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Storm surge in the San Francisco Bay/Delta and nearby coastal locations

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ABSTRACT

California's San Francisco Bay/Sacramento-San Joaquin Delta (bay/delta) estuary system is subject to externally forced storm surge propagating from the open ocean. In the lower reaches of the delta, storm surge dominates water level extremes and can have a significant impact on wetlands, freshwater aquifers, levees, and ecosystems. The magnitude and distribution of open-ocean tide generated storm surge throughout the bay/delta are described by a network of stations within the bay/delta system and along the California coast. Correlation of non-tide water levels between stations in the network indicates that peak storm surge fluctuations propagate into the bay/delta system from outside the Golden Gate. The initial peak surge propagates from the open ocean inland, while a trailing (smaller amplitude) secondary peak is associated with river discharge. Extreme non-tide water levels are generally associated with extreme Sacramento-San Joaquin river flows, underscoring the potential impact of sea level rise on the delta levees and bay/delta ecosystem.

ADDITIONAL KEYWORDS: Storm surge, sea level rise, levee erosion, tide data, San Francisco Bay, Sacramento-San Joaquin Delta.

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The San Francisco Bay/Sacramento-San Joaquin Delta (bay/delta) is subject to high river discharge and high storm-forced sea levels (storm surge). Both of these factors can severely impact the more than 1,700 km of levees (DWR 1995) that protect the integrity of the Sacramento-San Joaquin Delta (delta) islands and hydraulic system, which is vital to California's economy in providing a significant contribution to the state's agricultural, municipal, and industrial fresh water and recreational needs. Rising sea levels affect both tidal and storm surge amplitudes within the bay/delta. The delta levees are likely more vulnerable when extremes in river discharge and storm surge occur concurrently during extreme high tides in winter months.

Levee integrity is jeopardized by a host of conditions and processes besides sea level rise, storm surge, and flood flows. These include the fact that much of the land area is up to about 6 m below sea level, poor soil conditions, oxidation of organic material, continuing subsidence, seismicity, wind wave and boat wake erosion, animal burrowing, and inappropriate vegetation or lack of any vegetation (Bauer *et al.* 2002; Mount and Twiss 2005). In this paper we consider only the high water and flood flow factors, both because these seem to be the most serious threat to the levees and because long-term comprehensive measurements exist that have not previously been analyzed.

The bay/delta estuary supports an ecosystem that must respond to variable saltwater fluxes from the open ocean resulting from tides and storm surges, as well as fresh water from the Sacramento and San Joaquin watersheds. The habitable zones for a variety of flora and fauna depend on the salinity balance between freshwater river inflows and saltwater intrusion through the Golden Gate. Freshwater inflows have large year-to-year variability (Knowles 2002), with interannual salinity variabilition strongly affected by central and southern Sierra Nevada streamflow (Dettinger and Cayan 2003).

Circulation in bays and estuaries is induced by the outflow of brackish water near the surface with an associated inflow of saline water at depth (Stacey *et al.* 2001), apparently associated with the spring-neap tidal cycle that causes variations in mixing (Jay and Smith 1990), with associated vertical mixing affecting phytoplankton growth. Changes in ocean dynamics in the near-coastal zone can strengthen or weaken the es-

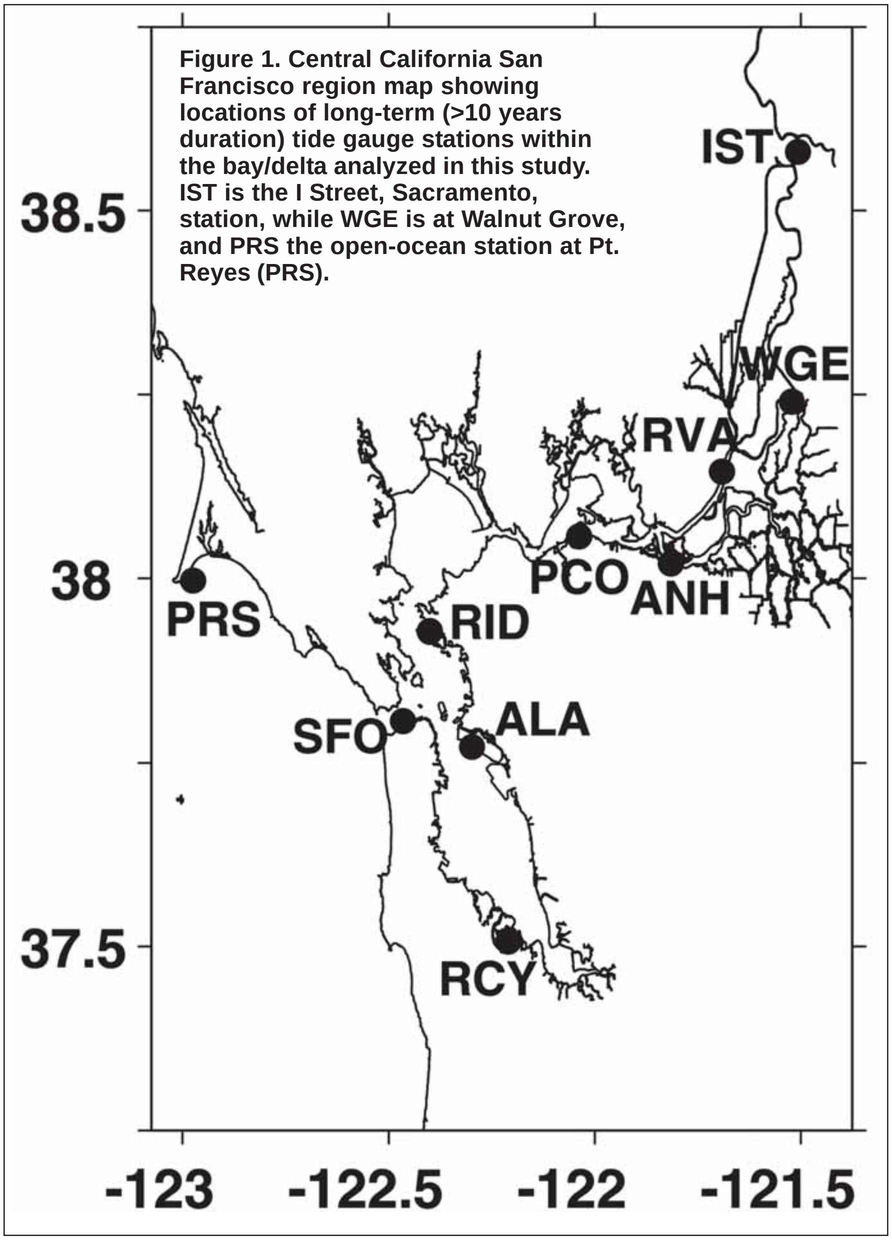


Figure 1. Central California San Francisco region map showing locations of long-term (>10 years duration) tide gauge stations within the bay/delta analyzed in this study. IST is the I Street, Sacramento, station, while WGE is at Walnut Grove, and PRS the open-ocean station at Pt. Reyes (PRS).

tuarine circulation feedback and change surge amplitudes. Because estuarine circulation is also affected by storm surge, changes in surge frequency and/or duration can have a significant ecosystem impact.

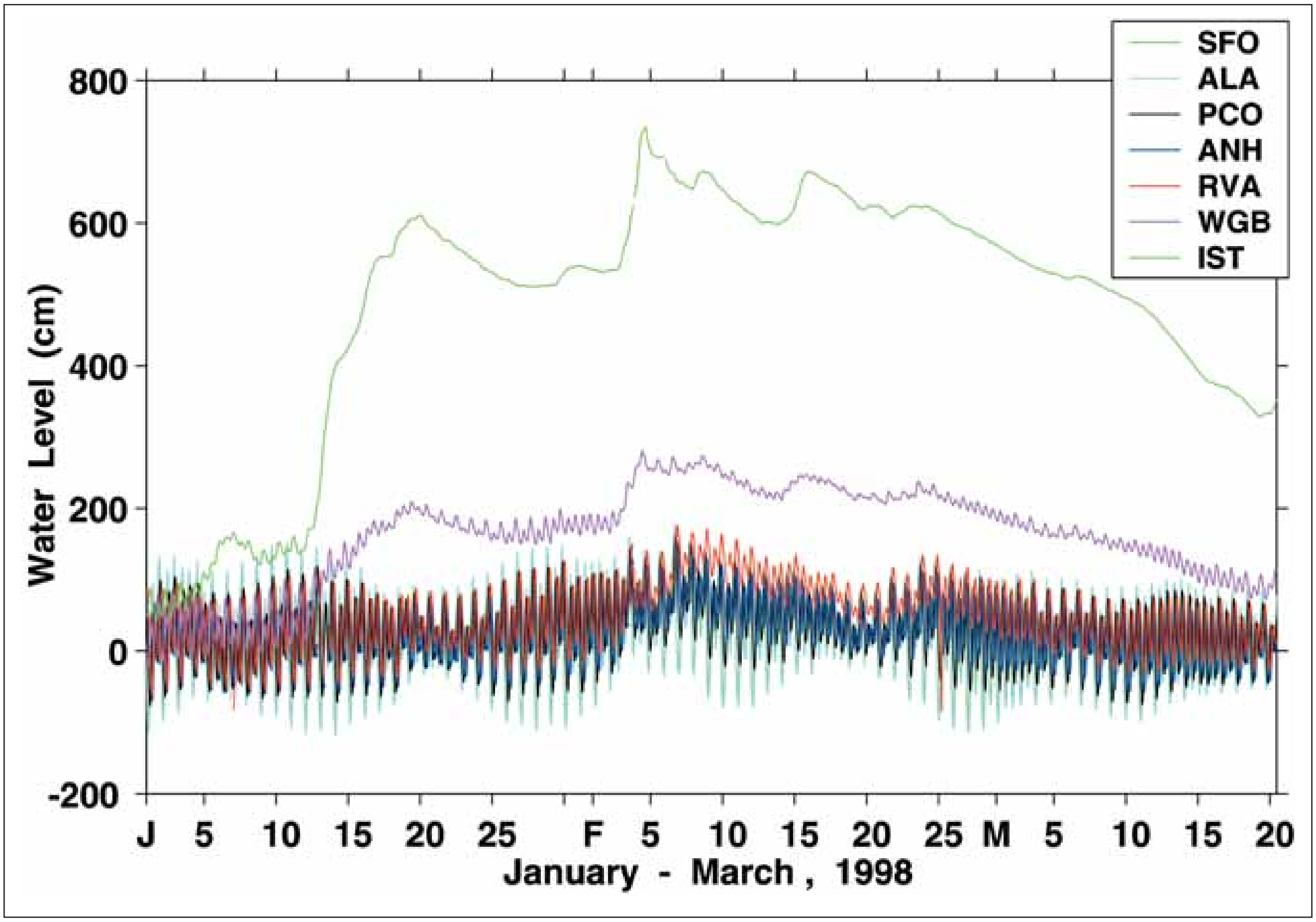
Rising sea levels will increase the frequency and severity of extreme surge events along the central California coast (Cayan *et al.* 2008). Along this coast, the total water level components include decadal scale variability of about 5-10 cm associated with broad-scale atmospheric and oceanographic circulation patterns possibly related to the Pacific Decadal Oscillation (PDO, Mantua *et al.* 1997), El Niño related northward-propagating coastally trapped waves that can raise sea level 10-30 cm during winter months, tides that range up to about 3 m, and storm surges that can reach about 80 cm (Bromirski *et al.* 2003), all superimposed on mean sea level.

The greatest risk to the delta levee system exits when extremes of each of these components occur simultaneously. Other than the tides, storm surge provides the largest ocean-generated component to water levels within the lower bay/delta. Rising sea levels, in conjunction with intense storm activity and associated high storm surge and high river flows, increase the risk of levee failure (Cayan *et al.* 2008). Because of the potential importance to surge levels and because astronomical tides and their extreme levels can be accurately predicted (Zetler and Flick 1985a, b), this study focuses on characterizing the magnitude, distribution, and timing of storm-forced non-tide water levels within the lower reaches of the bay/delta, and their temporal variability with respect to delta discharge and nearby open-ocean sea levels.

Previous studies of water level variability within the lower reaches of the bay/delta (e.g. Walters 1982; Walters and Gartner 1985; Wang *et al.* 1997; Ryan and Noble 2007) investigated subtidal water level fluctuations by lowpass filtering tide gauge records, removing signals at periods less than 30 hours. Such filtering removes a portion of the synoptic variability associated with storm surge and precludes accurate assessment of surge extremes and their temporal relationships within the bay/delta. In contrast, this study employs an alternate frequency domain tide removal methodology where the spectral estimates across the tidal bands are replaced by spectral estimates having the same trend and variance as the non-tide estimates on either side of these bands (Bromirski *et al.* 2003). This methodology preserves the important intra-tidal storm surge water level variation.

DATA: BAY/DELTA TIDE GAUGE AND COASTAL STATIONS

Hourly water level fluctuations have been recorded at several stations within the bay/delta and upstream along the Sacramento River for more than 10 years, with many extending back much longer. These stations include (with record start years indicated, from south to north, Figure 1), Redwood City (RCY, 1997), Alameda (ALA, 1979), Richmond (RID, 1996), Port Chicago (PCO, 1979), Antioch (ANH, 1984), Rio Vista (RVA, 1985), Walnut Grove (WGE, 1993), I St. at Sacramento (1984, IST), and Fort Point, San Francisco (indicated as SFO; note that the SFO designation does not refer to the San Francisco airport location). SFO provides one of the longest, nearly continuous, hourly tide gauge records in existence (1854-present) and serves as the reference level for the other stations. WGE and IST primarily measure river stage height and are included here as secondary data sources, with the other seven gauging stations the primary data records examined. The nearby open-ocean tide gauge station at Pt. Reyes (PRS) provides an additional record for comparison.



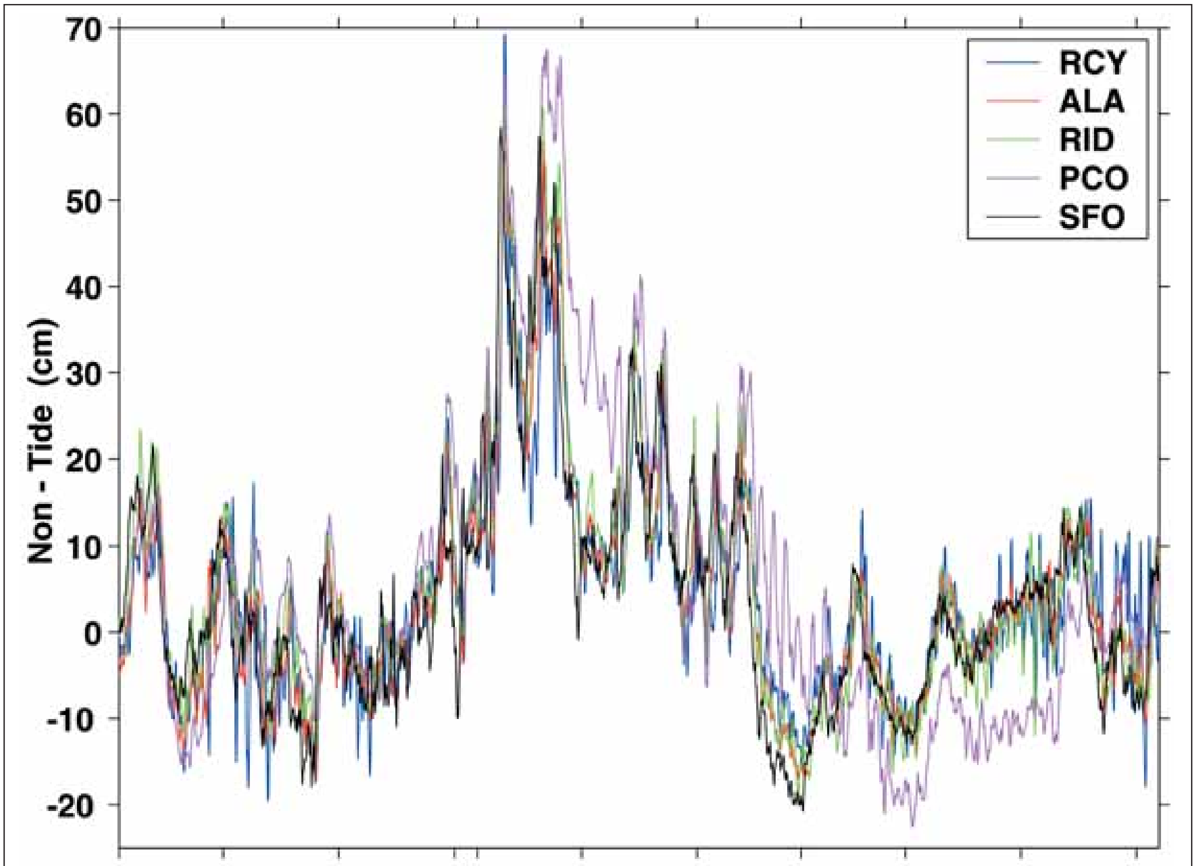


Figure 2 (above). Hourly water levels during the 1998 El Niño within the bay/delta, and on the Sacramento River at the "B" station at Walnut Grove and at I Street, Sacramento (WGB and IST, top curves, respectively).

Figure 3. Distribution of non-tide water levels within the bay/delta during the 1998 El Niño (see Figure 1 for locations).

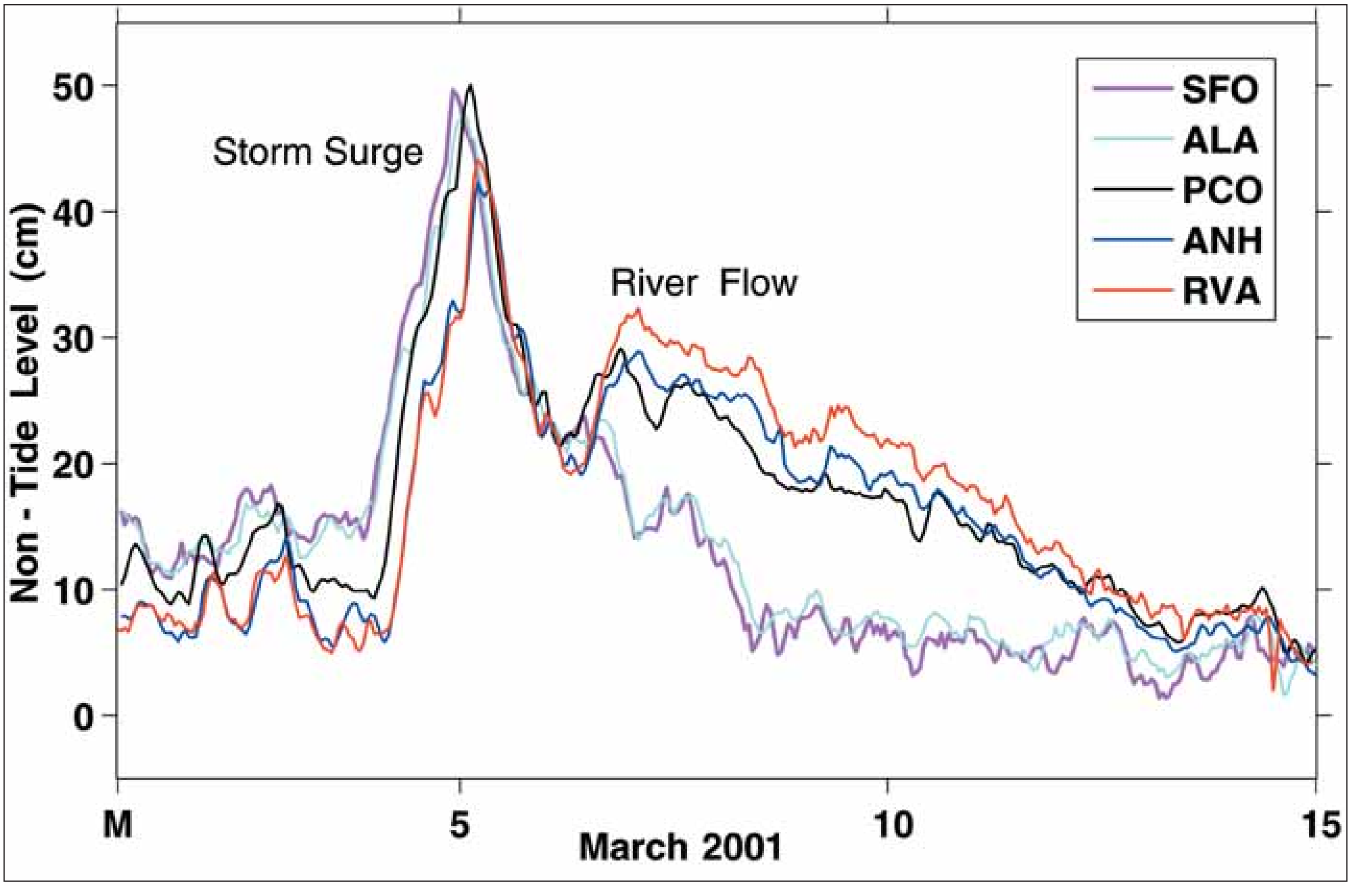


Figure 4. Non-tide water levels in the bay/delta during a storm event during March 2001.

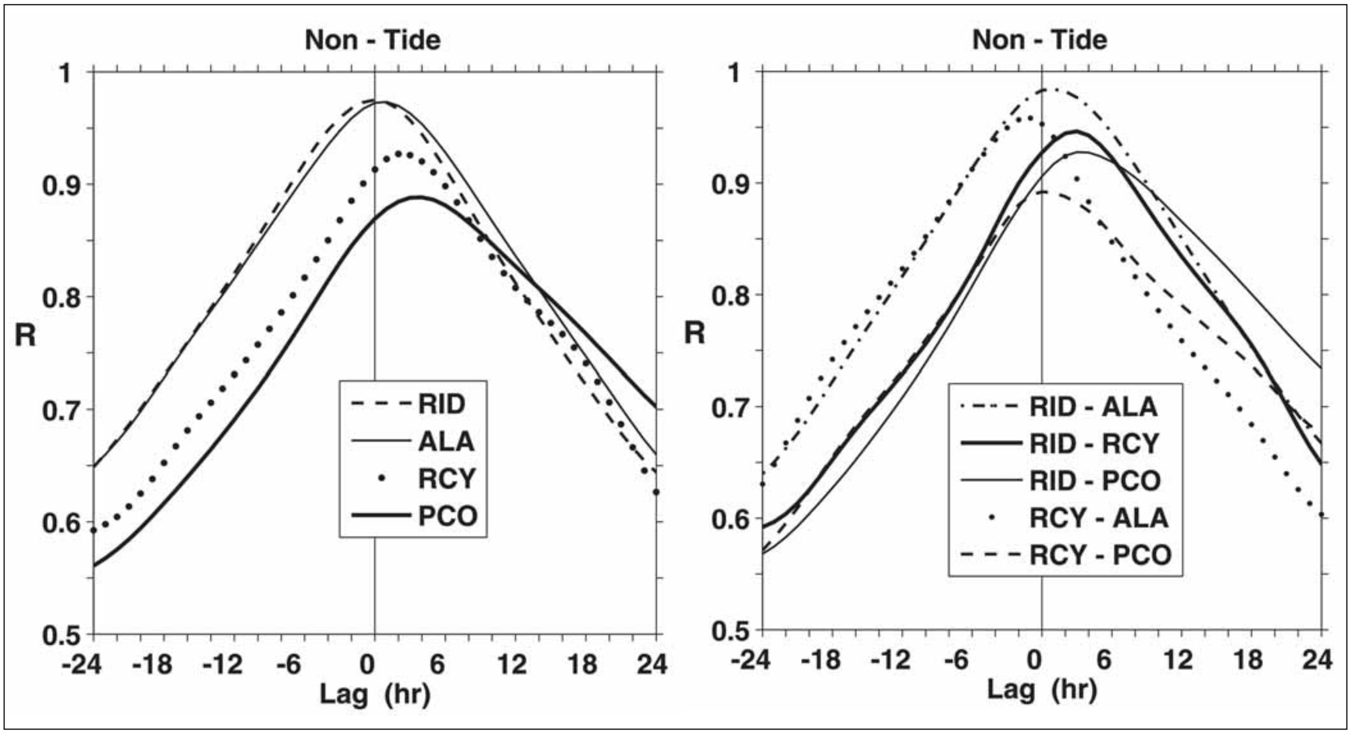


Figure 5. Lag correlations (left) of non-tide water levels between the Fort Point, San Francisco (SFO) station and selected stations within the bay (see Figure 1 for locations). Peak R at positive lags indicates that SFO leads the other stations. Intra-bay lag correlations (right) between the Richmond (RID) station in the north-bay and the Redwood City (RCY) station in the south bay, and with other stations within the bay/delta. Peak R at negative lags indicates that the first station lags the second. Non-tide residual data during the January-February 1998 period were used for both panels.

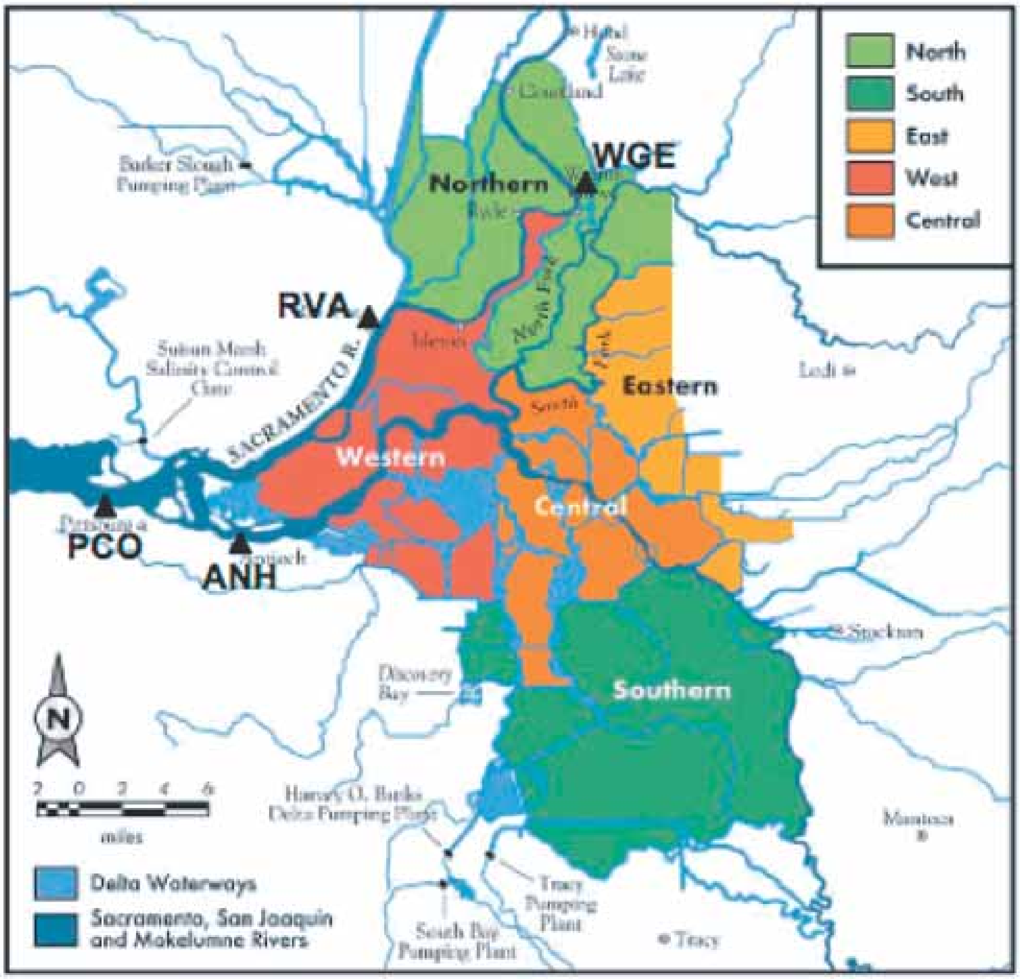
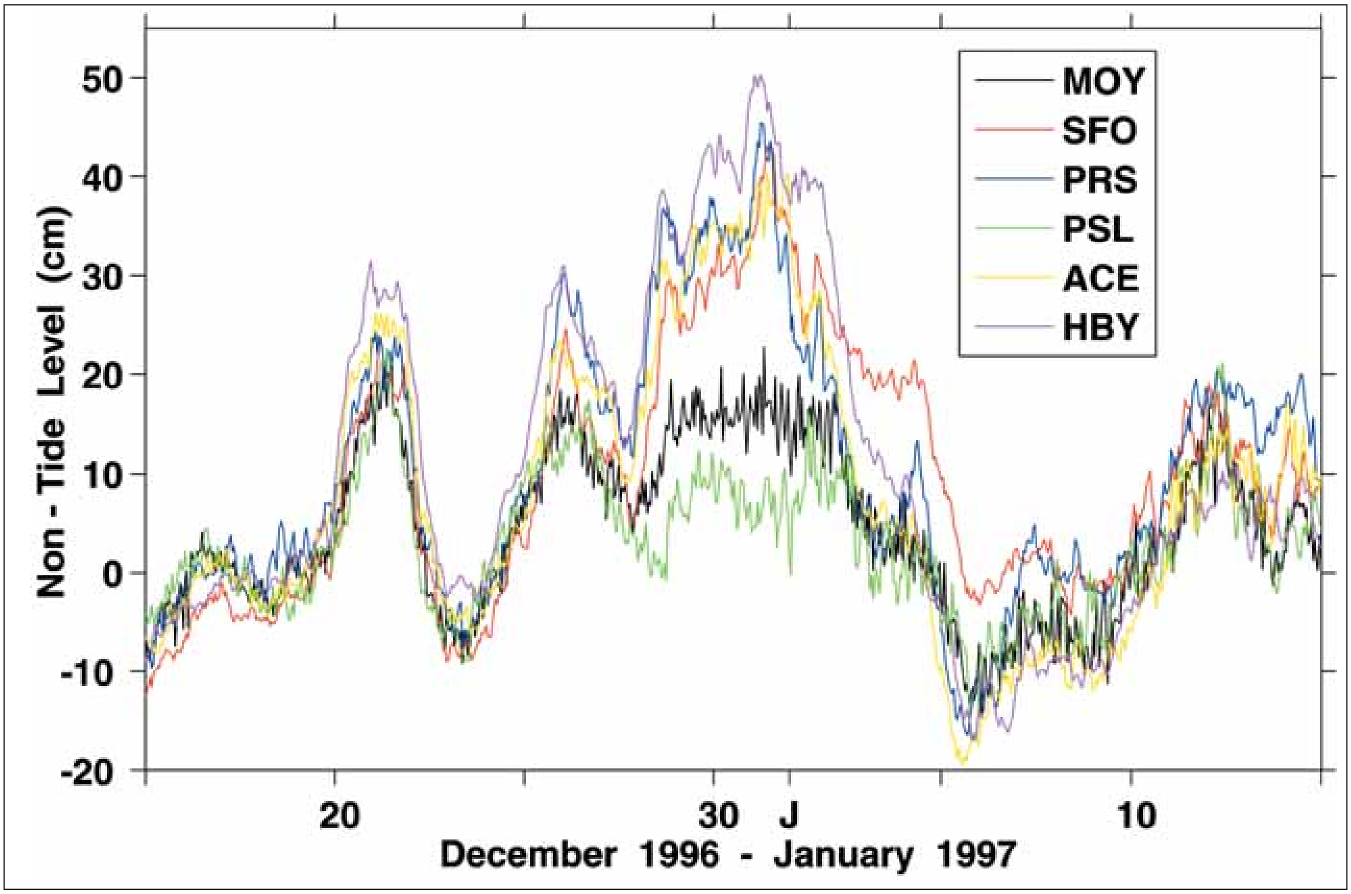


Figure 6. Partition of the bay/delta into levee risk zones (from Mount and Twiss 2005). Approximate locations of long-term (> 10 years) tide gauge/river stage stations at Port Chicago (PCO), Antioch (ANH), Rio Vista (RVA), and Walnut Grove (WGE) (triangles).

Figure 9 (below). Comparison of non-tide water level fluctuations along the California coast before and after the January 1997 extreme flood event in the bay/delta, from 15 December 1996 to 15 January 1997, at coastal tide gauges located at (from south to north) Port San Luis (PSL),Monterey (MOY), San Francisco (SFO), Pt. Reyes (PRS), Arena Cove (ACE), and Humboldt Bay (HBY).



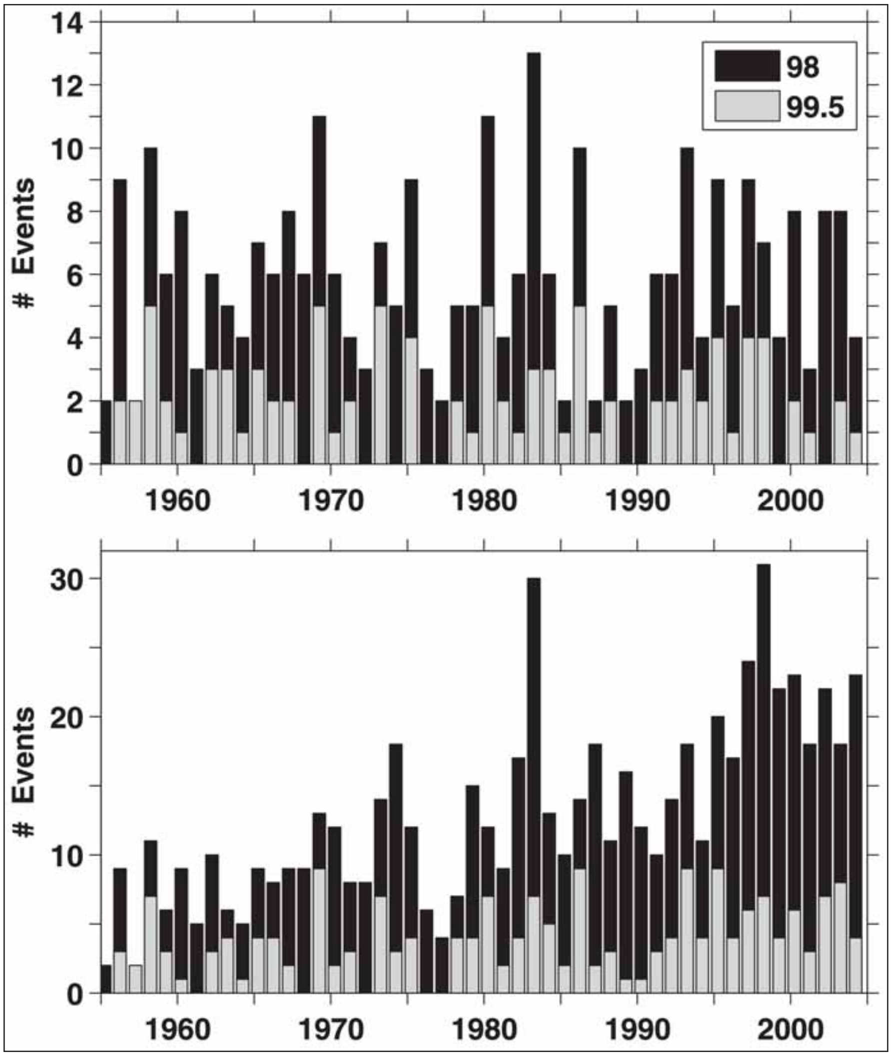


Figure 7. (top) Distribution of detrended extreme non-tide water level events at Fort Point, San Francisco (SFO) during the 1956-2004 water years (October-September). The 98th percentile level for all available hourly data is about 18 cm, and the 99.5th percentile is about 28 cm (about 1 ft). (bottom) Distribution of extreme non-tide water level events at SFO after imposing the 20 cm/century trend observed at SFO during the 20th century, using the same threshold levels as in the top panel. Note the difference in vertical scales.

WATER LEVEL VARIABILITY

Water levels within San Francisco Bay, and as far inland as RVA, have a substantial tidal component that produces significant diurnal fluctuations, even in the presence of extreme storm surge and high river flow during strong El Niño winters (Figure 2). The amplitudes of the diurnal tidal fluctuations decrease progressively upstream, such that they are clearly observable at IST only during relatively low river flows, e.g. prior to about 12 January 1998. The tide range decreases from about 3 m within the bay to about 2 m at PCO, ANH, and RVA (Cayan *et al.* 2008). Upstream from RVA, the tide range decreases to about 1.25 m at WGB and IST, where river flow dominates. Similar curves with the tide removed are shown in Cayan *et al.* (2006).

While tidal fluctuations are predictable, the two unpredictable factors that can impact delta levees and the bay/delta ecosystem are storm surge and flood discharge. Because storms are responsible for both of these water level components, they often occur concurrently, or nearly so. However, the variability of the timing of their respective extremes is an important factor.

The records from seven tide gauges are used to characterize the non-tide water level fluctuations within the San Francisco bay/delta. The long tide gauge record at SFO near the Golden Gate serves as the reference station for non-delta discharge since fluctuations here are dominated by near-coastal open-ocean forcing (Walters 1982; Walters and Gartner 1985). Non-tide variability at SFO is compared with three stations within the bay, and to the interior stations at Port Chicago (PCO), Antioch (ANH), and Rio Vista (RVA). The astronomical tide is removed from these data following the methodology of Bromirski *et al.* (2003), retaining detrended hourly water level fluctuations at periods of less than six months. This methodology removes the sea level rise trend and most of El Niño-related variability, leaving storm-forced fluctuations.

Storm surge during extreme events can force non-tidal fluctuations as much as about 70 cm at SFO, raising high tide water levels by more than 50% above non-storm high tide levels. Throughout the bay and lower delta, the non-tide water levels during the extreme storm events of 2-8 February 1998 (Figure 3) remain above 40 cm longer than 12 hours. Elevated levels at PCO (magenta line) near 10 February (the station of the group farthest inland), which likely results from high delta discharge associated with heavy rainfall in the upper reaches of the watershed, lags the peak surge and is muted within the bay. Elevated storm surge levels for extended time periods ensure that high surge levels will occur concurrently with high tide.

The temporal relationship of high surge and high delta inflow during early March 2001 is demonstrated in Figure 4. The initial high amplitude peaks during 4-5 March show the storm surge propagating from the open ocean (represented by SFO, thick magenta line) to other points in the bay/delta. Propagation from the open ocean is inferred by SFO leading the peaks at the other stations. The secondary peak on 7 March likely results from increased delta discharge from subsequent rainfall and snow melt in the upper reaches of the Sacramento-San Joaquin watersheds, having a progressively smaller expression at the bay stations SFO and Alameda (ALA) where the flow is less confined and exchange with the open ocean readily occurs.

Observed leads and lags, both relative to reference station SFO under the Golden Gate Bridge and between stations within the bay and lower delta (Figure 5), are consistent with surge propagation from the Golden Gate. These show about a 2-3 hour lag for surge propagation from the Golden

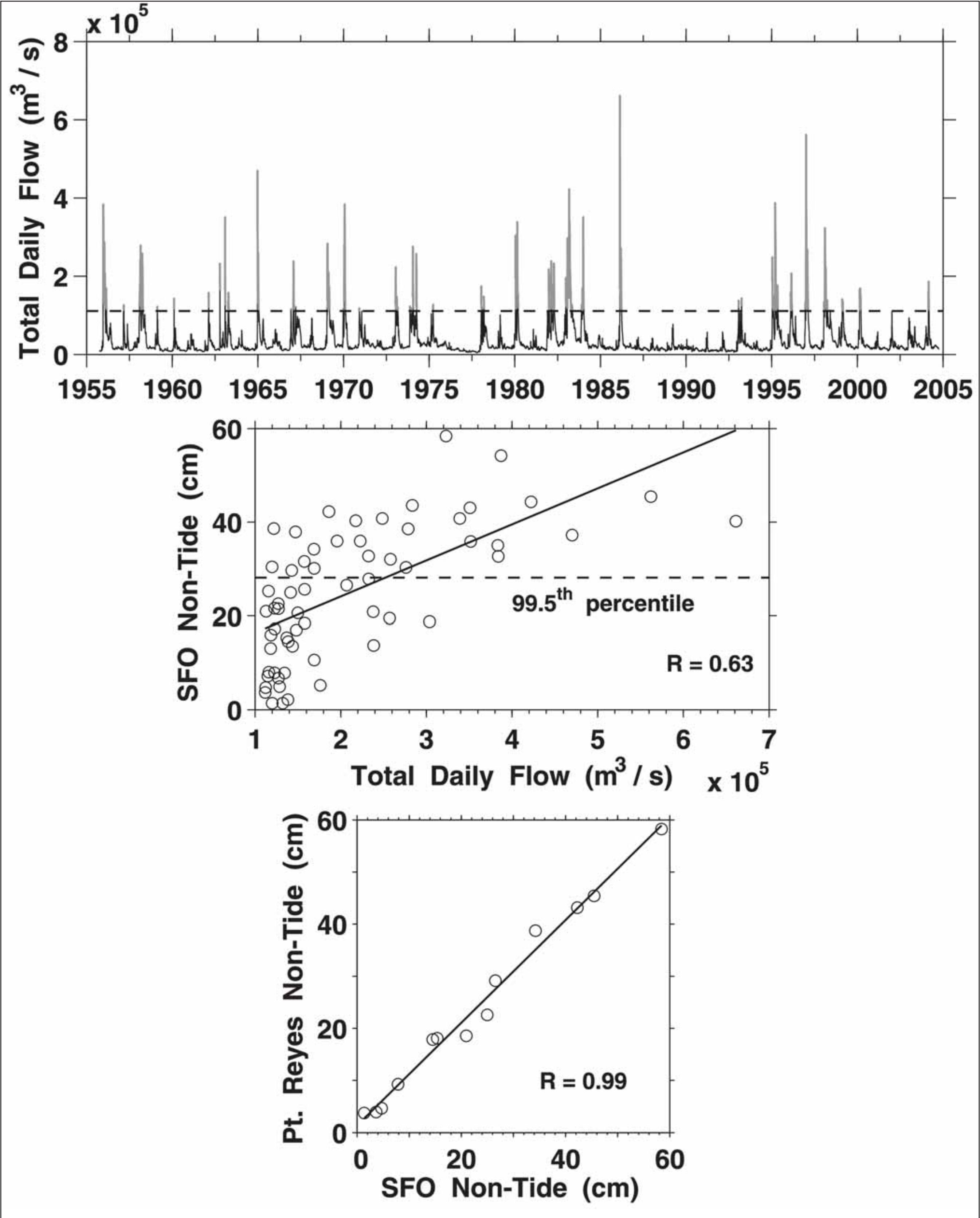


Figure 8. (top) Total daily fresh water inflows to the delta (DWR 2007), with extreme flows above the 95th percentile (dashed line). (middle) Maximum non-tide water levels measured at Fort Point (SFO) that occurred during the peak flows of the extreme flow events, with the extreme non-tide 99.5th percentile level for the 1955-2005 period indicated (dashed line). The least squares trend (solid line, significant at the 97.5 confidence level) shows that high storm surge is generally associated with high flows. (bottom) Peak non-tide levels at Pt. Reyes (outside San Francisco Bay) and at Fort Point (inside the Golden Gate) during common extreme flow events over the 1996-2005 period, with the least squares trend nearly unity.

Gate to Port Chicago (PCO). The estimated 2-3 hour lag is consistent with the shallow water phase speed, $(gh)^{1/2}$, where g is the gravitational acceleration and h is the water depth, along a propagation path from SFO to PCO of about 60 km, assuming an average water depth of 5 m.

EXTREME EVENTS

Delta areas closest to the bay generally have the greatest risk of levee failure, i.e. the western zone in Figure 6 (Mount and Twiss 2005). This zone is subject to high storm surge levels (see Figures 3-5), with the risk factor compounded during high river discharge through the delta. Increasing frequency of the joint occurrence of extreme surge and discharge levels, and the duration that these levels are maintained, also increases the risk of levee failure.

Because peak non-tide water level variability is dominated by open-ocean sources that propagate into the bay, extreme surge events within the delta and their occurrence can be characterized by the non-tide variability at SFO. Extreme surge events are defined by the 98th and 99.5th percentile levels of all hourly non-tide estimates over the 1956-2005 period, corresponding to the length of the daily delta flow record used. Events are found by first lowpass filtering the non-tide data. An event is identified when the filtered non-tide levels exceed the respective threshold for six consecutive hours.

During successive water years (a water year extends from 1 October of one year to 30 September of the next year to cover a full winter season), no clear trend is observed in the number of extreme non-tide events for the detrended tide gauge data (Figure 7, top). This suggests that no significant change in the frequency of extreme storms that impact the central California coast has occurred. However, when the sea level trend estimated from the raw SFO tide gauge data is re-introduced, a significant upward trend results in the 98th percentile time series (Figure 7, middle). This upward trend in the frequency of extreme water level events is similar to the upward trend in the number of hourly exceedences (Cayan *et al.* 2006; Cayan *et al.* 2008). The dramatic difference between the detrended and the more realistic trend-imposed number of surge events underscores the potential impact of sea level rise on the delta levees and bay/delta ecosystem, and also suggests an increased risk of saltwater intrusion into coastal aquifers at inland locations near Stockton.

As extreme surge has been shown to propagate from SFO throughout the delta, and as the non-tide levels throughout the bay/delta are well correlated (Figures 4 and 5), it can be assumed that extreme events observed at SFO have associated extremes within the delta. Comparison of the incidence of storminess, as indicated in Figure 7 (top), with freshwater delta inflows (Figure 8, above the dashed line) suggests that extremes in storm surge and floods likely coincide. This association is demonstrated by comparison of peak flows (Figure 8, top, above dashed line) with peak non-tide levels during extreme flow events (Figure 8, middle), which indicates that extreme storm surge (above the 99.5th percentile level) occurs during high flows about half the time. During such instances, the risk of levee failure is enhanced. The very close correspondence between non-tide peak levels at Pt. Reyes and at Fort Point (SFO) (Figure 8, bottom) suggests that peak surge levels within the bay/delta are generally dominated by storm-forced sea level fluctuations outside the bay.

The relationship of non-tide levels within the bay/delta to non-tide levels along the California coast is further demonstrated by their variability during an extreme storm event that resulted in an extreme delta flood event (Figure 9). Non-tide amplitudes generally increase along the California coast from south-to-north, indicating that the storm system forcing the elevated coastal sea levels moved from the north-to-south, and that the storm-forced sea levels dominate over other sea level variability components such as those associated with coastally-trapped Kelvin-type waves propagating from the south (Chelton and Davis 1982). Note that except during the 3-7 January 1997 flood event, non-tide levels at SFO (red line, Figure 9) within the bay near the Golden Gate are generally less than coastal stations to the north. Comparing SFO with nearby Pt. Reyes levels (PRS, blue line) suggests that the flood water discharge into the bay raised water levels on 3 January by 15-20 cm, and that water levels remained elevated within the bay due to delta discharge for about five days, likely causing significant changes in salinity and circulation in the bay/delta.

Comparison of non-tide levels during the 1982-1983 and 1997-1998 El Niño's (Figure 10), with a greater number of extreme 98th percentile surge events during the 1982-1983 event (Figure 7), suggests that the 1982-1983 episode may have had a greater impact on the bay/delta. The non-tide signals at SFO and interior station PCO are well correlated. Initial spikes in non-tide levels at SFO generally slightly precede PCO, consistent with Figure 5, indicating that the initial storm-forced signal propagates into the bay/delta from the open ocean. Figures 3, 4, and 9 (together with Figure 5) indicate that the initial surge propagating from the open ocean is substantially higher than trailing non-tide water levels associated with river flows.

Non-tide levels at PCO are consistently higher than at SFO during extreme events, likely resulting either from elevated delta discharge related to rainfall within the Sacramento-San Joaquin watersheds trailing the storm arrival at the coast, or from constricted flow within Suisun Bay for the inland-propagating surge. However, as Figure 4 shows, externally forced surge, associated with initial storm arrival at the coast, produces the peak storm-forced fluctuations as far inland as Rio Vista, reaching the high risk zones in the western delta identified by Mount and Twiss (2005, Figure 6). The extended duration of non-tide water levels at PCO above 40 cm for more than one day ensures coincidence with the semidiurnal high tides. The duration of extreme water levels is an important consideration in evaluating risk of levee failure.

The channel system within the delta may have a significant impact on surge propagation and significantly affect magnitudes at interior locations. Additional gauging stations within the delta have recently been installed. Comparison and correlation of the records at these new stations with the longer records discussed above will allow estimation of surge variability within the delta, and establish the added potential risk resulting from ocean-generated storm surge to the levees in the high risk western zone.

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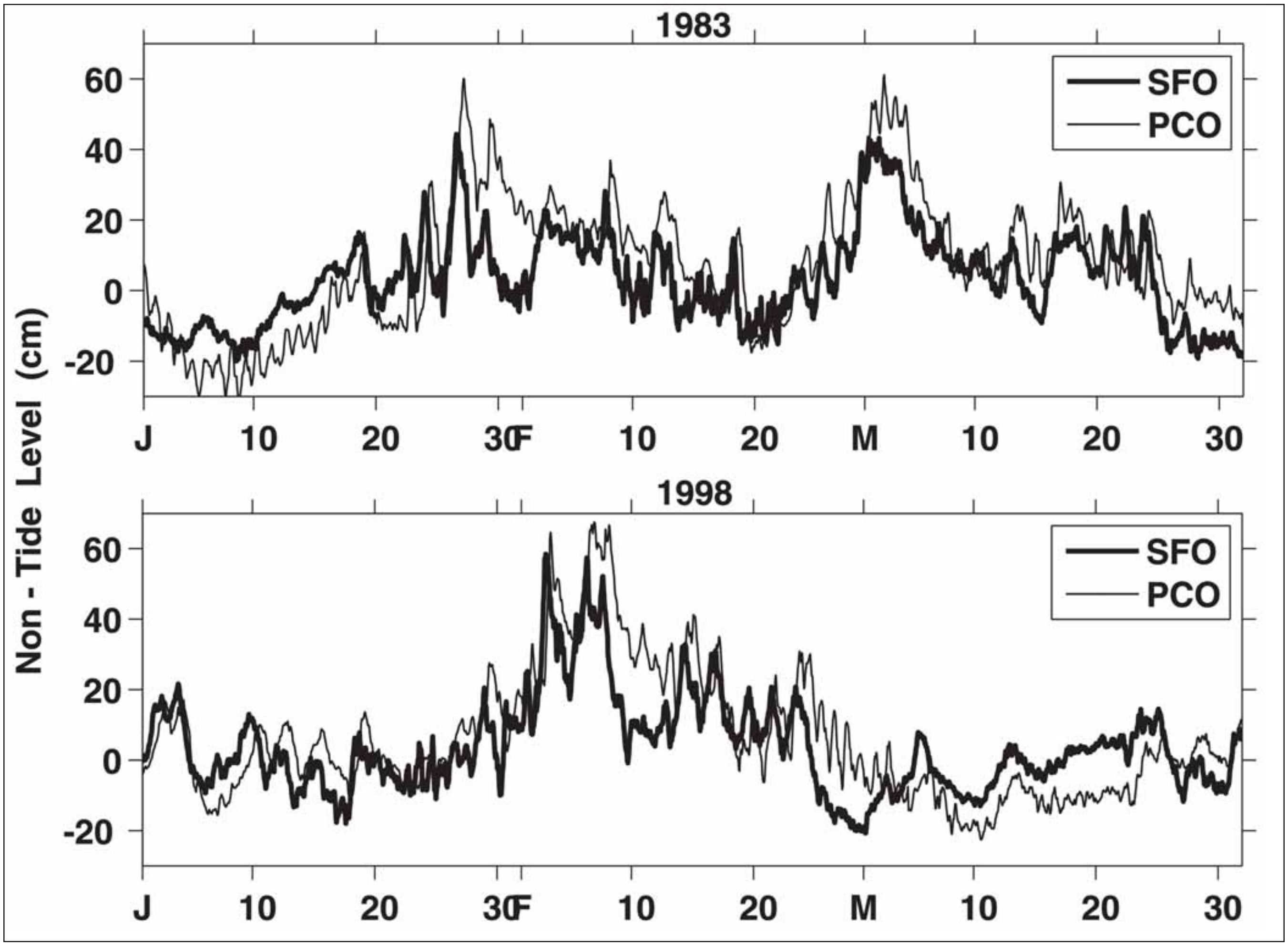

Figure 10. Comparison of total non-tide water levels at the Fort Point, San Francisco (SFO, thick line) and Port Chicago, Suisun Bay (PCO, thin line) tide gauges during the January-March periods of the 1982-83 and 1997-98 El Niños.

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