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Holocene Climates and Connections between the San Francisco Bay Estuary and its Watershed: A Review

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ABSTRACT

Climate across the watershed of the San Francisco Bay Delta-Estuary system varies on a wide range of space and time scales, and affects downstream estuarine ecosystems. The historical climate has included mild to severe droughts and torrential rains accompanied by flooding, providing important lessons for present-day resource managers. Paleoclimate records spanning the last 10,000 years, synthesized across the Estuary, watershed, and key regions beyond, provide a basis for increased understanding of how variable California's climate can be and how it affects the Bay Delta system.

This review of paleoclimate records reveals a gradual warming and drying in California from about 10,000 years to about 4,000 years before present. During this period, the current Bay and Delta were inundated by rising sea level so that by 4,000 years ago, the Bay and Delta had taken on much of their present shape and extent. Between about 4,000 and 2,000 years ago, cooler and wetter conditions prevailed in the watershed, lowering salinity in the Estuary and altering local ecosystems. Those wetter conditions gave way to increasing aridity during the past 2,000 years, a general trend punctuated by occasional prolonged and severe droughts and occasional unusually wet, cool periods. California's climate since A.D. 1850 has been unusually stable and benign, compared to climate variations during the previous 2,000 or more years. Thus, climate variations in California's future may be even more (perhaps much more) challenging than those of the past 100 years. To improve our understanding of these past examples of climate variability in California, and of the linkages between watershed climate and estuarine responses, greater emphases on paleoclimate records in and around the Estuary, improved temporal resolutions in several record types, and linked watershed-Estuary paleo-modeling capabilities are needed.

KEYWORDS

San Francisco Bay Estuary, climate, climate variability, paleoclimate, drought, flooding

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INTRODUCTION

The San Francisco Bay-Delta system forms a transition zone where freshwater runoff from upland watersheds, including the Sierra Nevada to the east and the Coastal Ranges to the west, meets and intermingles with ocean water to yield variably salty waters. Salinity in the estuary fluctuates seasonally and from year to year in response to climatic variations and the management of upstream reservoirs and diversions of freshwater (DWR 1993; Peterson et al. 1995; Knowles 2002). These salinity variations are pivotal to the Bay-Delta water management programs with goals of improving water-supply reliability, restoring ecosystems in and around the Estuary, and improving water quality (CALFED 2001). Efforts to achieve these goals, in the long run, will depend–among many other natural and engineering factors–on the robustness of present-day decisions and actions to the considerable buffeting that California's highly variable climate will impose on its water-resource and ecological systems in coming decades and centuries.

The watershed that drains to the Bay and Delta encompasses much of central California, including the Central Valley, Sierra Nevada, and Coastal Ranges. This broad, north-south trending watershed is, in most years, wetter in the north and drier in the south. However, it also straddles the transition zone between the wet-Southwest and dry-Northwest influences of the El Niño-Southern Oscillation (ENSO) on western North American precipitation (Cayan and Webb 1992). Central California is similarly the transition zone for the multi-decadal ENSO-like expressions of the Pacific Decadal Oscillation (PDO) (Mantua et al. 1997), and for other shorter and (especially) longer term climatic influences that are less understood. Superimposed on these natural climate fluctuations are recent warming trends in winter-spring temperatures (Cayan et al. 2001) and associated snowmelt and streamflow timing trends (Roos 1991; Dettinger and Cayan 1995; Mote 2003; Stewart et al. 2005). These trends may be harbingers for future global warming effects in the state, effects that will bring great challenges to the state's resource managers over the next 50 to 100 years. On even longer time scales, recent studies of California's paleoclimatic past also provide worrying evidence that the erratic precipitation regimes that have been observed (and largely accommodated) in California during the past century have been—by and large—benign and small in comparison to natural precipitation variations over the past 1,000 years or more (e.g., Meko et al. 2001, Ingram et al. 1996c, Stine 1994).

The climate that California will face in the future, and that water resource managers will face during the next 30-year planning period, is likely to reflect some combination of the kinds of climate (and runoff) variability described by California's paleoclimatic proxies (e.g., as described in this review), variations like those observed during its historical period (e.g., NRC 1999), and variations like those projected by current models of global climate change induced by human activities (e.g., Hayhoe et al. 2004). These climate variations need to be characterized (monitored, predicted, or reduced to statistical distributions, depending on application) to the extent possible, to provide the soundest possible scientific and engineering basis for upcoming decisions regarding the future of resource systems in the San Francisco Bay-Delta, and associated watershed region.

This paper provides a review of the scientific literature regarding California's climate during the past several thousand years, and a summary of available paleoclimatic proxies and resources for characterizing the natural climate of the Sacramento-San Joaquin Bay-Delta and its watershed. The range of variability within this natural climate will still exist even under projected global changes, and will still need to be accommodated in planning for future population growth and environmental needs. Following a discussion of the paleoclimatic "archives" available to describe the state's past climate variations, key points from the paleoclimatic history of the Estuary and watershed are reviewed. The Bay and Delta have been changed substantially in the time since Europeans first settled in California, and those changes have modified the ways that the systems experience and respond to climate variations. In particular, the vast marshlands that once surrounded the Bay-Delta, and which contained rich paleo-environmental archives have largely been lost to development, or cut off from tidal inundation (Nichols et al. 1986). We do not focus on those modern changes here (except for a discussion of how sediments and flood flows have been changed), nor on how they will affect the future survival of the Bay's ecosystem under future climate scenarios. Such impacts deserve careful study but are beyond the paleoclimatic aspirations of this review. In the concluding section of this paper, recommendations for additional paleoclimatic studies are offered. A much more detailed description of the archives and past variations in climate is provided by Malamud-Roam et al. (2006).

DISCUSSION

Available Paleoclimate Archives

Climate researchers can derive records of past climate conditions in California from natural archives. Most common among these are tree rings and accumulated sediment deposits. Paleoclimate records from the San Francisco Bay Estuary (including both Bay and Delta) and its larger watershed region provide the basis for characterizing the natural variability of precipitation and runoff in California over the past several thousand years. Current climate-change projections indicate that the range of precipitation variations as experienced over the last 100 years of record may increase somewhat as a result of global warming (Nichols et al. 1996). However, resource-management systems will also need to accommodate the even greater range of naturally occurring precipitation variations seen in paleorecords of various kinds, variations that may be presented at almost any time and that are beyond any that resource-management systems have faced during the twentieth century. Such challenges will probably supercede those expected from climate changes associated with the increasing greenhouse-gas concentrations of the twenty-first century, at least in the near-term (Dettinger 2005). The natural forces that drove California's climate during the past several millennia are not substantially different from the natural forces that have underlain historical fluctuations and that will continue to impose themselves even under the man-made climate changes of the twenty-first century. To understand and quantify the richer multi-millennial expanse of California's natural range of climate (and runoff) variations, a number of information sources are available. These include sediment cores from ocean, estuary, marshlands and lowland floodplains, tree rings, geomorphic patterns and stratigraphic structures, and lake sediments. Each of these "archives" of paleoclimatic information describes the large fluctuations of climate experienced locally or regionally during the past 4,000 years, and each offers its own unique perspective on those fluctuations and their impacts on the Estuary and watershed.

The San Francisco Bay-Delta catchment is outlined in Figure 1, along with representative locations of paleoclimate archives of particular interest to this review. From beyond the Estuary and its watershed, it is helpful to consider also some key paleoclimate archives from coastal-ocean basins and from the Great Basin east of the Sierra Nevada (Figure 1), because these particular sites reflect large-scale regional climate variations that span and influence the Estuary-watershed area.

Because one purpose of this paper is to characterize the paleoclimatic archives available to decision-makers in the Estuary and watershed, it is worth taking a moment to consider the range and character of the archives shown in Figure 1 from a broad perspective. The geographic distribution and available archives may be characterized in very general terms (Figure 2) as:

(i) *The Sierra Nevada, Coastal Ranges, and from the Great Basin beyond the watershed.* Tree rings and lake sediments provide chronologies of past precipitation, temperature, stream flow, and vegetation variations, with time resolutions ranging from annual (tree rings) to decadal (sediments);

(ii) *Central Valley floodplains and foothills above the Estuary.* The textures and configurations of flood deposits provide snapshots of high (and low) river stages and discharges, individual floods, and sediment transports and deposition, usually in terms of isolated (often extreme) episodes with timing known only loosely (within time frames on order of a century);

(iii) *San Francisco Bay and Delta*. Macro- and micro-fossil assemblages, geochemistry, and sediment stratigraphy of sediments on the Estuary floor and from its adjacent tidal wetlands provide long term records of estuarine salinity, freshwater inflows, sea levels, and sediment transports, with typical time resolutions ranging from decades to centuries; and

(iv) *Coastal-ocean basins*. Microfossil assemblages in, and the geochemistry of, unconsolidated sediments on the coastal-ocean basin floors provide proxy (or indirect) measures of sea-surface temperatures, mixing between ocean water layers, and flooding, at a wide range of time resolutions—depending on conditions in the basin sampled and on the methods employed to deconstruct the sedimentary records.

In reality, considerable overlap of archive types exists across the geographic regions, as sedimentary deposits are found in each of these settings, and tree-ring chronologies are being obtained across the full range

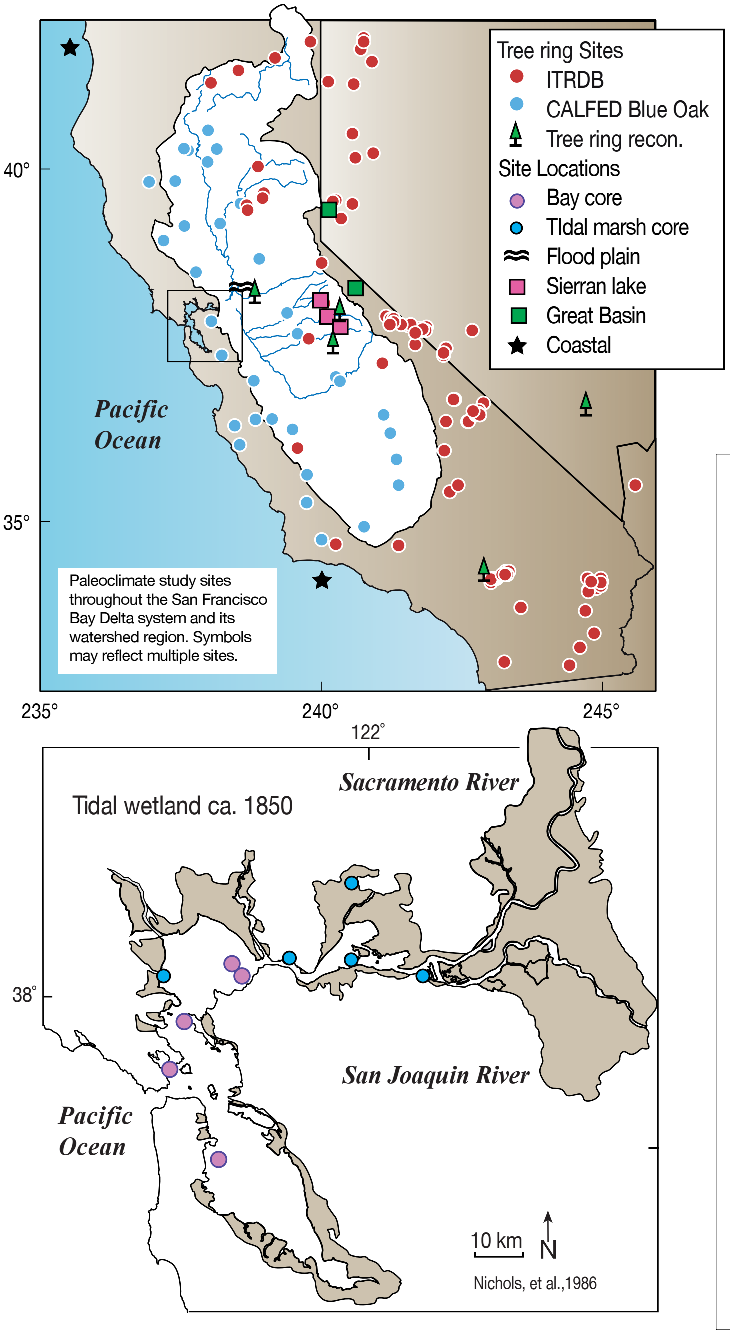


Figure 1. Map of paleoclimate research sites in the San Francisco Bay Estuary and its watershed region, California. Inset shows the San Francisco Bay with study site locations.

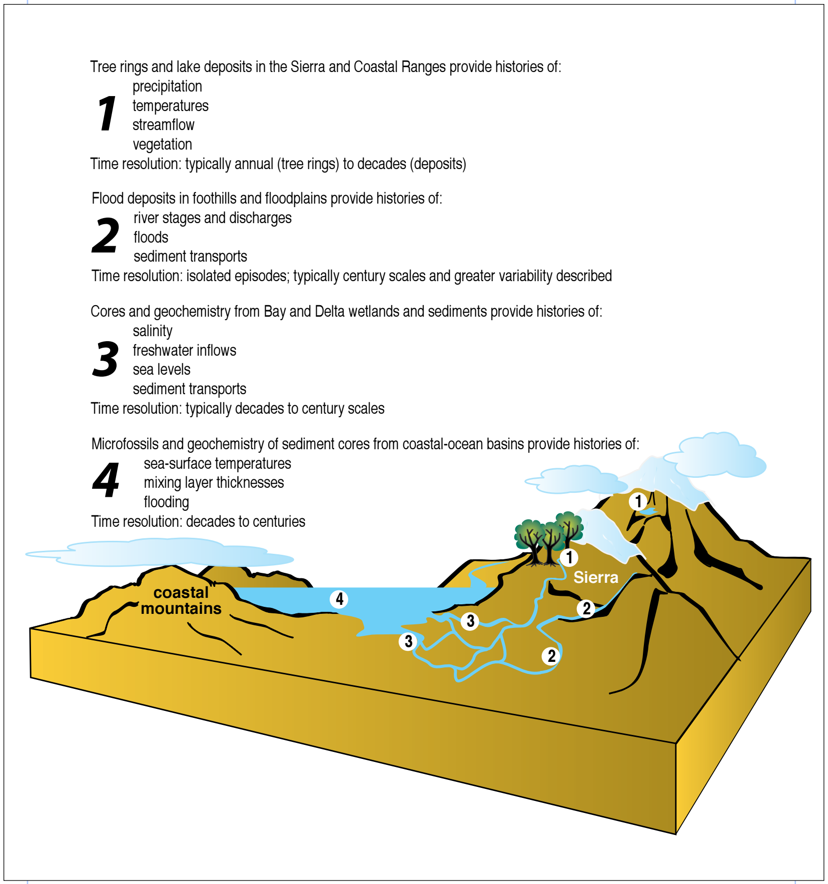


Figure 2. Paleoclimate archives and the types of climate variables they measure available throughout the San Francisco Bay and its watershed region.

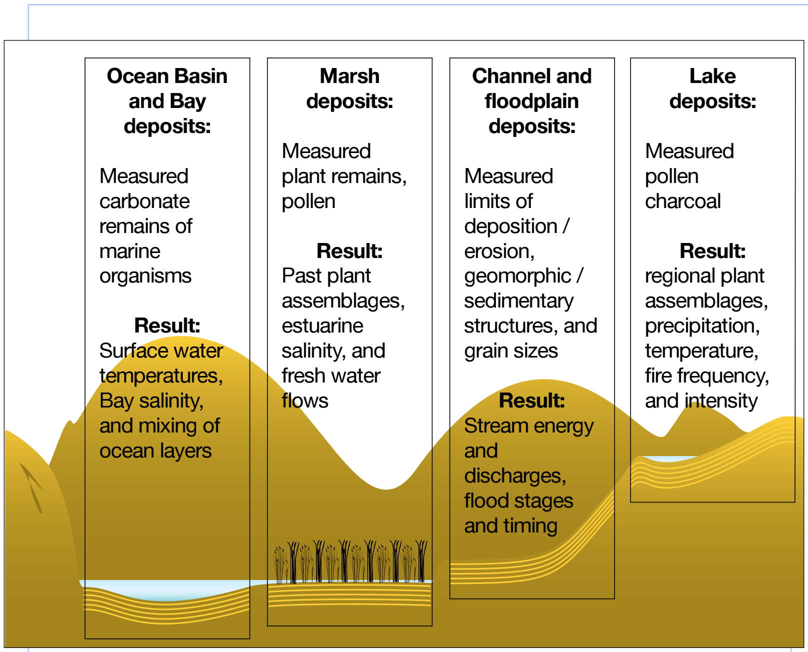


Figure 3. Similar kinds of archives (from Figure 2) are shown with the measured proxy and resulting paleoclimate record.

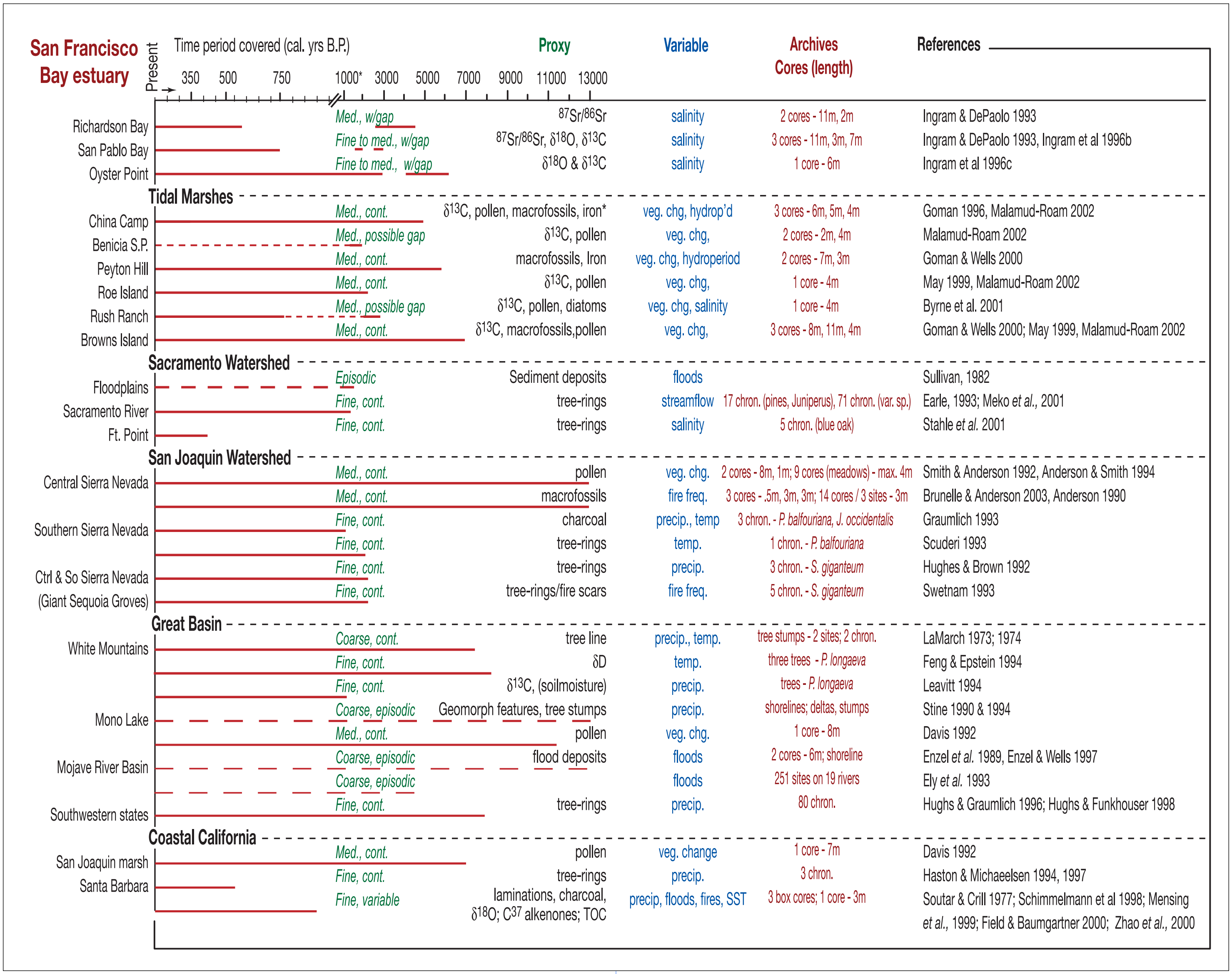
of elevations (e.g., Stahle et al. 2001). Similarly, technological advances and serendipity may increase the time resolution of some examples from almost any of these archive types. But the simplified distributions shown in Figure 2 are fairly typical, at present, and are indicative of one of the key issues confronting current reconstructions of past climatic influences in the Estuary-watershed system: different paleoclimatic proxies within the system tend to be located in different settings, to describe different aspects of the system, and (often) to describe them at different temporal resolutions.

These differences in the paleoclimatic archives from place to place, and from proxy to proxy, extend even to seemingly similar kinds of proxies obtained from different parts of the Estuary-watershed system, as illustrated in Figure 3. Sedimentary compositions, textures, and structures often are used to detect different aspects of past climates, depending on whether they are retrieved from the coastal ocean, marshes, upland floodplains, or highland lakes, in part because they reflect local climate differences and in part because the conditions of their deposition preserve different aspects of climate. These differences are both challenge and opportunity: At present, they can yield seemingly different stories of the system's past, which we struggle to reconcile. For example, we will review a megadrought that occurred in some parts of the watershed during the thirteenth century A.D. (Stine 1994) but that did not appear in a Sacramento river reconstruction (Meko et al. 2001) and that appeared only weakly in a San Joaquin River reconstruction (Meko et al. 2004). However, when we reconcile the seemingly disparate stories, they provide a single, overarching climate history for the system and deeper understanding of our naturally complex climatic setting. From this, we will obtain both a well cross-validated history and a firmer understanding of how climate influences cascade through the whole system to ultimately impact the "managed" properties like salinity, sediment supplies, and plant and benthic communities.

Table 1 provides a more detailed description of representative (and, in some cases, only) archives available from the various parts of the Estuary-watershed system reviewed for this study. The temporal spans of the various proxies are indicated in the table along the horizontal axis, along with indications of whether the archives produce continuous or episodic records, and the temporal resolution of the archives, e.g., fine (annual to decadal scale), medium (centennial to millennial), and coarse (millennial or greater). The particular proxies used, the climate variables revealed by those proxies, the numbers of archives available and reviewed here, and literature references are also presented. A comprehensive description and review from which this table was extracted is provided by Malamud-Roam et al. (2006).

Clearly, an important distinction between the various proxies is the temporal precision and accuracy with which the climatic events they record can be identified. Chronologies from in-Estuary proxies are generally dated by interpolations between depths with radiocarbon (^{14}C) dates, as are sediment studies in the watershed and coastal regions. Tree-ring studies, by contrast, are generally dated by comparisons of ring patterns among multiple trees at a given site, anchored by patterns from living trees and so give reliable, annual resolutions (Hughes 2002). The comparisons take the form of massively replicated pattern matching, a process known as "cross-dating" (see http://www.ltrr.arizona.edu/treerings.html). Because

Table 1. Paleoclimate records from the San Francisco Bay Estuary and watershed and surrounding regions. Records are organized by region (first column), followed by the temporal coverage of the records (second column), the proxies used (third column), the climate variable measured (fourth column), the archives (fifth column), and references (sixth column). *Note change in scale at 1,000 years BP.



San Francisco Bay estuary	Time period covered (cal. yrs B.P.)	Proxy	Variable	Archives Cores (length)	References
Richardson Bay	*Med., w/gap*	$^{87}Sr/^{86}Sr$	salinity	2 cores - 11m, 2m	Ingram & DePaolo 1993
San Pablo Bay	*Fine to med., w/gap*	$^{87}Sr/^{86}Sr$, $\delta^{18}O$, $\delta^{13}C$	salinity	3 cores - 11m, 3m, 7m	Ingram & DePaolo 1993, Ingram et al 1996b
Oyster Point	*Fine to med., w/gap*	$\delta^{18}O$ & $\delta^{13}C$	salinity	1 core - 6m	Ingram et al 1996c
Tidal Marshes					
China Camp	*Med., cont.*	$\delta^{13}C$, pollen, macrofossils, iron*	veg. chg, hydrop'd	3 cores - 6m, 5m, 4m	Goman 1996, Malamud-Roam 2002
Benicia S.P.	*Med., possible gap*	$\delta^{13}C$, pollen	veg. chg,	2 cores - 2m, 4m	Malamud-Roam 2002
Peyton Hill	*Med., cont.*	macrofossils, Iron	veg. chg, hydroperiod	2 cores - 7m, 3m	Goman & Wells 2000
Roe Island	*Med., cont.*	$\delta^{13}C$, pollen	veg. chg,	1 core - 4m	May 1999, Malamud-Roam 2002
Rush Ranch	*Med., possible gap*	$\delta^{13}C$, pollen, diatoms	veg. chg, salinity	1 core - 4m	Byrne et al. 2001
Browns Island	*Med., cont.*	$\delta^{13}C$, macrofossils,pollen	veg. chg,	3 cores - 8m, 11m, 4m	Goman & Wells 2000; May 1999, Malamud-Roam 2002
Sacramento Watershed					
Floodplains	*Episodic*	Sediment deposits	floods		Sullivan, 1982
Sacramento River	*Fine, cont.*	tree-rings	streamflow	17 chron. (pines, Juniperus), 71 chron. (var. sp.)	Earle, 1993; Meko *et al.*, 2001
Ft. Point	*Fine, cont.*	tree-rings	salinity	5 chron. (blue oak)	Stahle *et al.* 2001
San Joaquin Watershed					
Central Sierra Nevada	*Med., cont.*	pollen	veg. chg.	2 cores - 8m, 1m; 9 cores (meadows) - max. 4m	Smith & Anderson 1992, Anderson & Smith 1994
	Med., cont.	macrofossils	fire freq.	3 cores - .5m, 3m, 3m; 14 cores / 3 sites - 3m	Brunelle & Anderson 2003, Anderson 1990
Southern Sierra Nevada	*Fine, cont.*	charcoal	precip., temp	3 chron. - *P. balfouriana, J. occidentalis*	Graumlich 1993
	Fine, cont.	tree-rings	temp.	1 chron. - *P. balfouriana*	Scuderi 1993
Ctrl & So Sierra Nevada (Giant Sequoia Groves)	*Fine, cont.*	tree-rings	precip.	3 chron. - *S. giganteum*	Hughes & Brown 1992
	Fine, cont.	tree-rings/fire scars	fire freq.	5 chron. - *S. giganteum*	Swetnam 1993
Great Basin					
White Mountains	*Coarse, cont.*	tree line	precip., temp.	tree stumps - 2 sites; 2 chron.	LaMarch 1973; 1974
	Fine, cont.	δD	temp.	three trees - *P. longaeva*	Feng & Epstein 1994
	Fine, cont.	$\delta^{13}C$, (soilmoisture)	precip.	trees - *P. longaeva*	Leavitt 1994
Mono Lake	*Coarse, episodic*	Geomorph features, tree stumps	precip.	shorelines; deltas, stumps	Stine 1990 & 1994
	Med., cont.	pollen	veg. chg.	1 core - 8m	Davis 1992
Mojave River Basin	*Coarse, episodic*	flood deposits	floods	2 cores - 6m; shoreline	Enzel *et al.* 1989, Enzel & Wells 1997
	Coarse, episodic		floods	251 sites on 19 rivers	Ely *et al.* 1993
Southwestern states	*Fine, cont.*	tree-rings	precip.	80 chron.	Hughs & Graumlich 1996; Hughs & Funkhouser 1998
Coastal California					
San Joaquin marsh	*Med., cont.*	pollen	veg. change	1 core - 7m	Davis 1992
Santa Barbara	*Fine, cont.*	tree-rings	precip.	3 chron.	Haston & Michaeelsen 1994, 1997
	Fine, variable	laminations, charcoal, $\delta^{18}O$; C^{37} alkenones; TOC	precip, floods, fires, SST	3 box cores; 1 core - 3m	Soutar & Crill 1977; Schimmelmann et al 1998; Mensing *et al.*, 1999; Field & Baumgartner 2000; Zhao *et al.*, 2000

rates of radiocarbon production in the atmosphere have varied during the Holocene, radiocarbon dates are regionally calibrated against calendar dates obtained from tree-ring chronologies (Stuiver and Reimer 1993), and dates from some periods are more accurate than others. Marine-derived carbon requires additional corrections, as the ocean is depleted in radiocarbon relative to the atmosphere due to deep-water circulation (Ingram and Southon 1996; Kennett et al. 1997). This "reservoir residence" correction is complicated both by regional differences due to ocean mixing and circulation processes (e.g. upwelling of radiocarbon-depleted waters along the coast) (Ingram and Southon 1996) and by temporal variability of the circulations (Kennett et al. 1997; Ingram 1998). Thus, temporal comparisons among the various paleoclimate proxies from the Estuary and watershed cannot be too exacting, and some scatter in the timing of climatic events described by the various proxies must necessarily be tolerated.

For Estuary and ecosystem management purposes, past salinity and sediment-transport variations may be of most immediate interest; but, in many cases, the coarse temporal resolutions of archives that record salinity and sediment transport may limit some of their usefulness. In contrast, the highly resolved depictions of past precipitation variations that can be obtained from tree rings in the watershed regions may be closer to what a manager would want in terms of temporal resolution, but may not be directly informative about the issues of most immediate interest in the Estuary habitats. This dichotomy has even led to attempts to reconstruct estuarine salinity variations from upland tree-ring thicknesses (Stahle et al. 2001), attempts that were informative but would be enhanced by the development of more direct and highly resolved in-estuary proxies. Thus, to date, the significance and usefulness of available paleoclimate archives has been limited by the lack of an overarching, multi-proxy description of the region's past climates (and climatically driven Estuary conditions). A key unanswered question facing paleoclimate scientists in the Estuary-watershed system is: to what extent do upland proxies (tree rings, flood deposits, etc.) directly or indirectly describe the climatic fluctuations that dictated the ecological, salinity, and sediment-transport conditions expressed in the lowland proxies (e.g., marshland and lowland river sediment cores)? This question becomes most pressing when we note that tree-ring reconstructions of past precipitation and temperature fluctuations are far more common and widespread throughout the watershed system than are sediment cores (Figure 1), while the opposite is the case within the Bay-Delta system itself. Certainly, many of the most startling and disturbing revelations about past climate excursions have derived from tree rings and highly resolved sedimentary proxies from the upper reaches of the watershed and just beyond (e.g., the Medieval droughts detected in Pyramid and Mono Lake sediments and in tree ring records (Stine 1994, Hughes and Funkhouser 1998, 2003). However, the true significance of the challenges that these past-climate variations posed for the Estuary (and watershed) ecosystems will remain uncertain until the full range of proxies from the system have been integrated more fully than at present.

Holocene Climate Variations

We live in a period between Ice Ages (an interglacial period), characterized by a much warmer climate than prevailed during the Ice Ages. The current interglacial period, known as the Holocene, began approximately 10,000 years ago, by which time most of the world's large ice sheets and mountain glaciers had melted to near their current positions (Fairbanks 1989; Kutzbach et al. 1998; Ruddiman 2001). An abundance of paleoclimate records spanning parts of the Holocene in many parts of California has been published, including tree-ring reconstructions of climate and tree-line elevations in the White Mountains (Hughes and Funkhouser 2003; Hughes and Graumlich 1996; LaMarche 1973, 1974a,b), montane lake and meadow cores in the western Sierra Nevada (e.g. Edlund and Byrne 1991; Anderson 1990; Anderson and Smith 1994; Brunelle and Anderson 2003), Great Basin lake cores (e.g., Benson et al. 2002), tree ring chronologies from central and southern Sierra forests (e.g., Graumlich 1993; Hughes et al. 1996), flood plain stratigraphies (e.g., Shlemon and Begg 1975), estuary and tidal marsh sediment cores (e.g., Ingram and DePaolo 1993; Goman and Wells 2000; Byrne et al. 2001; Starratt 2003, 2004; Malamud-Roam and Ingram 2004, Brown and Pasternack 2004) and ocean cores from coastal basins (e.g., Friddell et al. 2003; Barron et al. 2003) (see Table 1).

Over the course of the Holocene, these paleoclimate archives tell of a wide range of climate variations, summarized in Figure 4. The figure shows a stylized transect from the White Mountains to the Pacific Ocean, and the changes occurring in different parts of the system during key parts of the Holocene; also indicated are the downstream linkages within the system. The most obvious linkages can be seen today in seasonal cycles of salinity within the Bay: copious winter precipitation in the Sierra Nevada results in reduced salinity in the Bay-Delta Estuary followed, in the summer, by peak salinities (Peterson et al. 1989, 1995). Less well understood linkages also exist. Different parts of the watershed often experience different cli-

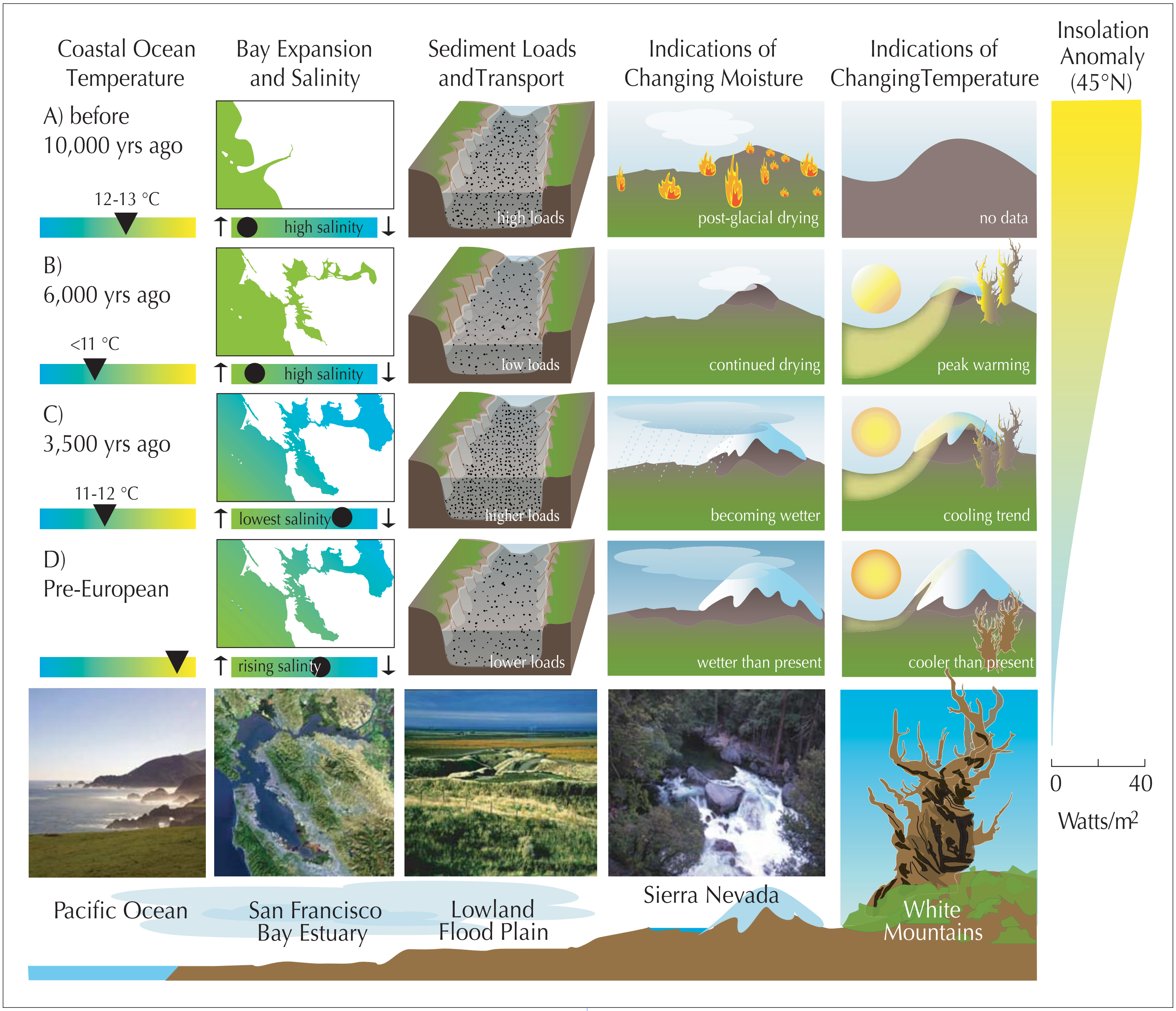


Figure 4. Paleoclimate and spatial linkages in California at periods in the Holocene. A)Before 10,000 years ago, climate in California was cooler than today, but warming and drying, indicated by open vegetation and frequent fires on mountain slopes. Glaciers had melted to their modern elevations, having delivered high sediment loads to lowland areas and the nascent Bay–Delta. Upland fire and sparse vegetation probably continued to deliver relatively high sediment loads to lowland areas. B) 6,000 years ago was the warmest period of the Holocene, as seen in the upslope migration of trees in the mountain ranges. Sediment loads to downstream lowland floodplains were likely low; ocean surface temperatures off the coast were also warm. C) 3,500 years ago, climate in California was cooler and wetter, seen in mountain vegetation changes. Sediment loads, associated with increased storm frequency, increased, and the Bay became fresher. D) Present conditions throughout the study region have been strongly influenced by human activities in the last century, though the Bay estuary is shown at its peak extent ca. 1850 A.D. Climatic conditions have included brief though severe droughts, but climate has overall been benign, and slightly wetter than in preceding centuries. Sources: White Mountains (LaMarche 1973, 1974a); Sierra Nevada (Edlund 1996; Anderson & Smith 1994); Sediment loads; Bay estuary (Atwater 1979; Goman & Wells 2000; Ingram et al. 1996a,b); coastal ocean temperatures (Friddell et al. 2003).

matic variations, and it is the combined effects of these differing climates that are reflected in Estuary tidal marsh deposits, in proportions determined by local marsh ecology. This section will first provide a general overview of Holocene climate history, followed by a more detailed discussion of the later part of the Holocene, for which we have the most complete paleoclimate records. Superimposed upon this climate history is a history of human occupation in California, which, while not the focus of this paper, will be touched upon when relevant, as humans have been both influenced by climate and have become increasingly dominant influences upon the Bay-Delta natural system. Finally, we will examine regional links to global climate that we are coming to understand from the combination of paleoclimate and modern climate records.

The early Holocene (Figure 4, upper panel) was characterized by warm temperatures and decreasing moisture availability, as the Earth shook off the mantle of continental glaciers and ice caps from the preceding Ice Age. Solar insolation on the midlatitudes of the Northern Hemisphere reached its summer maximum (far left of Figure 4; Brunelle and Anderson 2003) and remained high until ca. 8,000 years ago, after which insolation began to decline towards present values. The western slopes of the Sierra Nevada were in early stages of an ecological succession (recovery) following the recession of glaciers; climate conditions were cooler than twentieth century values, but becoming warmer and drier (Edlund and Byrne 1991; Anderson 1990; Porinchu et al. 2003). Fires were frequent (Brunelle and Anderson 2003; Edlund and Byrne 1991) and played an important role in that succession (Anderson 1990; Edlund 1996). At this time, the Estuary was in its infancy: sea level was rising rapidly, but had only just entered through the Golden Gate. Many parts of today's Estuary—such as Suisun Bay, San Pablo Bay and South Bay—were river valleys (Atwater 1979).

Warming continued, so that temperatures reached a maximum in the middle Holocene, around 5,000 to 6,000 years ago (Figure 4, middle panel). In the White Mountains, the Bristlecone-pine tree line moved upslope to higher elevations than at any time since (LaMarche 1973, 1974a), and Sierran meadow and lake cores indicate that other warm-loving tree species moved up-slope as well (Edlund 1996; Anderson and Smith 1994). Conditions became drier as well, so that lakes on the eastern side of the Sierran range, in its rain shadow, shrank considerably; e.g., Pyramid and Owens Lakes (Benson et al. 2002). Modern river-floodplain systems began to develop in the Central Valley as sediment deposition at the foot of the Sierra and Coastal Ranges formed geomorphic features such as flood basins in low lying areas between older range-front alluvial fans and natural levees along the Sacramento River (Gilbert 1917). Sea level, by this time, had risen high enough so that the outlines of the modern Bay–Delta Estuary were complete, and it was also at this time that the previously rapid rate of sea-level rise dropped to less than 20 cm per 100 years—a pace slow enough to allow tidal marshes to form around the edges of the Estuary (Atwater 1979; Goman and Wells 2000).

Following the mid-Holocene period of peak warmth, significant changes in climate are indicated by paleoclimate archives throughout the study region, from high- and low- altitude sites, from the White Mountains to the San Francisco Bay, in indicators of vegetation change, tree growth, lake level changes, and sedimentary sequences (Figure 4, lower panel). Paleoclimate records that describe part or all of the past 4,000 years have been recovered from locations in most of the study region (Table 1), and, in virtually every area, a cooling trend accompanied by increased moisture availability was underway at about 3,800 years ago. For example, in the White Mountains, studies of past tree lines and tree-ring widths (LaMarche 1973 1974a, b) show tree line retreating down slope in response to cooling, and tree rings in lower elevation bristlecone pines were wider in response to increased moisture (LaMarche 1974a). Playa sediments from the Mojave Desert indicate the presence of shallow lakes around 3,620 years ago, implying very wet conditions (Enzel et al. 1989). Pollen and other macrofossil evidence from lake and meadow deposits from the Sierra Nevada reflect trends toward cooler and moister conditions (e.g., Edlund 1991 and 1996; Edlund and Byrne 1991; Anderson 1990; Anderson and Smith 1994). Sierra Nevada lake sediments indicated that this trend may have intensified around 3,700 – 3,000 years ago (Smith and Anderson 1992), when the incidence of forest fires declined (Brunelle and Anderson 2003).

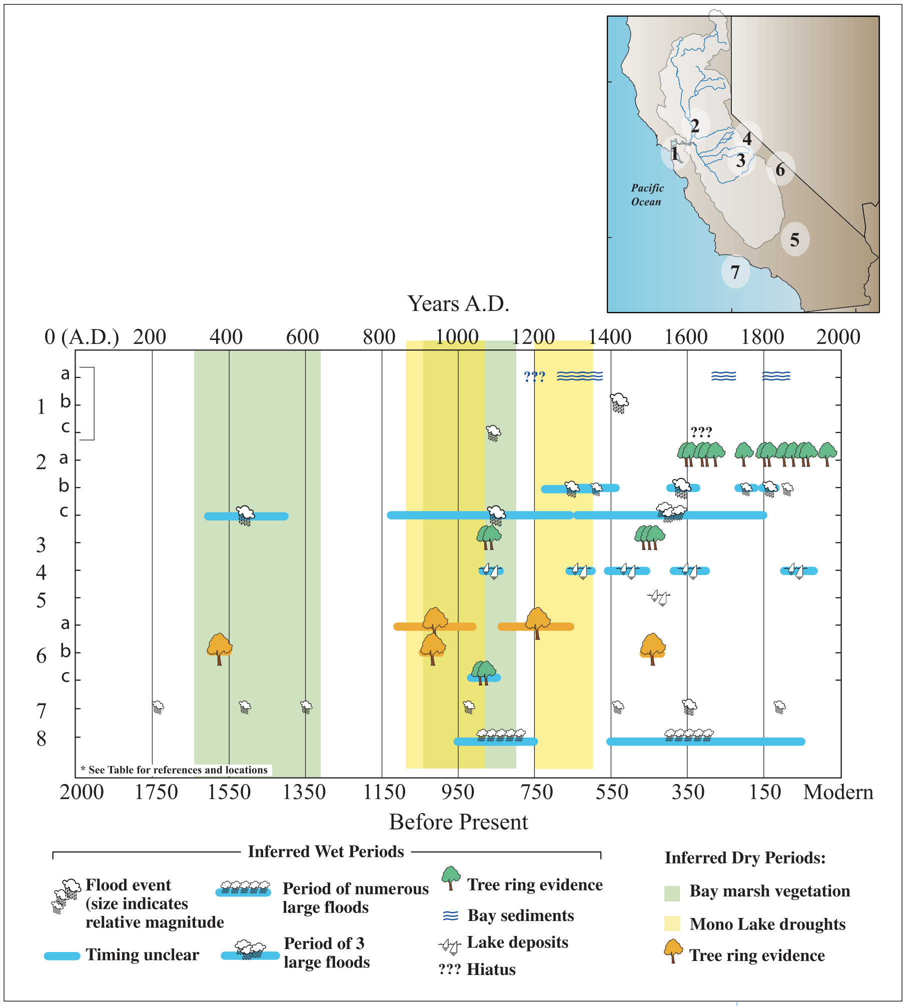


Figure 5. Evidences of extreme climate events of the late Holocene. Climatic events are indicated by symbols, with references enumerated on the Y-axis and shown on accompanying map. References are provided in Table 2; prolonged droughts are indicated by vertical color shading. Bay sediment records with hiatus indicated represent gaps in the chronology, possibly due to extreme flooding event that eroded sediments.

This period of relatively moist conditions is also evidenced downstream in the Bay–Delta Estuary (Figure 4). Every core collected, to date, from the Bay (Ingram and DePaolo 1993; Ingram et al. 1996 b,c) contains sedimentary and geochemical indications of higher freshwater inflows after 4,000 years ago. The indications include high sediment loads delivered to San Pablo Bay by greater river flows (Ingram and DePaolo 1993; Ingram et al. 1996b) and shifts in oxygen isotopes associated with increased freshwater inflow (Ingram et al. 1996b, c). The isotope record cannot easily be used to reconstruct paleotemperatures of the estuarine waters, but changes in foraminiferal assemblages from South San Francisco Bay at this time suggest the Estuary's water was cooler than during earlier periods in the Holocene (McGann et al. 2002). On the surrounding marshlands, pollen and isotopic compositions (Byrne et al. 2001; Goman and Wells 2000; Malamud-Roam and Ingram 2004; Malamud-Roam 2002) and diatom records (Starratt 2003, 2004) from tidal marsh cores indicate that plant assemblages were responding to estuarine salinity changes with a shift towards inclusion of more brackish and freshwater adapted species, and consequently towards greater diversity. The change to wetter conditions may have been abrupt; sedimentary evidence from several marsh sites indicates that an extremely large flood washed through the Estuary, carrying high and coarse-grained sediment loads around 3,600 years ago (Goman and Wells 2000). The development of marshes around the Estuary under these wetter conditions resulted in richly productive ecosystems that provided important new food supplies to native Americans. The shores became a "landscape of shell mounds" at about this time (Fagan 2003; Lightfoot 1997). For example, this is the period when the West Berkeley Shell Mound grew most rapidly (Ingram 1998). Similarly, in the Central Valley and foothills, this was a period of great population expansion and marked the establishment of acorn-harvesting cultures that would characterize and sustain many native Californian communities for millennia to come (Fagan 2003).

The generally cooler and wetter period appears to have ended about 2,000 years ago, when conditions became more arid. Using the changing upper and lower treelines of bristlecone pines in the White Mountains, in combination with tree-ring width chronologies, to infer concurrent temperature (upper tree line) and moisture (lower tree line) variations, LaMarche (1973 1974a, b) reconstructed a 5,500-year history of climate variations. The reconstructions show trends towards progressive cooling and drying of the region during the last 2,000 years, punctuated by both temperature and precipitation excursions, which LaMarche (1974a) referred to as "climate anomalies." Paleoclimate records from throughout the watershed and Estuary reflect the same cooling, drying trends and similar fluctuations of both during the past 2,000 years. Figure 5 (with references in Table 2) compares records of extreme climate events from throughout California. The most severe climate anomalies were two pronounced and prolonged droughts dramatically illustrated by submerged tree stumps and geomorphic indications of extreme lake-level fluctuations at Mono Lake (Stine 1990; 1994). The Mono Lake fluctuations, along with similar evidence from other eastern Sierra Nevada lakes and from the Walker River on the east side of the Sierra Nevada, strongly reflect two extreme droughts, one lasting from about 900 to 1150 AD and the other from 1200-1350 AD (Stine 1994). Evidence of these droughts is also found in tree rings (Hughes and Graumlich 1996; Hughes and Funkhouser 1998) and lake sediments throughout the Great Basin (Benson et al. 2002). As will be discussed further below, within the Bay-Delta watershed, a tree-ring reconstruction of San Joaquin River flows (Meko et al. 2002, 2004) seems to reflect these droughts considerably more than did a reconstruction of Sacramento River flows (Meko et al. 2001). The reconstructions of the Sacramento and, even more so, the San Joaquin River flows indicate that droughts of varying duration were more common before 1400 AD than after.

Table 2. Summary of evidence for very wet episodes during the late Holocene.

I.D.	Reference	Location	Year	Description
1a	Ingram et al. 1996c	San Francisco Bay	1270-1380, 1675-1730, 1800-1860 1200	High inflow Top of unconformity
1b	Goman and Wells, 2000	San Francisco Bay	1420	Browns Is Flood
1c	Malamud-Roam, 2002	San Francisco Bay	1090 1645	China Camp flood, unconformity (Benicia core)
2a	Earle, 1993	Sacramento River	1597-1613, 1641-1657, 1664-1675, 1725-1735, 1741-1754, 1798-1821, 1854-1869, 1874-1887, 1891-1916, 1962-1973	High flow
2b	Sullivan, 1982	Sacramento River	1235-1360 1295-1410 1555-1615 1750-1770 1810-1820 1861	large flood flood largest flood flood large flood Historic flood
2c	USBR, 2002	American River	350-550 825-1300 1300-1800	1 flood larger than historic & gauge records 1 very large flood 3 floods larger than historic records
3	Graumlich, 1993	So. Sierra	1071-1090, 1478-1527	high precipitation
4	Stine, 1990	Mono lake	1084 1270-1345 1400-1485 1575-1650 1857-1919	Post Office High Stand Rush Delta High Stand Danberg Beach H.S. Clover ranch H.S. Historic High Stand
5	Enzel et al. 1989	Mojave Desert	1527	Silver lake deposits
6a	LaMarche, 1974a	White Mts	850-1050, 1120-1300	Tree rings
6b	Hughes & Graumlich, 1996, Hughes & Funkhouser, 1998	White Mts	917-966, 1494-1543, 368-418	Periods of intense drought (50 yr, top 3)
6c	Leavitt, 1994	Great Basin	1080-1129	Abundant soil moisture
7	Schimmelmann et al. 2003	Sta Barbara Basin	212, 440, 603, 1029, 1418, 1605, 1840	Floods
8*	Ely et al. 1993	U.S. southwest	1000-1200, 1400-1900	Numerous large floods

* Not on map

Isotopic compositions from Estuary sediments deposited beginning about 2,000 years ago show increasing salinity in the Bay (above what would be expected from sea level rise alone) punctuated by a variety of shorter term fluctuations (Ingram and DePaolo 1993; Ingram et al. 1996b,c) (Figure 5). Marsh cores also give evidence of vegetation change in response to increasing salinities during this period, with shorter-term variability (Goman and Wells 2000; Byrne, et al. 2001; Malamud-Roam and Ingram 2004). The first of the two major Mono Lake droughts appears in Estuary vegetation records as significant shifts towards dominance of tidal marsh vegetation assemblages by more salt-tolerant plants (Byrne et al. 2001, Malamud-Roam and Ingram

2004). The annual average salinity in Suisun Bay near Roe Island during that drought was more than 10 ppt, and Byrne et al. (2001) estimated peak salinities near Rush Ranch between 15 and 20 ppt. These values imply more than a 35% reduction of fresh water inflow compared to modern flows (corrected for diversion). Indications of at least two other periods of low inflow appear in the marsh records: one (from about 300 to 650 AD) prior to the first of the Mono Lake droughts and one afterwards (between about 1550 to 1650 AD; Malamud-Roam and Ingram 2004).

The paleoclimate archives from the study region also contain evidence of anomalously wet periods, including several following prolonged droughts. The submerged tree stumps in Mono Lake and Walker River are themselves evidence of rapid transitions to wetter conditions following prolonged droughts (Stine 1994). In some cases, the reversals to wetter and cooler conditions lasted several centuries. For example, following the second of the Mono Lake droughts, conditions became wetter in the watershed for several hundred years (from about 1400 to 1700 AD, coincident with a time that has been called the "Little Ice Age"; Bradley et al. 2003). This period of relatively cool and wet conditions is evidenced in bristlecone pines in the White Mountains (LaMarche 1973, 1974a, Hughes and Funkhouser 1998; Hughes and Graumlich 1996), in ancient shorelines of Mono Lake (Stine 1990, 1994), in tree-ring chronologies from central Sierra (Graumlich 1993), in floodplain sediments (Sullivan 1982) and other paleoflood deposits (USBR 2002), in Estuary and tidal marsh cores from the Bay and Delta, and in ocean cores that indicate cooler coastal waters then (Jones and Kennett 1999).

Coastal sediments from the Santa Barbara Basin document six mega-floods along the central California coast during the past 2,000 years (Schimmelmann et al. 2003). Schimmelmann et al. (2003) correlated these floods with large-scale climatic anomalies spanning the western hemisphere. Extremely wet episodes from paleoclimate records are summarized in Figure 5, with details and references listed in Table 2. As can be seen in this figure, even during long-term dry epochs, wet to extremely wet years still occurred. These wet episodes within dry epochs are often particularly well documented because such conditions favor erosion and large sediment transports. Two of these large floods, which appear to coincide with the termination of the Mono Lake droughts, are seen in the Bay marsh sediment cores, around 1100 AD (Malamud-Roam 2002) and around 1400 AD (Goman and Wells 2000). These wet episodes in the Estuary also were times when the ancient trees growing on the Mono Lake bottom and elsewhere in the eastern Sierra were rapidly submerged (Stine 1994). Tree-ring width chronologies from the southern Sierra Nevada (Graumlich 1993) and from the Great Basin (Hughes and Graumlich 1996) also indicate wet periods around these times (1071 to 1090 AD and 1478 to 1527 AD). Stable isotopes of carbon (-^{13}C) in tree rings from the White Mountains provide another line of evidence for very wet soils during the period from 1080 to 1129 AD (Leavitt 1994). Along the lowland Cosumnes River near its confluence with the Mokelumne, fine sediments are interlayered with coarser sediments, reflecting higher energy floods, and illustrate numerous episodes of extreme flooding and geomorphic change between about 1000 to 1800 AD (Atwater and Marchand 1980; Florsheim and Mount 2003).

Native Californian communities in the study region experienced intermittent, widespread, climatic and non-climatic stresses during the past 2000 years, punctuated as they were by occasional extended droughts and very wet episodes. Some of these stresses were probably due to the large, interconnected human populations that had filled in the region by the beginning of the period, and some stresses probably were climatic in origin (Fagan 2003). Human populations varied widely in response to times of drought and plenty, regionally and, especially in more marginal settings, like some upland river basins. Around the Bay, native Californians appear to have developed more dispersed rounds of hunting, gathering, and acorn harvesting during this time, and although large populations may still have lived close to the Bay, their artifacts are nowhere near as evident on the landscape as are those from the earlier, climatically more benign times of the preceding 2,000 years (Fagan 2003). Thus the lean and highly variable climate of the past 2,000 years appears to have increased the land area necessary to support populations that were already in place, and, in some places, decreased the natural resources available reliably per inhabitant.

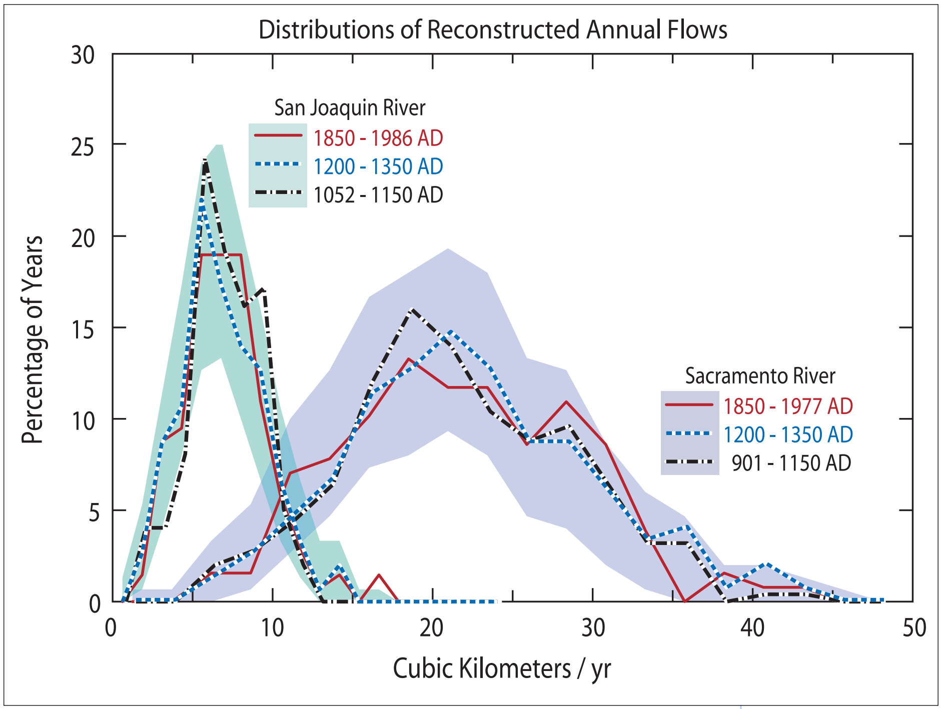


Figure 6. Frequency (probability) distributions estimated from reconstructed annual streamflows (km^3/year) in the Sacramento and San Joaquin Rivers (Meko et al. 2001, 2002) for the historical period (1850 AD to end of reconstruction); and first (beginning of reconstructions to 1150 AD) and second medieval Mono Lake drought (1200-1350 AD). Shaded areas indicate the 95% confidence intervals on distributions obtained by similarly analyzing 10,000 random samples of 150 years from the reconstructions. The confidence intervals shown here test whether or not the differences between the various distributions fall beyond the range of fluctuations that might be encountered in random subsamples of the overall reconstructions.

Finally, a notably benign period, with comparatively little precipitation variability, from about A.D. 1850 – 1950, is described by many of the archives. In a 420-year reconstruction of Sacramento River flows based on tree rings, Earle (1993) found that the historical period (since 1850) was generally wetter than preceding periods, with four 10- to 15-year periods of above average flows. In the midst of these cycles of plenty, however, the longest lower-than-average flow period (34-yr) occurred during the historical period, centered on the decade of the 1930s. Based on tree rings from the giant sequoia groves on the western slopes of the Sierra Nevada, Hughes and Brown (1992) and Hughes et al. (1996) described the twentieth century as having a frequency of short sharp droughts generally lower than the long-term mean for the last 2,000 years.

To put this “benign” modern era and the two medieval Mono Lake drought epochs into their proper contexts in the watershed, Figure 6 presents probability distributions of annual river flows that were estimated for selected periods within tree-ring reconstructions of annual stream flow in the Sacramento and San Joaquin Rivers during the past millennium, kindly provided by David Meko of the Laboratory for Tree-Ring Research at the University of Arizona (Meko et al. 2001, 2002). The distributions may be skewed by the tendency for reconstructed flows to be less variable and more normally distributed than historical and, presumably, actual flows from past epochs. However, the general tendencies indicated by these estimated distributions probably describe qualitative differences between flows in the various periods. Overall, the distributions of reconstructed flows from each of the periods fall mostly within the range of 95% of random samples (of comparable lengths, ca. 150 years) that can be drawn from the overall records (shaded bands in Figure 6), indicating that the benign historical period and the medieval droughts were not completely different from the overall flow statistics of the past 1,000 years. Thus, each of these periods could well be a random run of good or bad luck within otherwise statistically homogeneous climate variations. Considered in more detail, the effects of the Mono Lake droughts (often referred to as medieval droughts) are more notable in the San Joaquin River reconstruction than in the Sacramento, with much greater than modern frequencies of moderately less (as much as 25%) than normal flows. Notably, extremely low flows were no more common during the medieval droughts (particularly the first drought) than during the modern era. Instead, the absence of very high flow years may have contributed more to the character of the medieval droughts. For example, extremely high San Joaquin River flows (more than 12 km3/yr) were much less common during the earlier (ca. 900 – 1150 AD) Mono Lake drought than during either the 1200 – 1350 AD drought or the modern period. Modern San Joaquin River flows have included more frequent moderately-more-than-normal flows and more extremely high flows than did either of the medieval droughts or the overall range of distributions.

Comparison of the distributions of reconstructed Sacramento River flows from the Mono Lake drought periods and the modern era indicate that extremely low reconstructed flows were no more common during the Mono Lake drought periods than during the modern era. Moderately smaller-than-normal (by as much as 25%) flows were considerably more common during the first medieval drought than during the modern era, and, conversely, moderately greater-than-normal flows were notably more common during the modern period than during either of the droughts or than most of the random samples from the past 1,000 years (as indicated by the shaded bands). Thus the medieval droughts, as experienced within the Bay–Delta watershed, were a period of more frequent moderately dry years and less frequent (than modern) moderately wet years, but do not appear to include an unusual number of extremely dry years. The modern era has yielded more frequent moderately wet years and, in the San Joaquin River, a few notable extremely wet years. A related analysis of year-to-year differences in the reconstructed flows (not shown) indicates that year-to-year persistence of annual flows were not significantly different among the periods shown in Figure 6, except that extremely dry years were actually less likely to follow extremely dry years in the reconstructions of the two medieval droughts; instead they tended to be interrupted by near normal or even above normal flows.

Records and reports from the modern, mostly benign period have formed the basis for most of the design and engineering of systems to accommodate California's highly variable climate. Unfortunately, the climate observations from this instrumented period have provided us with a limited, somewhat optimistic perspective on the carrying capacities of California's landscapes and resources, including our water supply and flood control infrastructure (Dettinger and Cayan 2003). Our primary, if sadly incomplete, basis for understanding and envisioning the climate processes that led to these extended paleoclimate fluctuations are the long- and short-term fluctuations found in instrumental records of global climate during the twentieth century, which for California have had origins mostly in the climate of the Pacific Ocean basin. The probability distributions indicated by Fig. 6 represent more complete indications of the possible natural variations of California's climate, and are at once a matter of some concern (what if, for example, we revisit a century or mode of climate variations like those during the medieval droughts?) and a basis for some optimism (as devastating as the medieval droughts were in the eastern Sierra, they represent mostly changes in the frequency of moderately dry rather than of extremely dry years in the Bay–Delta's watershed).

Regional Links to Global Climate

The San Francisco Bay Estuary is closely tied to the climate of the coastal ocean through daily tides and gradual sea level rise, salinity, water temperature and chemistry, and sediments (Cayan and Peterson 1993), especially in the westernmost parts of the Estuary. However, in most of the Estuary, the most direct response to climate is through the annual variations in freshwater inflows from the watershed. Through these watershed effects, important indirect climatic linkages between the Estuary and coastal ocean exist because the coastal ocean and watershed generally respond to the same large-scale atmospheric circulations (Cayan and Peterson 1993). Temperature and current changes and variations in the coastal ocean frequently coincide with periods of drought and plenty in the Estuary and its watershed in paleoclimate archives (e.g., Roark et al 2003, Barron et al. 2003). Similarly, in the instrumental records of the past century, important, global-scale climatic events have been observed to influence both the coastal ocean and Estuary-watershed systems (e.g., Peterson et al. 1995). These regional to global influences can be addressed on three time scales: subdecadal, corresponding roughly to time scales less than 10 years; decadal to multidecadal; and centennial- to multicentennial-scale.

Subdecadal climate variability in the region is dominated by the ENSO phenomenon of the tropical Pacific (Cayan and Webb 1992). The influence of this phenomenon has been recorded in many paleoclimate archives around the world (e.g., Mann et al. 2000; Stahle et al. 1998; Cobb et al. 2001; Evans et al. 2001), although the precise linkages that bind ENSO fluctuations to the proxies are incompletely understood and vary in robustness. The climatic teleconnections and mechanisms linking the ocean-atmosphere interactions of the tropical Pacific Ocean to California during ENSO events have been described in historical and instrumental climate records (Cayan, et al. 1999; Dettinger, et al. 1998; Dettinger et al. 2001). ENSO reflects irregular oscillations of the tropical Pacific climate that have, as one extreme, warmer-than-average tropical-ocean, "El Niño" states and, as the other extreme, cooler-than-average tropical, "La Niña" states. During El Niño winters, barometric pressures within the Aleutian Low atmospheric-pressure center are generally lower than normal, and winter storms are preferentially steered towards southern California and the Southwest (Cayan and Webb 1992). Thus, El Niño winters are often unusually wet in southern California, an effect amplified and expressed by increased streamflows (Cayan et al. 1999) and sediment transports (Inman and Jenkins 1999; Mertes and Warrick 2001). During La Niña winters, pressures in the Aleutian Low are not as low and winter storms are steered more towards the Pacific Northwest and northern California (e.g., Johnstone 2004). Precisely where storms pass through California varies from storm to storm, and from year to year. On average, though, the Estuary itself is located near the point where either El Niño or La Niña conditions can bring rain or drought. Locally, the influences of El Niño and La Niña conditions can even vary from river basin to river basin (Andrews et al. 2004). Thus, the precise outcome in the Bay of any given El Niño is highly uncertain and unpredictable, and much of the ENSO signal found in the paleoclimate archives arises directly or indirectly from its influences in the northern and southern parts of the watershed, where the ENSO influences are somewhat more reliable. Along with these hydroclimatic connections, El Niño episodes bring warm ocean water to coastal California, both by changing wind patterns and attendant coastal upwelling patterns and by some northward propagation of oceanic currents and deep-seated waves (Enfield and Allen 1980). Indeed, California (and much of the West) is generally warmer during El Niño episodes and cooler during La Niñas (Dettinger et al. 2001), and thus coastal ocean and watershed conditions are linked at these subdecadal scales by, and through, their responses to ENSO events (which are only the most celebrated and predictable of a wide range of large-scale climate events that buffet California and its coastal waters from year to year).

The multidecadal variability of Pacific climate and, less directly, of California's temperature and precipitation, have been described in terms of the PDO (Mantua et al. 1997), the dominant multidecadal mode of North Pacific sea surface temperatures. The PDO is largely (and perhaps even entirely) a reflection of the irregularity of the higher-frequency ENSO episodes as they vary from decade to decade (e.g., Newman et al. 2003). El Niños and La Niñas occur irregularly through time, with no reliable sequences, other than very approximate return intervals on the order of two to five years (Ghil et al. 2002). Their appearances are so irregular that some decades are much more El Niño-rich (with more frequent and stronger El Niños) and others are more La Niña-rich. These multi-decadal swings in the ENSO forcings contribute to the notably multidecadal character of California's precipitation, with extended drought or "drought-y" periods separated by extended wetter intervals. Granger (1979), for example, noted a roughly 15-year cycle in California seasonal precipitation variability during the twentieth century. PDO is mostly associated with climatic fluctuations on the order of 25-35 years long (Mantua et al. 1997), but with elements apparently ranging to as long as 70 years (e.g., Minobe 1997).

PDO fluctuations contribute as much variability to California's climate as does ENSO (e.g., Dettinger et al. 2001; Benson et al. 2003), preferentially steering winter storms northward or southward, and yielding warmer or cooler coastal and inland temperatures, depending on PDO status much as does ENSO, but on much slower time scales. Several reconstructions of paleoclimate variations, from beyond the Estuary and watershed, have attempted to chronicle PDO variations during (Hereford et al. 2003) or before the instrumented period (Biondi et al. 1999, 2001; Gedalof and Mantua 2002; D'Arrigo et al. 2001; Gedalof and Smith 2001) using a variety of tree-ring chronologies from

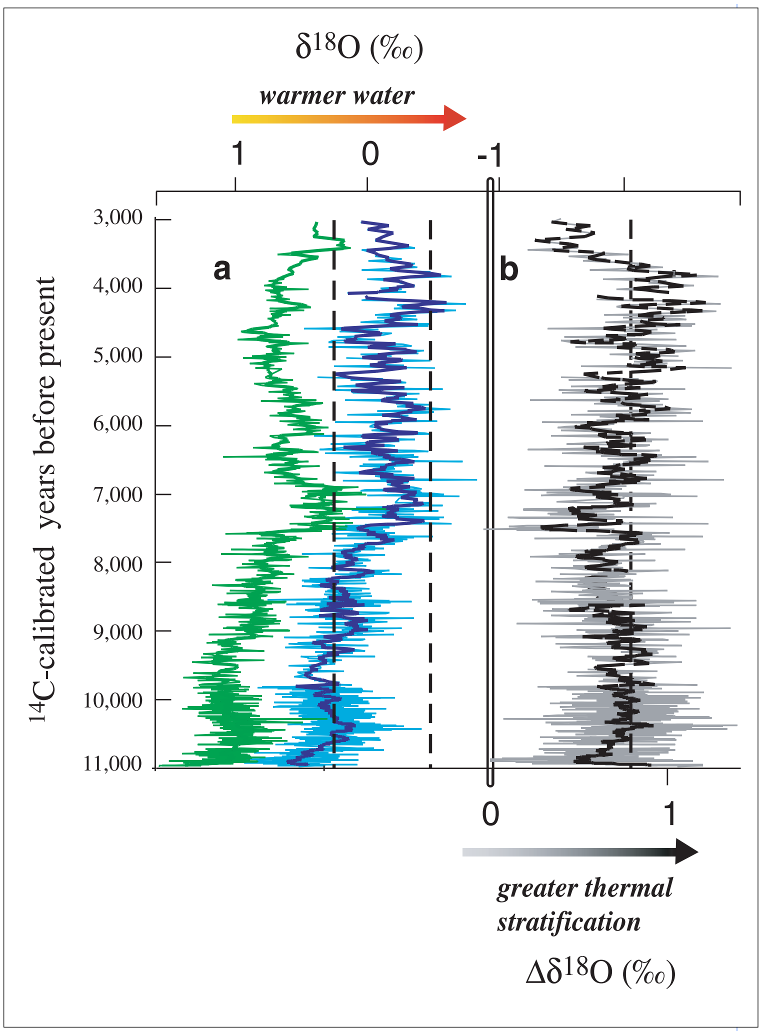


Figure 7. Oxygen isotopes from central Santa Barbara Basin (AII-125 JPC-76) showing A) δ^{18}O values of foraminifera, including benthic N. *pachyderma* (green) and *planktic G. bulloides* (blue) and B) δ^{18}O values derived from the difference between the benthic and planktonic foraminifera; 50-yr averages (heavy lines) accentuate multi-decadal to centennial variability (Friddell et al. 2003).

western North America, along with—in some studies—tropical corals and other paleoclimatic resources. These reconstructions describe multidecadal climate fluctuations (and hiatuses of multidecadal variability; e.g., Dettinger et al. 1998) that might plausibly explain some of the multidecadal character of the Estuary and watershed's past climates described above. Recent work in progress (MacDonald 2004) adds lake records from the central Sierra Nevada to tree ring archives to expand the previous more regional reconstructions of Pacific climates and to focus it more precisely on California. Preliminary results indicate 60-year PDO-like periodicities that have varied significantly during the past 1,000 years. Recent efforts to quantify relations between western drought (McCabe et al. 2004) and paleodrought (Gray et al. 2003) patterns and the slow evolutions of the North Atlantic climate have not yet extracted clear linkages to California, but may ultimately provide another climate mechanism for explaining multidecadal paleoclimate fluctuations of the Estuary and watershed.

In coastal California, variations in the δ^{18}O isotopic compositions of benthic (bottom) and planktic (surface) foraminifera contained in sediment archives from Santa Barbara Basin, may provide records of Holocene PDO fluctuations (Friddell et al. 2003). Figure 7 uses differences ($\Delta\delta^{18}$O) between the isotopic compositions of the benthic and planktic foraminifera as a measure of PDO status (warm versus cold coastal water). The benthic-planktic differences indicate that coastal waters during the warm middle Holocene period (especially around 5,200 to 3,600 years ago) were warm, so that PDO may have been in a warm phase, with more intense El Niños. After about 3,600 years ago, coastal temperatures cooled rapidly, with an associated weakening of interannual variations believed to be associated with ENSO (Friddell, et al. 2003). Very long-term excursions in the Pacific climate forces affecting California are thus a natural part of its climate. Due to anomalously low sedimentation rates in the top part of the marine core, their isotope record does not cover the most recent millennia, but instead ends 3,000 years before present.

The persistence and extreme severity of some of the century-long and multi-century paleoclimate episodes during the past 2,000 years are beyond the range of climate variations witnessed in the instrumental period. The past two millennia have included droughts of unexpected severity and duration and floods larger than any that we have directly experienced. During this time, solar-insolation (Figure 4) and other natural climate forcings (like volcanoes) on the climate system were not so different from today (Bradley 2003). Thus there is every reason to believe that ENSO and PDO played much their "usual" roles during that period. Neither of these oscillations—as we understand them from the historical period—seems adequate to explain the megadroughts and megafloods of the "recent" past, if only because (in our experience) both are fundamentally modes of variation of the Pacific climate system and not static conditions. Thus we will need to develop a combination of increasing confidence in what the paleoclimate archives are telling us about the past climates and more explanatory options (perhaps to be obtained by more analyses of droughts and floods in very long control runs of modern coupled ocean-atmosphere climate models), if we are to understand the reasons and harbingers of megadroughts and extended wet epochs (pluvials) in California.

Nineteenth and Twentieth Century Influences

Capping many of these paleoclimatic archives are evidences of the rapid changes imposed on the Bay-Delta and watershed during the modern period of European-American development of the state. During the past two centuries, our society has substantially modified the landscape of the Bay–Delta and its watershed. Most of the paleoclimate archives discussed so far describe climate variations and landscape responses that occurred prior to these modifications. However, many of the records also reveal significant ecological changes during the last two centuries, reflecting the major effects of European-American activities on the Bay–Delta and watershed systems. These changes were not always recorded well in documentary sources, as some of the changes spanned generations (e.g., shifting plant assemblages on the marsh surfaces towards increasingly salt tolerant species), and all were embedded in considerable human tumult and natural variability. Because they are objective and present even when documents fail, California's paleoarchives can provide crucial information about processes in the modern era.

One important aspect of the Bay-Delta and watershed system that recent landscape modifications have impacted is its sediment budgets. Prior to large-scale modifications of the Estuary-watershed landscape during European-American settlement, geomorphic processes in the lowland portion of the Sacramento and San Joaquin River system were dominated by abrupt channel changes (avulsion), progressive channel migration, erosion, and sedimentation, mostly during floods of various magnitudes. These dynamic processes governed long-term sediment loads and deposition rates, supported habitat heterogeneity and biodiversity in the Central Valley's riparian systems, and have, during the late Holocene, varied widely in response to climatically-driven events and episodes. Since the time of the Gold Rush, the natural sediment budgets of the Estuary and watershed have been virtually overwritten by many different actions. Hydraulic mining for gold between 1853 and 1884 (Gilbert 1917; James 1991, 1993; Mount 1995) dramatically changed watershed landscapes and released vast volumes of sediment into the region's rivers. Dams, levees, channelization, water diversions, filling and diking of wetlands, clearing and agricultural domination of floodplains, and Delta islands have since been imposed upon the landscape and on the continuing impacts of hydraulic mining (Gilbert 1917; SFEP 1992; Mount and Twiss, 2005). The sediment released by some of these changes, as well as the sediment deficits created by others, have rippled through the watershed and into the Estuary, and are evidenced in Bay and marsh sediments (Jaffe et al 1998; Cappiella et al. 1999) and in stratigraphic sequences beneath the lowland floodplains (Florsheim and Mount 2003). The Gold Rush sediment "pulse" (and subsequent anthropogenically accelerated sediment source) was eventually transported through the Delta to the Bay, where net sediment accretion dominated the geomorphology of the Bay, particularly in San Pablo Bay and Suisun Bay, well into the twentieth century (Jaffe et al. 1998; Cappiella et al. 1999). This influx of sediment is recorded in sedimentary deposits throughout the system and created new areas of tidal marsh during the past century (SFEP 1992; Malamud-Roam 2002).

In addition to altering sediment transport through the system, engineered structures in the region's rivers and floodplains have also changed the character of floods and geomorphic processes. Under natural conditions, most (lowland) rivers followed multiple-channel and flood-basin pathways; human engineering has restricted most river segments to flow instead in single channels isolated by levees from increasingly developed floodplains into flood-bypass channels. Extensive levees and multiple dams currently regulate flow on most large Sierran and Coast Range rivers, so that flows in the Sacramento and San Joaquin Rivers and their tributaries are now under human control at most times and places. In particular, the timing of flows has been modified by emplacement of large reservoirs so that waters are retained during the wet winter months, stored in reservoirs, and released and diverted during the drier summer and fall months (Knowles 2002). Most large and small flood peaks are ameliorated in the process. However, historically, existing dams and levees have not been able to control floods and geomorphic processes as completely as society might intend, during anything but small to moderate events. For example, the combination of aging levees with significant sediment-transport changes that raised lowland river channels relative to surrounding floodplain elevations following hydraulic mining activities, or incised channels and increased bank heights following upstream dam construction and aggregate extraction have made some reaches more vulnerable to flood damages. As a consequence, levee breaches along lowland reaches of the Sacramento-San Joaquin Rivers system have not declined despite the flood control infrastructure (Florsheim and Dettinger 2004; 2005). Moreover, Knowles (2002) showed that the largest floods and droughts still are strongly reflected (on longer time scales) in flows and flooding in the upland rivers and in flows and salinities in the Estuary, despite best efforts to control these climatically driven fluctuations. At the same time, along with the flood controls, reclamation of Delta islands has been followed by the aging of their bounding levees and subsidence of their interior lands, progressively destabilizing the Delta landscapes (Mount and Twiss 2005). Thus along with degradation of ecological systems (Josselyn 1983), recent human activities have impacted sediment supply and degraded the region's structural stability (in the face of flooding).

Finally, vegetation records from Bay tidal marshes from the past century indicate increases in salt tolerant plant species (Byrne et al. 2001; Malamud-Roam and Ingram 2004; May 1999). In many cases, these historic changes in marsh vegetation were abrupt and coincided with the mid-twentieth century completion of major reclamation projects in the Central Valley (Shasta Dam, Friant Dam, and the Delta-Mendota and Friant-Kern canals). Diversions of water from the Delta for agriculture and urban use in the southern part of the state have further reduced the overall amount of freshwater flowing through the Delta (SFEP 1992). The diversions have contributed to declines of some estuarine ecosystems, and—for our purposes here—may also be making current and restored ecosystems of the Estuary and watershed even more sensitive to climate variability and change than under prehistoric conditions.

SUMMARY

Paleoclimate records from the San Francisco Bay-Delta Estuary and watershed describe a wider range of climatic conditions than has been witnessed in twentieth century instrumental climate records. In general, paleoclimate records from both the Estuary and watershed suggest that the period from about 4000 to 2000 yr B.P. was relatively wet and cool, compared to both the preceding millennia and modern times. Thereafter, California became generally drier, albeit with both extended droughts and extremely wet events appearing within the drier conditions. A particularly dry period in California occurred during medieval times (roughly 900 – 1100 AD), leaving traces in sedimentary records, tree rings, and archeological remnants from the Great Basin to the Bay. This extreme drought period coincided with anomalously warm coastal-ocean temperatures off Santa Barbara (Barron et al. 2003; Friddell et al. 2003; Roark et al. 2003) in an area where the ocean temperatures are generally linked to global climate processes like ENSO and PDO. In contrast, the Little Ice Age (roughly 1400 – 1800 AD) appears to have been a wetter period in California, with notably cooler coastal ocean temperatures (Roark et al. 2003).

By and large, the climate of the twentieth century has been just more of the irregular, chaotic fluctuations of climate recorded in the paleoclimate archives during the past two millennia, except that it has been a notably stable subset of those fluctuations. The character of California's recent climate is just an indication that modern Californians have been uncommonly fortunate during our tenure in the state. No aspect of the climate system, as we currently understand it, precludes

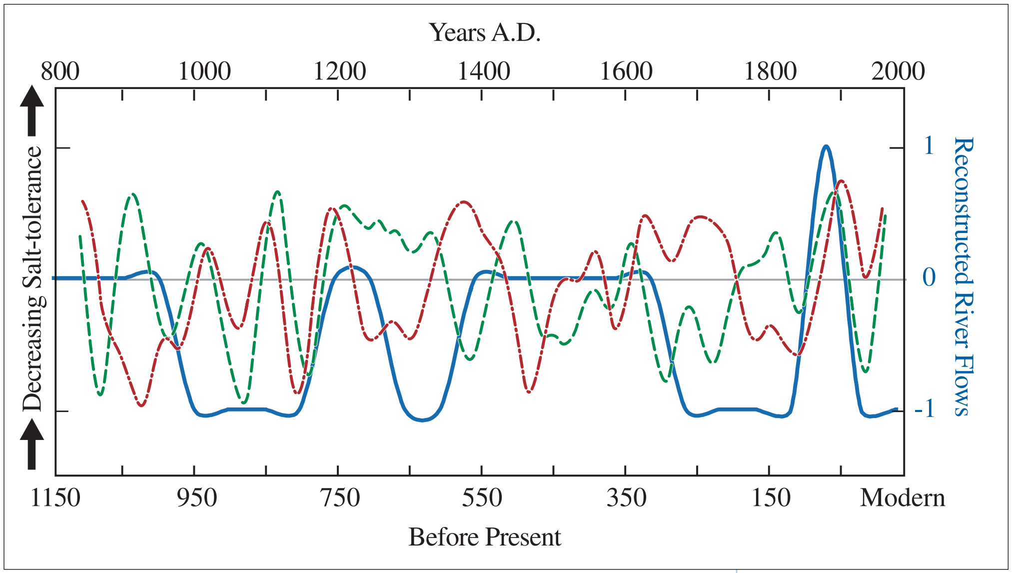


Figure 8. Relative dominance of salt-tolerant plants in the Bay-Estuary tidal marshes over time as a measure of vegetation response to changes in freshwater inflow (values are relative index with -1 reflecting greater dominance of salt tolerant plants, or decreased inflow). These data are superimposed on smoothed tree ring-based reconstructions of the San Joaquin (red line) and Sacramento (green) rivers (river reconstruction source: Meko et al. 2002).

a return to the more common erratic and less-than-benign climates of recent millennia. Rather than being lulled into a false sense of confidence by the capacity of our civil structures to weather "normal" twentieth century climate variations, the paleoclimate observations underscore the importance of developing methods for incorporating long-term paleoclimate records into planning and policy decisions. Although the paleoclimate record does not allow us to predict when the next major drought or deluge may occur, it informs us that major climate extremes beyond those experienced in the past 100 years have occurred all too often during California's prehistory. We therefore must assume that they can, and eventually will, occur again, so that the probabilities and responses to such events need to be explored with whatever tools are at our disposal.

Paleoclimatic records inform us not only of the probabilities of these extreme events; when synthesized regionally, the records provide us with the opportunity to understand the vulnerabilities of various parts of the Bay-Delta-watershed system. For example, multi-decadal to centennial variations in the occurrence of salt-tolerant plants in the Bay tidal marshes (e.g., Malamud-Roam and Ingram 2004, Byrne et al. 2001, Goman and Wells 2000, May 1999) are compared to smoothed reconstructions of flows in the Sacramento and San Joaquin Rivers in Figure 8. Some swings (e.g., around 1200 and 1850 AD) towards less dominantly salt-tolerant tidal marsh plants coincide with wetter reconstructed river conditions. Other developments in the time series are not as well synchronized. Quite likely, the tidal marsh vegetation responses to runoff variations depend on more than just changes in annual runoff from the watershed as a whole. Rather, the plants probably respond to "details" not yet captured by the runoff reconstructions, like when, during their life-cycles, freshwater-inflow changes occurred and thus the subannual and subregional patterns of the climate shifts. The linkages between estuarine responses and watershed changes, now and in the future, are likely to be just as subtle. Therefore the more we can evaluate, understand and explain the agreements and disagreements between estuarine and watershed prehistories in figures like Figure 8, the more we will be able to predict long-term estuarine responses to future climate, landscape, and runoff changes. Thus, research aimed at a more complete integration and intercomparison of paleoclimate archives spanning the length of the Estuary-watershed system should be a high priority. If paleoarchives in the uplands of the watershed tell us of major and extended droughts during medieval times, then a pressing question must be: What were the effects of such droughts in the Bay and Delta? If paleoarchives tell us of saltier and thus presumably drier conditions in the Bay during some epoch, then a pressing question must be: how dry were the uplands to evoke such a response?

An important early step towards accomplishing this will be to accelerate efforts to develop paleoclimate archives in the Estuary proper. Table 1 provides details of all the paleoclimate archives collected from the Estuary proper to date: a total of 6 sediment cores from sites in the Bay and 12 from the surrounding tidal marshes. This list is tiny compared to the richer paleoclimatic stores that have been collected from the watershed (e.g., Figure 1), and that disparity will need to be addressed if past estuarine-watershed connections are to be reliably documented. Even within the short list of estuarine paleorecords, disparities need to be addressed. This call for accelerated efforts in the Estuary should not be interpreted as suggesting that there is not a large body of important research that remains to be done in the watershed; however, the number and temporal precision of paleorecords from the Estuary lag so far behind those of the watershed that a new emphasis in the Estuary is needed to augment the many ongoing and future studies in the watershed in order to meet the information needs of local and regional planning agencies. Furthermore, the vast majority of the estuarine cores have been taken from the northern reaches of the Estuary, and efforts are needed to collect and analyze bay and marsh sediment samples from all the sub-basins of the Estuary. With the resulting broader estuarine coverage, climatic responses from more parts of the Estuary will be documented and differences in climatic vulnerability around the Estuary will become clearer.

Studies in the Estuary must also develop higher resolution paleorecords with more accurate chronologies, particularly for the past several hundred years. Improved age-resolution will allow better analysis of natural conditions just prior to, and during, the period of European occupation. These centuries were times of great change, but also are the periods most commonly documented by the high-resolution, high-quality tree-ring chronologies from around most of the watershed. An important opportunity for improving the resolution and accuracy of dating of the estuarine sediments will be application of lead-isotope (^{210}Pb) dating methods to sediments from approximately the past 100 years. Where various plant species were introduced by Europeans, pollen identification can add another 30 to 50 years to the length of time when estuarine cores can be accurately dated. On longer time scales, an important step towards better chronological controls would be a concerted effort to improve the databases and statistical relations that describe past fluctuations of ^{14}C in the atmosphere and coastal ocean of the Bay-Delta and watershed region. The more accurate the available models of local ^{14}C ages are, the more confident and accurate will be comparisons among paleoarchives around the Bay-Delta-watershed system.

The effects of subdecadal to decadal climate fluctuations (e.g., ENSO and PDO) on the San Francisco Bay system should continue to be explored in the paleoarchives. The Bay–Delta watershed spans almost 7° of latitude along the west coast of North America. Precipitation varies significantly over these latitudes, in response to important global-scale climate processes. Extending the work that others have started on spatial reconstructions of precipitation in California on interannual to multidecadal time scales will improve our understanding of the effects of ENSO and PDO, and may provide the firmest basis for characterizing the centennial precipitation changes illustrated by the longer paleoclimate archives. For example, a 400-year spatial reconstruction of precipitation in California from the latitude of San Francisco Bay south to the Mexican border (Haston and Michaelsen 1997) found precipitation anomalies, including wetter and drier than the mean, to be more common at the latitude of the Bay and Delta than farther south during the period 1560 - 1760 AD, possibly the result of stronger meridional flow in the atmosphere during that period than in more recent times. This was also a period with less multidecadal precipitation variability along the West Coast as a whole (Dettinger et al 1998). Similar studies specifically addressing the variations within the San Francisco Bay watershed could help to focus scientific progress on the spatial scales of most interest to managers of California water and land resources.

More research is also needed to better characterize spatial differences of climate within the watershed and how those differences affect the Estuary. It is clear that short-term climate variations over the northern part of the watershed, the Sacramento River drainage, differ from climate variations over the San Joaquin River drainage to the south. For example, Meko et al.

(2004) presents tree-ring reconstructions of annual flows in the Sacramento and the San Joaquin Rivers that show considerable year-to-year asynchronies between the flows from the two rivers during the past 1,000 years in a context of substantial synchronization at multidecadal time scales. The Bay and Delta (and, indeed, the statewide water systems) respond to the flows from both halves of the Central Valley, and thus the longer-term histories of synchronous-asynchronous fluctuations of flows from the two halves need to be better documented and explored.

Finally, one of the primary limitations on the use of paleoclimatic archives in engineering and planning is the lack of clear, quantitative links between the paleoclimatic indicators and the (usually) larger scale discharges, transports, and conditions that must be managed or accommodated. A spatially extensive and linked set of process models is needed that can simulate paleochanges of salinity, sediment texture, erosion, sediment transports, sediment deposition, and soil moisture in response to the best paleoclimatic archives of precipitation, stream flows, temperatures, water qualities, ecosystem changes, and geomorphic changes in the watershed. Such models could support more detailed quantification and interpretation of the climate and runoff variations that resulted in measured changes in the paleoclimatic archives than is possible now. Such models could be linked from the watersheds (where climate signals usually “enter” the system) to the Bay and Delta. A modeling effort of this scope and scale would expand (and test) our understanding of how long-term climate variations propagate through the estuarine and watershed systems to the region’s rivers, landforms, marshes, and ecosystems, at a time when long-term trends in climate are rapidly approaching. Such models would also provide a basis for evaluating the effectiveness of today’s infrastructures and decisions in the face of the more complete depiction of California’s climate that is offered by the region’s paleoclimate archives.

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