest on record, so that water released in coping with the winter floods was sorely missed later in the year. Although these conditions are disruptive to the human built system, flood and drought are natural conditions that the Delta's ecosystems have evolved to accommodate and, in some cases, even benefit from (e.g., Opperman et al. 2009; Moyle et al. 2010; Opperman 2012).

Two important "climate change" problems that Delta science will need to resolve (or see resolved) are better understanding and prediction of future extreme events and their implications for ecosystem conservation and water supply, and identifying and anticipating thresholds beyond which these extreme events will result in substantially new adverse effects on management and adaptation.

WATER RESOURCES EFFECTS

Water management in and for the Delta is an ever-evolving process of addressing competing needs for a reliable supply of high-quality water, protecting and restoring ecosystems, controlling floods, and satisfying legal and regulatory requirements in the face of highly variable climatic and hydrologic conditions (CDWR 2008; Lund 2016). Climate change will almost certainly exacerbate the challenges inherent in that process.

The many effects of climate change on the Delta outlined earlier will very likely affect operation of all water projects and uses that rely on freshwater transports through the Delta. Along with the climate uncertainties, changes in land cover and use in response to climate-change and other stresses will exacerbate the challenges to water-resources and flood-risk management even more, and should be an important focus of future assessments.

Trends toward declining late-winter and spring flows are already evident on both the Sacramento and San Joaquin rivers (Figure 6). Since the upper reaches of the Sacramento watershed are at lower elevation than those of the San Joaquin watershed, the Sacramento watershed is more sensitive to the modest temperature increases—and the attendant shifts of

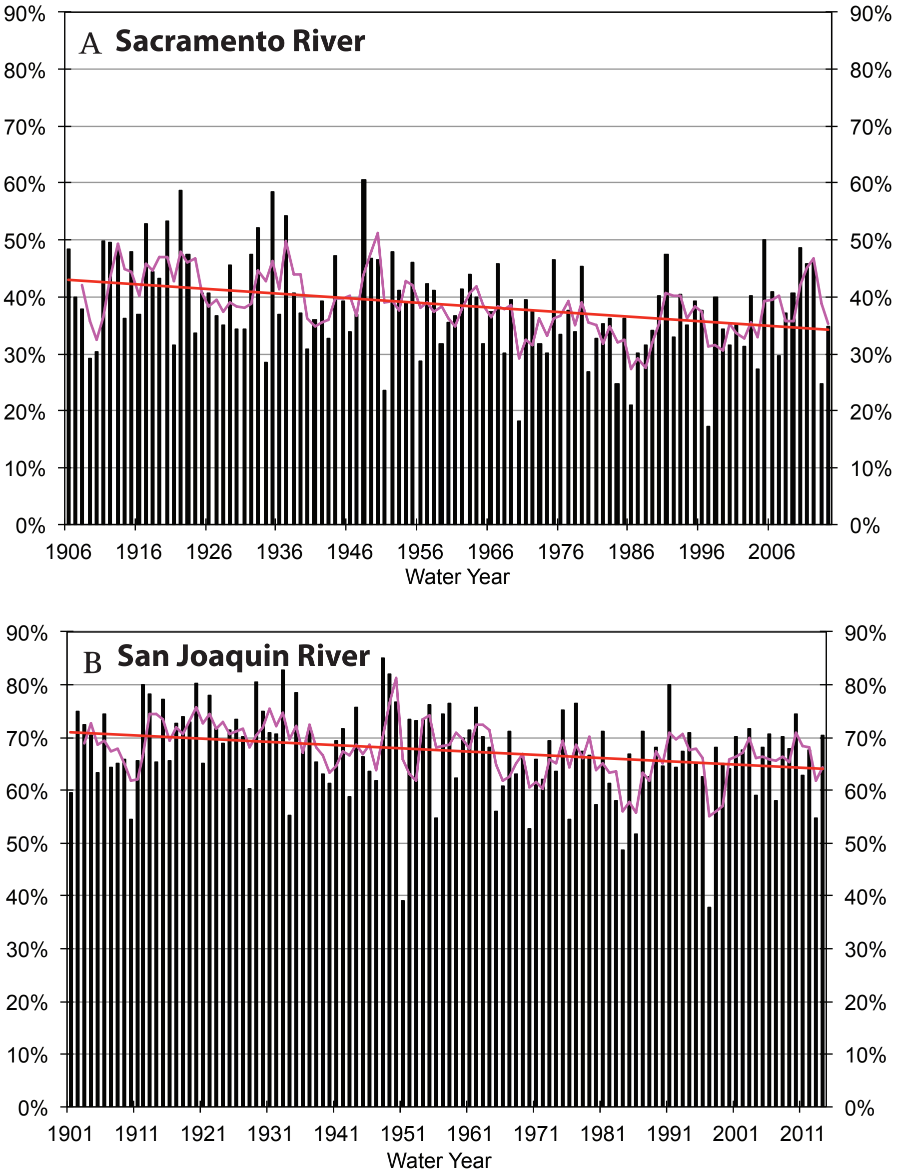


Figure 6 Full-natural (reconstructed natural) April–July streamflows in the **(A)** Sacramento and **(B)** San Joaquin Rivers, as fractions of water year totals, since early 20th century (from CDWR); red line is a least-squares trend and pink curve is a 3-year moving average. The variance captured (r^2) by the fitted trends are (a) 9.5% and (b) 6.1%, respectively, with $p < 0.05$ in both cases.

precipitation from snow to rain and earlier melting of snowpacks—experienced thus far. In the second half of the 21st century, however, warming will have long since driven precipitation-form changes and earlier snowmelt to their practical limits in the Sacramento catchments but will continue to cause ever-larger increases in peak flows and more dramatic shifts in seasonal timing from the San Joaquin Basin (Das et al. 2013; Maurer et al. 2007). Since the Sacramento River provides nearly 80% of the freshwater inflow into the Delta (CDWR 2014b), losing the natural reservoir of snowpack in that basin will be a major challenge to the state's water resources management (Dettinger and Anderson 2015). On the other hand, the snowfields of the San Joaquin Basin have more capacity to change in the face of continuing warming trends, so that by the end of this century some of the largest proportional challenges will likely arise from this tributary.

Water managers have recently been confronted with present-day examples of what these future changes might look like. During the current drought, each year's average April 1 snowpack water content has been among the bottom 10 values in the record dating back to 1950. Before 2015, the previous low snow pack was 25% in water years 1977 (from lack of precipitation) and 2014 (from the combination of a moderate lack of precipitation and record-breaking warm winter–spring temperatures). Then, in 2015, the April 1 snow pack was an unprecedented 5% of historical average, reflecting moderate lack of precipitation again and even higher winter temperatures. Recent climate-change projections do not yield snowpacks this low more than 10% of the time until after about 2070 (Figure 7). But, as climate change proceeds, such low snowpacks will become progressively more common, so that 2015 can be viewed as an early warning of challenges to come.

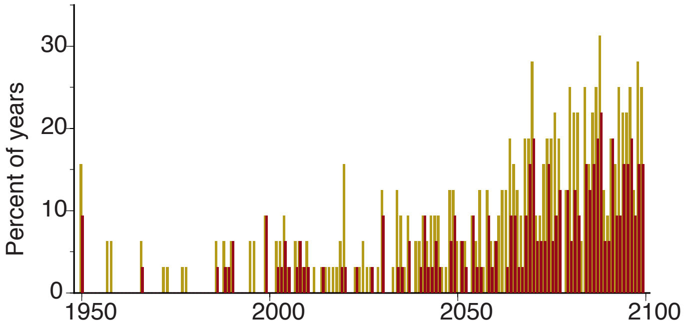


Figure 7 Odds that a year yields less than 5% (red) or 10% (orange) of 1961–1990 average April 1 snow-water equivalent across the mountains of California, in an ensemble of simulations and projections by the VIC macrohydrologic model (Liang et al. 1994) as forced by BCSD-downscaled (Wood et al. 2004) outputs from 16 global-climate models under high-(A2) and low-(B1) emissions scenarios. (Updates to results in Cayan et al. 2008b.)

These changes in temperature, snowpack, and runoff timing result in a greater fraction of annual flow volumes passing through the Delta during the time of year historically managed (by mandate) for flood control, that is, before April 1. This timing shift is expected to cause a cascade of changes in the watershed and Delta systems. For example, it has been estimated that, by the end of the 21st century, one or more of the major reservoirs that feed the Delta will be unable to release water during critical warm-season months because of low reservoir levels as often as once every 3 to 8 years (CDWR 2009); reservoir levels this low have not yet been experienced. Future declines in the amounts of water in storage at the end of the water year in upstream reservoirs (CDWR 2009) are analogous to a shrinking saving account, which reduces the ability to draw from those savings later, in times of need and shortfall. Reductions in upstream reservoir releases can be expected to result in increased groundwater pumping downstream (CDWR 2009, 2014a; Hanak and Lund 2012).

Projected SLR will increase pressure on over 1000 km of levees that surround Delta islands and protect the river channels that constitute a water supply conveyance corridor (CDWR 2014b). Many of these levees were not designed or built to modern engineering standards (Deverel et al. 2016). Salinity intrusion from SLR will require increased releases of freshwater from upstream reservoirs to repel that salinity (CDWR 2009). Careful evaluations of California's water operations have indicated that Delta inflows can be managed to maintain the position of the X2 (position with a bottom-water salinity concentration of 2 ppt) under many such futures (CDWR 2009). However, maintenance of salinity levels at other locations (e.g., Vernalis on the San Joaquin River) poses its own challenges

(Vicuna et al. 2007). Reservoir releases to repel salinity reduce the amount of water available for other purposes (CDWR 2009). With current operating rules, this tradeoff has been projected to reduce the amount of water available for export from the Delta by about 10% under mid-century climate projections, and by about 25% by end of century (CDWR 2009). Current operations are governed by complex water rights, contracts, water quality standards, biological opinions, flood control rules, agricultural and economic forces and demands, and human health and safety requirements. However, the actual effects of climate change will depend on future operating rules and future decisions, including responses to climate change itself, and the California Water Plan states that "The water management community has invested in, and depends on, a system based on historical hydrology, but managing to historical trends will no longer work because historical hydrology no longer provides an accurate picture of future conditions" (CDWR 2014a).

In addition to these salinity-management challenges, projected changes in the amount and timing of fresh water inflows combined with SLR could change water quality in other ways. For example, Ficklin et al. (2013) simulated water quality in the Sacramento and San Joaquin watershed and found that water-temperature increases of 2 to 2.5 °C could result in 10% declines in dissolved oxygen (DO) in the rivers, with high potential for detrimental effects on water quality and aquatic species. Rising sea levels and more frequent flooding of the Yolo Bypass may inundate previously dry areas, and, if conditions are right these could become new areas for the occurrence of mercury methylation (Fong et al., submitted). Increased bromide concentrations from seawater intrusion might threaten drinking-water uses (Fong et al., submitted). Much additional research is needed if we are to understand and predict the effects of climate change on water-supply quality.

Another complication in evaluating the effects of climate change is that the geometry of the Delta will likely change as a result of planned structural modifications, natural forces, and combinations of the two (Lund et al. 2008). The currently proposed Water Fix and Eco Restore programs (formerly known as the Bay Delta Conservation Plan) include plans to add water-conveyance tunnels under the Delta to move high-quality water from the Sacramento River safely to the export pumps in the south Delta (CNRA 2015), resulting in a hydrodynamically very different Delta. Delta islands could become flooded by levee failures (e.g., the 2004 Jones Tract levee failure) from an earthquake or major flood, or by planned breaching of levees to flood islands (Lund et al. 2008; Florsheim and Dettinger 2015). How changes in the geometry of the Delta might exacerbate or mitigate challenges from climate change is another area that needs more study.

More than 200 federal, state, regional, and local agencies are responsible for managing various components of the Delta system (CDWR 2014b), and have a long history of coping with the region's highly variable climate and hydrology. As noted earlier, this is a cause for some limited optimism. However, although many future conditions will fall within the range of historically observed conditions, even more extreme events are expected to occur in the future. For example, increases in heavy precipitation are projected with high confidence and are already being observed (Kunkel et al. 2013; Pierce et al. 2013a; Dettinger 2016). At the other extreme, future droughts are projected to become more frequent, with, under the influence of warmer temperatures, higher evaporative demands and increased numbers of dry days overall (Cayan et al. 2010; Polades et al. 2014; Cook et al. 2015). Notably, the persistent high pressure over the northeastern Pacific that has steered storms away from California, causing most of the precipitation shortfall in the ongoing 2013–2015 California drought, has been projected to be three to four times more likely in today's changed climate than under pre-industrial conditions (Swain et al. 2014). The combined effects of precipitation deficits and record-breaking warm temperatures have resulted in the current drought being even more intense than the 1977 drought, with an estimated 200-year recurrence interval (Aghakouchek et al. 2014). In fact, extremely dry soil-moisture conditions during 2014 and 2015 may be without precedent in a 1,200-year tree-ring record for the region (Griffin and Anchukaitis 2014).

The current drought offers numerous examples of what climate change responses may look like. In February 2014, for the first time, the state and federal

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water projects set water allocations to zero because of low water supplies (CDWR 2014a). In 2015, drought measures for the first time included curtailments of pre-1914 water rights (SWRCB 2015a). In 2015, the State of California and the U.S. Bureau of Reclamation jointly petitioned the State Water Quality Control Board to temporarily modify Delta water quality standards (SWRCB 2015b). The U.S. Bureau of Reclamation drafted a *Shasta Temperature Management Plan* to guide use of the limited cold-water pool available in Shasta Reservoir to protect temperature-sensitive Chinook Salmon eggs during late summer (*https://www.usbr.gov/mp/drought/docs/shasta-temp-mgmt-plan-key-components-06-18-15.pdf*). The California Department of Water Resources built a $28 million emergency temporary barrier in West False River to try to protect the interior Delta from encroaching ocean salinity caused by low freshwater outflows (*http://www.water.ca.gov/news/newsreleases/2015/052915.pdf*). These are all examples of how the Delta's operational and infrastructure frameworks may be modified with increasing frequency and increasing desperation in response to conditions caused—or exacerbated—by climate change. It is imperative that plans for protecting the Delta evaluate all trade-offs and opportunities, with the aim of being sufficient to meet the coming challenges and robust enough to accommodate large uncertainties that will not disappear.

FISHERIES, HABITATS AND ECOSYSTEM EFFECTS

Though the effects of climate change on the Delta ecosystem are expected to be profound, their exact nature is difficult to predict. This is partly because ecosystems comprise many species, each of which will respond to changes in the physical environment in its own way, affecting food web cycles (Brown et al. 2016a) and other ecological processes. The unpredictability also exists because ecosystem responses to climate change will depend on decisions about restoration and management that are being made now and in the future. That is, climate change will have very different effects on a future Delta with massive tunnels to protect export water qualities vs. a future Delta with freshwater throughflows aggressively managed to repel salt. Both futures would have winners and losers, but not the same winners and losers.

Generally, however, gradual changes in average environmental conditions are unlikely to be the largest challenges to the Delta's organisms until those averages exceed organismic tolerances. It is much more likely that the extreme events attending those gradually deteriorating baselines will be the most challenging for biological systems for a long time to come. For example, a heat wave associated with a drought occurred in 2014, and 95% of naturally spawned winter-run Chinook Salmon eggs and fry died because the temperatures of releases from Shasta Reservoir releases exceeded their tolerance (NMFS 2015). A similar event also occurred in 2015 (*http://www.sacbee.com/news/state/california/water-and-drought/article41684160.html*).

Next we consider several of the expected effects of climate change on Delta species from a factor-by-factor perspective. We also consider some upstream ecological effects. Just as upstream processes affect what occurs in the Delta hydrologically, upstream processes also have important effects on in-Delta species.

In a natural system, the most obvious effects of SLR on ecosystems would be at the land–water interface, particularly in tidal marshes. As sea level rises, tidal marshes can respond in two ways. A tidal marsh might respond to SLR with increased sediment trapping and accumulation of organic material (peat building), allowing the elevation of the marsh plain to follow along with SLR, and thus maintaining a marsh–open water elevations differential similar to the historical difference. However, importantly, tidal marshes also might encroach on terrestrial habitat as the water level rises. Essentially, the marsh might extend landward with the deeper portions "drowning" and converting to other habitat types, such as a mudflat or subtidal habitat. Effects on the aquatic organisms could be minimal since they would be able to find suitable habitat conditions by moving short distances landward. However, in today's landscape, few tidal wetlands remain, and many of those that remain cannot move landward because of the presence of levees and other hard infrastructures. Under these circumstances, SLR must be accommodated primarily by accumulation of sediment and organic material that raises the marsh levels in place. A number of models have been applied to this problem with results that depend on the models and assumptions used (Stralberg et al. 2011; Swanson et al. 2013). Some modeled marshes keep pace with SLR, though others cannot, depending on assumed rates of SLR, amounts of sediments in the water column, and rates of organic detritus accummulation. More research is needed.

A spatially and temporally varying salinity gradient is a defining feature of the estuary's waters. Estuarine organisms are adapted to geographically variable salinity fields that change on tidal, seasonal, annual, and longer time-scales. The most mobile organisms can simply move to remain within their preferred salinity ranges. Less mobile organisms, such as benthic invertebrates (e.g., clams), can adapt to fluctuating salinity through dispersal of eggs and larvae that can colonize new areas of appropriate habitat. In the estuary, Feyrer et al. (2015) identified five salinity guilds of fishes, ranging from freshwater to saltwater guilds. Salinity intrusion can also affect terrestrial, emergent, submerged, and floating vegetation, and other organisms.

Under natural conditions, these various species communities might respond to changing salinity conditions by simply moving (via colonization of appropriate habitats within a new salinity regime). However, salinity changes affect spatial extents, locations, and abundances of species. Moyle and Bennett (2008) have argued that management-induced reductions of variability in the Delta's salinity fields have contributed to declines in native species, changing the Delta from a naturally variable estuarine system that supports native fishes to a reservoir-like freshwater system that favors invasive submerged aquatic plants (i.e., *Egeria densa*) and fishes such as largemouth bass and other centrarchids. Freshwater releases to prevent saltwater intrusion in the summer and fall now result in salinity gradients that historically would have been typical of extreme drought in all but the wettest years. Climate change-induced reductions in late-season water availability will make such salinity conditions even more common (Brown et al. 2013, 2014; Feyrer et al. 2010).

Overall, many of the invasive species present in the Delta are better adapted to warm temperatures and low inflows than are native species (Kiernan et al. 2012; Moyle et al. 2013, 2016). Rising water temperature will be one of the most significant climate-change stressors in the Delta. Ficklin et al. (2013) examined the effects of climate change on Sierra Nevada streams and found that spring and summer water temperatures are likely to increase from 1 °C to 5.5 °C, depending on location. Biota in sub-basins with the greatest warming are more likely to be adversely affected. Within the Delta, statistical modeling of water temperatures by Wagner et al. (2011) has projected that water temperature will likely become stressful for Delta Smelt through much of their range during the summer, and will likely change the timing of important events in their life history, such as spawning time (Brown et al. 2013). Warmer temperatures in the fall combined with earlier spawning would severely limit the time available for adult Delta Smelt to mature, with unknown consequences for the reproductive success (Brown et al. 2016b) of this bellwether species that is already on the verge of extinction (Moyle et al. 2016).

Water management actions taken to support upstream fisheries will also alter conditions in the Delta. Warmer inflows and enhanced floods and droughts are likely to adversely affect the cold-water pools of large reservoirs that support downstream Chinook Salmon, Steelhead, and Sturgeon fisheries. Several modeling studies have indicated that management of salmonids below dams and diversions will become more difficult as climate change proceeds (Yates et al. 2008; Cloern et al. 2011; Thompson et al. 2012; Null et al. 2013). These challenges are real and serious, as demonstrated by the recent mortality of federally listed winter-run Chinook Salmon below Shasta Dam (described earlier).

Although potentially disastrous in many ways, future levee failures might ultimately be of some benefit for some aquatic organisms because more aquatic habitat would be created. Many Delta "islands" are completely surrounded by levees that hold Delta waters away from their interiors, wherein land surfaces are well below the water levels outside the levees (Deverel et al. 2016). Once levees are breached and the interiors flooded, the flooding of these low-lying islands is often permanent. The benefits or damages from this flooding will vary with the species being considered, the location and specifics of the levee failure, and the type and physical attributes of the habitat created. For example, Liberty Island, flooded in 1998, provides habitat for Delta Smelt because it has not been extensively invaded by *Egeria densa* or *Corbicula* to date, the water remains turbid, and the habitat is accessible to native species (Lehman 2010, 2015). In contrast, the flooded Mildred Island of the southern Delta has been extensively invaded by *Egeria densa* around its perimeter, supporting mainly invasive fish species (Grimaldo et al. 2012). The interior of the flooded island is too deep for *Egeria densa,* and pelagic production is relatively high; however, dense *Corbicula* in the outflow channels rapidly deplete exported chlorophyll–*a*, greatly reducing the benefit of primary production there to adjacent habitats (Lucas et al. 2002; Lopez et al. 2006). Flooded islands in warmer areas might well be ideal habitat for harmful algal blooms (see Fong et al., submitted). Depending on the size and location of newly flooded areas, there may be largely unexpected effects on the hydrodynamics of the entire Delta with unknown effects on the ecosystem.

Flooding in the late winter and early spring tends to benefit native fishes, particularly Splittail and Chinook Salmon (Perry et al. 2016), if floodplains remain inundated for a sufficient time (Sommer et al. 2004; Moyle et al. 2007; Jeffres et al. 2008; Moyle et al. 2016). This early flooding is important because native species tend to reproduce at cooler temperatures than many invasive species (Moyle et al. 2013). If inundations recede before water temperature increases much, reproduction of exotic species will be less successful. Conversely, droughts tend to favor exotic species because they yield fewer floodplain inundations and thus less opportunity for natives to reproduce in isolation from exotic species.

All of the above factors will be changing at the same time, and all of the communities and species will be responding with their respective individual strengths and vulnerabilities as best as each can throughout their respective life cycles. Given all the moving parts, our ability to predict in advance how climate change will affect Delta ecosystems and interact with human efforts to maintain desired ecosystem services is extremely limited. Most assuredly, there will be many surprises that require flexibility in our management systems. However, some changes we can expect. Success of habitat protection and restoration projects will require them to be designed to accommodate SLR, or to evolve gracefully into other desired habitat types as SLR proceeds. The entire life cycles of organisms of interest will need to be considered if we are to anticipate ecological effects of climate changes and attendant salinity and water temperature responses. Specifically, management that increases salinity and hydrodynamic variability in the Delta is likely to be an important tool for improving conditions for native fishes, but we need to understand far better than we do now which variations are beneficial, and how all the moving parts will interact if we are to use this tool successfully.

THE WAY FORWARD

We have called out earlier many specific knowledge gaps. More generally, global climate change is a "new" stressor that will influence many different climate, hydrologic, and ecosystem variables in the Delta system. Climate change will influence variables everywhere in the Delta's catchment, but not in the same way everywhere. Initially, this century, effects will arise mostly through enhanced extreme events. In response to this inter-meshed complex of challenges, making use of the assets we have to avoid dire outcomes will require integrated monitoring systems, integrated modeling approaches, and integrated assessments of vulnerabilities and options, as well as adaptive and adaptable decision-making processes. Models of the many complex and interacting subsystems that comprise the Delta will need to be better developed to provide more realistic and reliable guidance for planning and management of the overall Delta system. The long-standing Delta Science Program-funded Computational Assessments of Scenarios of Change in the Delta Ecosystem (CASCaDE) program is one example of how such a modeling integration across scientific fields might look (e.g., Cloern et al. 2011). Greater life-cycle and end-to-end understanding of processes and responses, whether biological or technological, is needed. That is, such integrations and attention to the extremes have not always been the norm in the past.

We posed three questions concerning "how important is this event or change" in the "Introduction." Answering these questions in the Delta, and anticipating cascading and potentially unexpected consequences of climatic events and of our responses to those events, will require a new generation of models and observations that cut across the scientific disciplines that connect as many of the parts of the Delta system, from mountain ridges to coastal ocean with all the varied landscapes in between. Meeting this requirement will depend on sustained research and observations (Dettinger and Culberson 2008), as well as considerable investment in developing the best reconstructions (through all means available) of past climates and climate effects as a baseline for the challenges and changes to come. These actions can reduce many uncertainties and help to avoid some unintended and unanticipated consequences of managing the Delta in a time of climate change. However, the uncertainties associated with climate change in the Delta will not disappear in time to allow precise outcomes to be predicted or planned for. Instead, we will know most precisely what the climate changes and effects will be as they emerge (or afterwards), and management of the Delta needs to accommodate this limitation with an urgency commensurate with what we do know or expect, and with a flexibility borne of the humble recognition of what we won't know until later.

REFERENCES

Aghakouchak A, Cheng L, Mazdiyasni O Farahmand A. 2014. Global warming and changes in risk of concurrent climate extremes: Insights from the 2014 California drought. Geophys Res Lett 41:847–8852. doi: *http://dx.doi.org/10.1002/2014GL062308*

Allan RJ, Lindesay J, Parker D. 1996. El Niño, Southern oscillation and climate variability. CSIRO Publishing, 405 p.

Ault TR, Cole JE, Overpeck JT, Pederson GT, Meko DM. 2014. Assessing the risk of persistent drought using climate model simulations and paleoclimate data. J Clim 27:7529–7549. doi: *http://dx.doi.org/10.1175/JCLI-D-12-00282.1*

Bromirski PD, Miller AJ, Flick RE, Auad G. 2011. Dynamical suppression of sea level rise along the Pacific coast of North America: indications for imminent acceleration. J Geophys Res—Oceans 116:C07005. doi: *http://dx.doi.org/10.1029/2010JC006759*

Brooks BA, Bawden G, Manjunath D, Werner C, Knowles N, Foster J, Dudas J, Cayan D. 2012. Contemporaneous subsidence and levee overtopping potential, Sacramento–San Joaquin Delta, California. San Franc Estuary Watershed Sci 10(1). doi: *http://dx.doi.org/10.15447/sfews.2012v10iss1art4*

Brown LR, Baxter R, Castillo G, Conrad L, Culberson S, Erickson G, Feyrer F, Fong S, Gehrts K, Grimaldo L, Herbold B, Kirsch J, Mueller–Solger A, Slater S, Souza K, Van Nieuwenhuyse E. 2014. Synthesis of studies in the fall low-salinity zone of the San Francisco Estuary, September–December 2011. U.S. Geological Survey Scientific Investigations Report 2014–5041. 136 p.

Brown LR, Bennett WA, Wagner RW, Morgan–King T, Knowles N, Feyrer F, Schoellhamer DH, Stacey MT, Dettinger M. 2013. Implications for future survival of delta smelt from four climate change scenarios for the Sacramento–San Joaquin Delta, California. Estuaries Coasts 36:754–774. doi: *http://dx.doi.org/10.1007/s12237-013-9585-4*

Brown LR, Kimmerer W, Conrad L, Lesmeister S, Mueller–Solger A. 2016a. Food webs of the Delta, Suisun Bay, and Suisun Marsh: an update on current understanding and possibilities for management. San Franc Estuary Watershed Sci 14(3). doi: *http://dx.doi/10.15447/sfews.2016v14iss3art4*

Brown LR, Komoroske LM, Wagner RW, Morgan–King T, May JT, Connon RE, Fangue NA. 2016b. Coupled downscaled climate models and ecophysiological metrics forecast habitat compression for an endangered estuarine fish. PLoS One 11:e0146724, doi: *http://dx.doi.org/10.1371/journal.pone.0146724*

Cai W, Santoso A, Wang G, Yeh S–W, An S–I, Cobb KM, Collins M, Guilyardi E, Jin F–F, Kug J–S, Lengaigne M, McPhaden MJ, Takahashi K, Timmermann A, Vecchi G, Watanbe M, Wu L. 2015, ENO and greenhouse warming. Nature Clim Chg 5:849–859, doi: *http://dx.doi.org/10.1038/nclimate2743*

Cayan DR, Bromirski P, Hayhoe K, Tyree M, Dettinger M, Flick R. 2008a. Climate change projections of sea-level extremes along the California coast. Clim Change 87(Suppl 1):S57–S73. doi: *http://dx.doi.org/10.1007/s10584-007-9376-7*

Cayan DR, Das T, Pierce DW, Barnett TP, Tyree M, Gershunov A. 2010. Future dryness in the southwest US and the hydrology of the early 21st century drought. Proc Nat Acad Sci 107:21271–21276. doi: *http://dx.doi.org/10.1073/pnas.0912391107*

Cayan DR, Maurer EP, Dettinger MD, Tyree M, Hayhoe K. 2008b. Climate change scenarios for the California region. Clim Change 87(Suppl 1):S21–S42. doi: *http://dx.doi.org/10.1007/s10584-007-9377-6*

Cayan DR, Redmond KT, Riddle LG. 1999. ENSO and hydrologic extremes in the western United States. J Clim 12:2881–2893. doi: *http://journals.ametsoc.org/doi/abs/10.1175/1520-0442%281999%29012%3C2881%3AEAHEIT%3E2.0.CO%3B2*

Cayan DR, Webb RH. 1992. El Niño/Southern Oscillation and streamflow in the western United States. In: Diaz HF, Markgraf V, editors. El Niño: historical and paleoclimatic aspects of the Southern Oscillation. Cambridge (UK): Cambridge University Press. 29–68 p.

[CCTAG] California Department of Water Resources. Climate Change Technical Advisory Group. 2015. Perspectives and guidance for climate change analysis. California Department of Water Resources Technical Information Record. 142 p.

[CDWR] California Department of Water Resources. 2008. Managing an uncertain future: climate change adaptation strategies for California's water. Available from: *http://www.water.ca.gov/climatechange/docs/ClimateChangeWhitePaper.pdf*

[CDWR] California Department of Water Resources. 2009. Using future climate projections to support water resources decision making in California. Prepared by the California Department of Water Resources for the California Energy Commission. CEC-500-2009-052-F.

[CDWR] California Department of Water Resources. 2014a. California Water Plan Update 2013: highlights. 46 p. Available from: *http://www.water.ca.gov/waterplan/docs/cwpu2013/Final/00-CWP-Update2013_Highlights_FINAL_10-28-2014.pdf*

[CDWR] California Department of Water Resources. 2014b. California water plan update 2013. Vol. 2., Regional reports, Sacramento–San Joaquin Delta. 84 p. Available from: *http://www.water.ca.gov/waterplan/docs/cwpu2013/Final/Vol2_DeltaRR.pdf*

Cloern JE, Knowles N, Brown LR, Cayan D, Dettinger MD, Morgan TL, Schoellhamer DH, Stacey MT, van der Wegen M, Wagner RW, Jassby AD. 2011. Projected evolution of California's San Francisco Bay–Delta river system in a century of climate change. PLoS One 6(9):e24465. doi: *http://dx.doi.org/10.1371/journal.pone.0024465*

[CNRA] California Natural Resources Agency. 2015. EcoRestore and water fix fact sheet. *http://gov.ca.gov/docs/Delta_Fact_Sheets_4.30.15.pdf*

Cook BI, Ault TR, Smerdon JE. 2015. Unprecedented 21st century drought risk in the American Southwest. Central Plains Sci Adv 1:e1400082. doi: *http://dx.doi.org/10.1126/sciadv.1400082*

Das T, Maurer EP, Pierce DW, Dettinger MD, Cayan DR. 2013. Increases in Flood Magnitudes in California Under Warming Climates. J. Hydr 501:101–110, doi: *http://dx.doi.org/10.1016/j.jhydrol.2013.07.042*

DeConto RM, Pollard D. 2016. Contribution of Antarctica to past and future sea-level rise. Nature 531:591–597. doi: *http://dx.doi.org/10.1038/nature17145*

Dettinger MD. 2011. Climate change, atmospheric rivers and floods in California—a multimodel analysis of storm frequency and magnitude changes. J. American Water Resources Assoc 47:514–523. doi: *http://dx.doi.org/10.1111/j.1752-1688.2011.00546.x*

Dettinger MD. 2013a. Atmospheric rivers as drought busters on the US west coast. J Hydromet 14:1721–1732. doi: *http://dx.doi.org/10.1175/JHM-D-13-02.1*

Dettinger MD. 2013b. Projections and downscaling of 21st century temperatures, precipitation, radiative fluxes and winds over the southwestern US, with a focus on Lake Tahoe. Clim Change 116:17–33. doi: *http://dx.doi.org/10.1007/s10584-012-0501-x*

Dettinger MD. 2016. Historical and future relations between large storms and droughts in California. San Franc Estuary Watershed Sci 14(2). doi: *http://dx.doi.org/10.15447/sfews.2016v14iss2art1*

Dettinger MD, Anderson ML. 2015. Storage in California's reservoirs and snowpack in this time of drought. San Franc Estuary Watershed Sci 13(2). doi: *http://dx.doi.org/10.15447/sfews.2015v13iss2art1*

Dettinger MD, Cayan DR. 2014. Drought and the California Delta—a matter of extremes. San Franc Estuary Watershed Sci 12(2). doi: *http://dx.doi.org/10.15447/sfews.2014v12iss2art4*

Dettinger MD, Cayan DR, Meyer MK, Jeton AE. 2004. Simulated hydrologic responses to climate variations and change in the Merced, Carson, and American River basins, Sierra Nevada, California, 1900–2099. Clim Change 62:283–317. doi: *http://dx.doi.org/10.1023/B:CLIM.0000013683.13346.4f*

Dettinger MD, Culberson S. 2008. Internalizing climate change—scientific resource management and the climate change challenges. San Franc Estuary Watershed Sci 6(2). doi: *http://dx.doi.org/10.15447/sfews.2008v6iss2art5*

Dettinger MD, Ghil M, Keppenne CL. 1995. Interannual and interdecadal variability of United States surface-air temperatures, 1910-1987. Clim Change 31:35-66. doi: *http://dx.doi.org/10.1007/BF01092980*

Dettinger M, Ingram, L. 2013. The coming megafloods. Sci Am 308(1):64-71. doi: *http://dx.doi.org/10.1038/scientificamerican0113-64*

Dettinger MD, Ralph FM, Das T, Neiman PJ, Cayan D. 2011. Atmospheric rivers, floods, and the water resources of California. Water 3:455-478. doi: *http://dx.doi.org/10.3390/w3020445*

Deverel S, Bachand S, Brandenberg S, Cosio G, Jones C, Stewart J. Levee system vulnerability. Submitted to *San Francisco Estuary and Watershed Science.*

Feyrer F, Cloern JE, Brown LR, Fish MA, Hieb KA, Baxter RD. 2015. Estuarine fish communities respond to climate variability over both river and ocean basins. Global Change Bio doi: *http://dx.doi.org/10.1111/gcb.12969*

Feyrer F, Newman K, Nobriga M, Sommer T. 2010. Modeling the effects of future freshwater flow on the abiotic habitat of an imperiled estuarine fish. Estuaries Coasts 34:120–128. doi: *http://dx.doi.org/10.1007/s12237-010-9343-9*

Ficklin DL, Stewart IT, Maurer EP. 2013. Effects of climate change on stream temperature, dissolved oxygen, and sediment concentration in the Sierra Nevada in California. Water Resour Res 49:2765–2782. doi: *http://dx.doi.org/10.1002/wrcr.20248*

Florsheim J, Dettinger M, 2015. Promoting atmospheric-river and snowmelt fueled biogeomorphic processes by restoring river-floodplain connectivity in California's Central Valley. In: Hudson P, Middelkoop H, editors. Geomorphic approaches to integrated floodplain management of lowland fluvial systems in North America and Europe. New York(NY): Springer. p. 119-141.

Fong S, Connon RE, Louie S, Werner I, Davis J, Smith L, Connor V. Contaminant effects on California Delta species and human health. Submitted to San Francisco Estuary and Watershed Science.

Fritze H, Stewart IT, Pebesma E. 2011. Shifts in western North American snowmelt runoff regimes for the recent warm decades. J Hydromet 12:989–1006. doi: *http://dx.doi.org/10.1175/2011JHM1360.1*

Gao Y, Lu J, Leung LR, Yang Q, Hagos S, Qian Y. 2016. Dynamical and thermodynamical modulations on future changes of landfalling atmospheric rivers over western North America. Geophys Res Lett 42:7179-7186, doi: *http://dx.doi.org/10.1002/2015GL065435*

Griffin D, Anchukaitis KJ. 2014. How unusual is the 2012-2014 California drought? Geophys Res Lett 41:9017–9023. doi: *http://dx.doi.org/10.1002/2014GL062433*

Grimaldo LF, Miller RE, Peregrin CM, Hymanson Z. 2012. Fish assemblages in reference and restored tidal freshwater marshes of the San Francisco Estuary. San Franc Estuary Watershed Sci 10(1). doi: *http://dx.doi.org/10.15447/sfews.2012v10iss1art2*

Guan B, Molotch NP, Waliser DE, Fetzer EJ, Neiman PJ. 2010. Extreme snowfall events linked to atmospheric rivers and surface air temperature via satellite measurements. Geophys Res Lett 37:L20401. doi: *http://dx.doi.org/10.1029/2010GL044696*

Hanak E, Lund JR. 2012. Adapting California's water management to climate change Climatic Change 111:17-44. doi: *http://dx.doi.org/10.1007/s10584-011-0241-3*

Hansen J, Sato M, Heart P, Ruedy R, Kelley M, Masson–Delmotte V, Russell G, Tseliousdis G, Cao J, Rignot E, Velicogna I, Tormey B, Donovan B, Kandiano E, von Schuckmann K, Kharecha P, Legrande AN, Bauer M, Lo K-W. 2016. Ice melt, sea level rise and superstorms—Evidence from paleoclimate data, climate modeling, and modern observations that 2°C global warming could be dangerous. Atmos Chem Phys 16:3761-3812, doi: *http://dx.doi.org/10.5194/acp-16-3761-2016*

Hawkins E, Sutton R. 2009. The potential to narrow uncertainty in regional climate predictions. Bull Amer Meteorol Soc AMS 90:1095. doi: *http://dx.doi.org/10.1175/2009BAMS2607.1*

Hawkins E, Sutton R. 2011. The potential to narrow uncertainty in projections of regional precipitation change. Clim Dynamics 37:407. doi: *http://dx.doi.org/10.1007/s00382-010-0810-6*

Hay CC, Morrow E, Kopp RE, Mitrovica JX. 2015. Probabilistic reanalysis of twentieth-century sea-level rise. Nature 517:481-484. doi: *http://dx.doi.org/10.1038/nature14093*

Hoell A, Hoerling M, Eischeid J, Wolter K, Dole R, Perlwitz J, Xu T, Cheng L. 2015. Does El Niño intensity matter for California precipitation? Geophys Res Lett doi: *http://dx.doi.org/10.1002/2015GL067102*

Hoerling M, Dettinger M, Wolter K, Lukas J, Eischeid J, Nemani R, Liebmann B, Kunkel K. 2013. Present weather and climate—evolving conditions. In: Garfin G, Jardine A, Merideth R, Black M, LeRoy S, editors. Assessment of climate change in the southwest United States. Island Press. p. 74-100.

Holleman RC, Stacey MT. 2014. Coupling of sea level rise, tidal amplification and inundation. J Phys Oceanog 44:1439-1455. doi: *http://dx.doi.org/10.1175/JPO-D-13-0214.1*

Hughes M, Mahoney KM, Neiman PJ, Moore BJ, Alexander M, Ralph FM. 2014. The landfall and inland penetration of a flood-producing atmospheric river in Arizona—Part II, Sensitivity of modeled precipitation to terrain height and atmospheric river orientation. J Hydromet 15:1954-1974. doi: *http://dx.doi.org/10.1175/JHM-D-13-0176.1*

Jeffres C, Opperman JJ, Moyle P. 2008. Ephemeral floodplain habitats provide best growth conditions for juvenile Chinook salmon in a California river. Environ BioFishes 83:449-458. doi: *http://dx.doi.org/10.1007/s10641-008-9367-1*

Kapnick S, Hall A. 2012. Causes of recent changes in western North American snowpack. Clim Dyn 38:1885-1899. doi: *http://dx.doi.org/10.1007/s00382-011-1089-y*

Kelley R. 1998. Battling the inland sea—floods, public policy and the Sacramento Valley. University of California Press. 420 p.

Kiernan JD, Moyle PB, Crain PK. 2012. Restoring native fish assemblages to a regulated California stream using the natural flow regime concept. Ecol Appl 22:1472–1482. doi: *http://dx.doi.org/10.1890/11-0480.1*

Knowles N, Cayan DR. 2002. Potential effects of global warming on the Sacramento/San Joaquin watershed and the San Francisco estuary. Geophys Res Lett 29:1891. doi: *http://dx.doi.org/10.1029/2001GL014339*

Knowles N, Cayan DR. 2004. Elevational dependence of projected hydrologic changes in the San Francisco Estuary and watershed. Clim Change 62:319-336. doi: *http://dx.doi.org/10.1023/B:CLIM.0000013696.14308.b9*

Knowles N, Dettinger MD, Cayan DR. 2006. Trends in Snowfall versus Rainfall in the Western United States. J Clim 19:4545-4559. doi: *http://dx.doi.org/10.1175/JCLI3850.1*

Kunkel KE, Karl T, Brooks H, Kossin J, Lawrimore JH, Arndt D, Bosart L, Changnon D, Cutter SL, Doeskin N, Emanuel K, Groisman PY, Katz RW, Knutson T, O'Brien J, Paciorek CJ, Peterson TC, Redmond K, Robinson D, Trapp J, Vose R, Weaver S, Wehner M, Wolter K, Wuebbles D. 2013 Monitoring and understanding trends in extreme storms: State of knowledge. Bull Amer Met Soc 94:499-514. doi: *http://dx.doi.org/10.1175/BAMS-D-11-00262.1*

Lavers D, Waliser D, Ralph FM, Dettinger, M. 2016. Predictability of horizontal water vapor transport relative to precipitation—enhancing situational awareness for forecasting western U.S. extreme precipitation and flooding. Geophys Res Lett 43, doi: *http://dx.doi.org/10.1002/2016GL067765*

Lebassi B, Gonzalez J, Fabris D, Maurer E, Miller N, Milesi C, Switzer P, Bornstein R. 2009. Observed 1970-2005 cooling of summer daytime temperatures in coastal California. J Clim 22:3558-3573. *http://dx.doi.org/10.1175/2008JCLI2111.1*

Lee J, De Gryze S, Six J. 2011. Effect of climate change on field crop production in the Central Valley of California. Clim Change 109(Suppl1):335-53. doi: *http://dx.doi.org/10.1007/s10584-011-0305-4*

Lehman PW, Mayr S, Liu L, Tang A. 2015. Tidal day organic and inorganic material flux of ponds in the Liberty Island freshwater tidal wetland. SpringerPlus 4:273. doi: *http://dx.doi.org/10.1186/s40064-015-1068-6*

Lehman PW, Mayr S, Mecum L, Enright C. 2010. The freshwater tidal wetland of Liberty Island, CA was both a source and sink of inorganic and organic material to the San Francisco Estuary. Aquatic Ecol 44:359-372. doi: *http://dx.doi.org/10.1007/s10452-009-9295-y*

Liang X, Lettenmaier DP, Wood EP, Burges SJ. 1994. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. J Geophys Res 99(D7):14415–14428. doi: *http://dx.doi.org/10.1029/94JD00483*

Lopez CB, Cloern JE, Schraga TS, Little AJ, Lucas LV, Thompson JK, Burau JR. 2006. Ecological values of shallow-water habitats: Implications for restoration of disturbed ecosystems. Ecosystems 9:422–440. doi: *http://dx.doi.org/10.1007/s10021-005-0113-7*

Lucas LV, Cloern JE, Thompson JK, Monsen NE. 2002. Functional variability of habitats within the Sacramento-San Joaquin Delta: restoration implications. Ecol Apps 12:1528–1547. doi: *http://dx.doi.org/10.1890/1051-0761(2002)012[1528:FVOHWT]2.0.CO;2*

Lund J. 2016. California's agricultural and urban water supply reliability and the Sacramento–San Joaquin Delta. San Franc Estuary Watershed Sci 14(3). doi: *http://dx.doi.org/10.15447/sfews.2016v14iss3art6*

Lund J, Hanak E, Fleenor W, Bennett W, Howitt R, Mount J, Moyle P, 2008. Comparing futures for the Sacramento-San Joaquin Delta. San Francisco (CA): Public Policy Institute of California. 147 p. Available from: *http://www.ppic.org/main/publication.asp?i=810*

Mantua NJ, Hare SR, Zhang Y, Wallace JM, Francis RC. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bull Am Met Soc 78:1069-1079. doi: *http://dx.doi.org/10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2*

Mastrandrea M, Luers AL. 2012. Climate change in California: scenarios and approaches for adaptation. Clim Change 111:5-16. doi: *http://dx.doi.org/10.1007/s10584-011-0240-4*

Maurer EP. 2007. Uncertainty in hydrologic impacts of climate change in the Sierra Nevada, California under two emissions scenarios. Clim Change 82(3-4):309-325. doi: *http://dx.doi.org/10.1007/s10584-006-9180-9*

Maurer EP, Stewart IT, Bonfils C, Duffy PB, Cayan D. 2007. Detection, attribution, and sensitivity of trends toward earlier streamflow in the Sierra Nevada. J Geophys Res 112:D11118. doi: *http://dx.doi.org/10.1029/2006JD008088*

Meko DM, Woodhouse CA, Touchan R. 2014. Klamath–San Joaquin–Sacramento hydroclimatic reconstructions from tree rings. Report to the California Department of Water Resources 4600008850. 117 p. Available from: *http://www.water.ca.gov/waterconditions/docs/tree_ring_report_for_web.pdf*

Moftakhari HR, Jay DA, Talke SA, Kukulka T, Bromirski PD. 2013. A novel approach to flow estimation in tidal rivers. Water Resour Res 49:4817–4832. doi: *http://dx.doi.org/10.1002/wrcr.20363*

Mote PW. 2006. Climate-driven variability and trends in mountain snowpack in western North America. J Clim 19:6209–6220. doi: *http://dx.doi.org/10.1175/JCLI3971.1*

Mount J, Twiss R. 2005. Subsidence, sea level rise, and seismicity in the Sacramento–San Joaquin Delta. San Franc Estuary Watershed Sci 3(1). doi: *http://dx.doi.org/10.15447/sfews.2005v3iss1art7*

Moyle PB, Bennett WA. 2008. The future of the Delta ecosystem and its fish. Technical Appendix D. In: Lund J, Hanak E, Fleenor W, Bennett W, Howitt R, Mount J, Moyle P, editors. Comparing futures for the Sacramento–San Joaquin Delta. San Francisco (CA): Public Policy Institute of California. Available from: *http://www.ppic.org/main/publication.asp?i=810*

Moyle PB, Bennett WA, Fleenor WE, Lund JR. 2010. Habitat variability and complexity in the upper San Francisco Estuary. San Francisco Estuary Watershed Sci 8(3). doi: *http://dx.doi.org/10.15447/sfews.2010v8iss3art1*

Moyle PB, Brown LR, Durand JR, Hobbs, JA. 2016. Delta Smelt: life history and decline of a once abundant species in the San Francisco estuary. San Franc Estuary Watershed Sci 14(2). doi: *http://dx.doi.org/10.15447/sfews.2016v14iss2art6*

Moyle PB, Crain PK, Whitener K. 2007. Patterns in the use of a restored California floodplain by native and alien fishes. San Franc Estuary Watershed Sci 5(3):1-27. doi: *http://dx.doi.org/10.15447/sfews.2007v5iss5art1*

Moyle PB, Kiernan JD, Crain PK, Quinones RM. 2013. Climate change vulnerability of native and alien freshwater fishes of California: a systematic assessment approach. PLoS ONE 8(5):e63883. doi: *http://dx.doi.org/10.1371/journal.pone.0063883*

[NMFS] National Marine Fisheries Service. 2015. Letter from National Marine Fisheries Service to U.S. Bureau of Reclamation regarding incidental take statement for the combined operation of the Central Valley Project and State Water Project for 2015. Sacramento (CA): National Marine Fisheries Service.

[NRC] National Research Council. 2012. Sea-level rise for the coasts of California, Oregon, and Washington—Past, present and future. Report of the Committee on sea level rise in California, Oregon, and Washington. Washington, D.C.: National Academies Press. 202 p.

Null SE, Viers JH, Deas ML, Tanaka SK, Mount JF. 2013. Stream temperature sensitivity to climate warming in California's Sierra Nevada: impacts to coldwater habitat. Clim Change 116:149-170. doi: *http://dx.doi.org/10.1007/s10584-012-0459-8*

Opperman JJ. 2012. A conceptual model for floodplains in the Sacramento-San Joaquin Delta. San Franc Estuary Watershed Sci 10(3). doi: *http://dx.doi.org/10.15447/sfews.2012v10iss3art4*

Opperman JJ, Galloway GE, Fargione J, Mount JF, Richter BD, Secchi S. 2009. Sustainable floodplains through large-scale reconnection to rivers. Science 326:1487-1488. doi: *http://dx.doi.org/10.1126/science.1178256*

Pavelsky T, Kapnick S, Hall A. 2011. Accumulation and melt dynamics of snowpack from a multiresolution regional climate model in the central Sierra Nevada, California. J Geophys Res–Atmos 116:D16115. doi: *http://dx.doi.org/10.1029/2010JD015479*

Perry RW, Brandes PL, Buchanan RA, Burau JR, Israel JA. 2016. Anadromous salmonids in the Delta: new science 2006-2016. San Franc Estuary Watershed Sci 14(2). doi: *http://dx.doi.org/10.15447/sfews.2016v14iss2art7*

Pfeffer WT, Harper JT, O'Neel S. 2008. Kinematic constraints on glacier contributions to 21st century sea-level rise. Science 321:1340-1343. doi: *http://dx.doi.org/10.1126/science.1159099*

Pierce DW, Cayan DR. 2013. The uneven response of different snow measures to human-induced climate warming. J Clim 26:4148-4167. doi: *http://dx.doi.org/10.1175/JCLI-D-12-00534.1*

Pierce D, Cayan DR, Das T, Maurer EP, Miller NL, Bao Y, Kanamitsu MK, Yoshimura K, Snyder MA, Sloan LC, Franco G, Tyree M. 2013a. The key role of heavy precipitation events in climate model disagreements of future annual precipitation changes in California. J Clim 26:5879–5896. doi: *http://dx.doi.org/10.1175/JCLI-D-12-00766.1*

Pierce DW, Das T, Cayan DR, Maurer EP, Miller N, Bao Y, Kanamitsu M, Yoshimura K, Snyder MA, Sloan LC, Franco G, Tyree M. 2013b. Probabilistic estimates of future changes in California temperature and precipitation using statistical and dynamical downscaling. Clim Dyn 40(3-4):839-856. doi: *http://dx.doi.org/10.1007/s00382-012-1337-9*

Pierce DW, Westerling AL, Oyler J. 2013c. Future humidity trends over the western United States in the CMIP5 global climate models and variable infiltration capacity hydrological modeling system. Hydrol Earth Syst Sci 17:1833-1850. doi: *http://dx.doi.org/10.5194/hess-17-1833-2013*

Polade SD, Pierce DW, Cayan DR, Gershunov A, Dettinger MD. 2014. The key role of dry days in changing regional climate and precipitation regimes. Nature Sci Reports 4(4364). doi: *http://dx.doi.org/10.1038/srep04364*

Ralph FM, Dettinger MD. 2011. Storms, floods and the science of atmospheric rivers. Eos 92:265-266. doi: *http://dx.doi.org/10.1029/2011EO320001*

Ralph FM, Dettinger MD. 2012. Historical and national perspectives on extreme west-coast precipitation associated with atmospheric rivers during December 2010. Bull. Amer Meteorol Soc 93:783-790. doi: *http://dx.doi.org/10.1175/BAMS-D-11-00188.1*

Ralph FM, Prather K, Cayan D, Spackman JR, Demott P, Dettinger M, Fairall C, Leung R, Rosenfeld D, Rutledge S, Waliser D, White A, Cordeira J, Martin A, Helly J, Intieri J. 2016. CalWater field studies designed to quantify the roles of atmospheric rivers and aerosols in modulating US West Coast precipitation in a changing climate. Bull Amer Meteorol Soc 97(7). doi: *http://dx.doi.org/10.1175/BAMS-D-14-00043.1*

Redmond KT. Koch RW. 1991. Surface climate and streamflow variability in the western United States and their relationship to large-scale circulation indices. Water Resour Res 27:2381-2399. doi: *http://dx.doi.org/10.1029/91WR00690*

Snyder MA, Sloan LC, Diffenbaugh NS, Bell JL. 2003. Future climate change and upwelling in the California Current. Geophys Res Lett 30(15):1823. doi: *http://dx.doi.org/10.1029/2003GL017647*

Sommer TR, Harrell WC, Kurth R, Feyrer F, Zeug SC, O'Leary G. 2004. Ecological patterns of early life stages of fishes in a river-floodplain of the San Francisco Estuary. Amer Fisheries Soc Symp 39:111–123. Available from: *http://www.water.ca.gov/aes/docs/Sommer_et_al_2004.pdf*

St. George S, Ault TR. 2011. Is energetic decadal variability a stable feature of the central Pacific Coast's winter climate? J Geophys Res 116:D12102. doi: *http://dx.doi.org/10.1029/2010JD015325*

Stralberg D, Brennan M, Callaway JC, Wood JK, Schile LM, Jongsomjit D, Kelly M, Parker VT, Crooks S. 2011. Evaluating tidal marsh sustainability in the face of sea-level rise: a hybrid modeling approach applied in San Francisco Bay. PLoS ONE 6(11):e27388. doi: *http://dx.doi.org/10.1371/journal.pone.0027388*

Swain DL, Tsiang M, Haugen M, Singh D, Charland A, Rajaratnam B, Diffenbaugh NS. 2014. The extraordinary California drought of 2013–2014: character, context, and the role of climate change. In: Herring SC, Hoerling MP, Peterson TC, Stott PA, editors. Explaining extreme events of 2013 from a climate perspective: a special supplement. Bull Am Meteorol Soc 95:S3-S7. doi: *http://dx.doi.org/10.1175/1520-0477-95.9.S1.1*

Swanson KM, Drexler JZ, Schoellhamer DH, Thorne KM, Casazza ML, Overton CT, Callaway JC, Takekawa JY. 2013. Wetland accretion rate model of ecosystem resilience (WARMER) and its application to habitat sustainability for endangered species in the San Francisco Estuary. Estuaries Coasts 37:476-492. doi: *http://dx.doi.org/10.1007/s12237-013-9694-0*

[SWRCB] State Water Resources Control Board. 2015a. Notice of unavailability of water and need for immediate curtailment for those diverting water in the Sacramento–San Joaquin watersheds and Delta with a pre-1914 appropriative claim commencing during or after 1903. *http://www.swrcb.ca.gov/waterrights/water_issues/programs/drought/docs/pre14curtailmentjun2015.pdf*

[SWRCB] State Water Resources Control Board. 2015b. State Water Project and Central Valley Project temporary urgency change petition. *http://www.waterboards.ca.gov/waterrights/water_issues/programs/drought/tucp.shtml*

Tebaldi C, Arblaster JM. 2014. Pattern scaling: Its strengths and limitations, and an update on the latest model simulations. Clim Change 122(3):459-471. doi: *http://dx.doi.org/10.1007/s10584-013-1032-9*

Thompson L, Escobar M, Mosser C, Purkey D, Yates D, Moyle P. 2012. Water management adaptations to prevent loss of spring-run Chinook salmon in California under climate change. J Water Resour Plann Manag 138:465–478. doi: *http://dx.doi.org/10.1061/(ASCE)WR.1943-5452.0000194*

[USBR] U.S. Bureau of Reclamation. 2015. Basin study report and executive symmary, Sacramento and San Joaquin basins study, report to Congress 2015. Prepared for U.S. Department of the Interior, Bureau of Reclamation, Mid Pacific Region, by CH2M Hill. 142 p.

Vautard R, Cattiaux J, Yiou P, Thépaut J-N, Ciais P. 2010. Northern hemisphere atmospheric stilling partly attributed to an increase in surface roughness. Nat Geosci 3:756–761. doi: h*ttp://dx.doi.org/10.1038/ngeo979*

Vecchi GA, Wittenberg AT. 2010. El Niño and our future climate—where do we stand? WIREs Climate Change 1:260-270. doi: *http://dx.doi.org/10.1002/wcc.33*

Vicuna S, Maurer EP, Joyce B, Dracup JA, Purkey D. 2007. The sensitivity of California water resources to climate change scenarios. J Amer Water Resour Assoc 43:482-498. doi: *http://dx.doi.org/10.1111/j.1752-1688.2007.00038.x*

Wagner W, Stacey M, Brown L, Dettinger M. 2011. Statistical models of temperature in the Sacramento-San Joaquin Delta under climate-change scenarios and ecological implications. Estuaries Coasts 34:544-556. doi: *http://dx.doi.org/10.1007/s12237-010-9369-z*

Wang Q, Fan X, Wang M. 2014. Recent warming amplification over high elevation regions across the globe. Clim Dyn 43:87-101. doi: *http://dx.doi.org/10.1007/s00382-013-1889-3*

Warner MD, Mass CF, Salathe EP Jr. 2015. Changes in winter atmospheric rivers along the North American west coast in CMIP5 climate models. J Hydromet 16:118-128. doi: *http://dx.doi.org/10.1175/JHM-D-14-0080.1*

White AB, Anderson ML, Dettinger MD, Ralph FM, Hinojosa A, Cayan DR, Hartman RK, Reynolds DW, Johnson LE, Schneider TL, Cifelli R, Toth Z, Gutman SI, King CW, Gerhke F, Johnston PE, Walls C, Gottas DJ, Coleman T. 2013. A 21st century California observing network for monitoring extreme weather events. J Atmos Oceanic Tech 30:1585-1603. doi: *http://dx.doi.org/10.1175/JTECH-D-12-00217.1*

Wick GA, Neiman PJ, Ralph FM, Hamill TM. 2013. Evaluation of forecasts of the water vapor signature of atmospheric rivers in operational numerical weather prediction models. Weather Forecast 28:1337-1352. doi: *http://dx.doi.org/10.1175/WAF-D-13-00025.1*

Yates D, Galbraith H, Purkey D, Huber–Lee A, Sieber J, West J, Herrod-Julius S, Joyce B. 2008. Climate warming, water storage, and Chinook salmon in California's Sacramento Valley. Clim Change 91:335-350. doi: *http://dx.doi.org/10.1007/s10584-008-9427-8*

Zhu Y, Newell RE. 1998. A proposed algorithm for moisture fluxes from atmospheric rivers. Mon Wea Rev 126:725-735. doi: *http://dx.doi.org/10.1175/1520-0493(1998)126<0725:APAFMF>2.0.CO;2*