Sea level fluctuations in central California at subtidal to decadal and longer time scales with implications for San Francisco Bay, California

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Abstract

Sea level elevations from near the mouth of San Francisco Bay are used to describe the low-frequency variability of forcing of the coastal ocean on the Bay at a variety of temporal scales. About 90% of subtidal fluctuations in sea level in San Francisco Bay are driven by the sea level variations in the coastal ocean that propagate into the Bay at the estuary mouth. We use the 100-year sea level record available at San Francisco to document a 1.9 mm/yr mean sea level rise, and to determine fluctuations related to El Nino-Southern Oscillation (ENSO) and other climatic events. At time scales greater than 1 year, ENSO dominates the sea level signal and can result in fluctuations in sea level of 10 cm. Alongshore wind stress data from central California are also analyzed to determine the impact of changes in coastal elevation at the mouth of San Francisco Bay within the synoptic wind band of 2–30 days. At least 40% of the subtidal fluctuations in sea level of the Bay are tied to the large-scale regional wind field affecting sea level variations in the coastal ocean, with little local, direct wind forcing of the Bay itself. The majority of the subtidal sea level fluctuations within the Bay that are not related to the coastal ocean sea level signal are forced by an east–west sea level gradient resulting from tidally induced variations in sea level at specific beat frequencies that are enhanced in the northern reach of the Bay. River discharge into the Bay through the Sacramento and San Joaquin River Delta also contributes to the east–west gradient, but to a lesser degree.

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1. Introduction

The response of San Francisco Bay, California to changes in the coastal ocean modulates the Bay’s response to freshwater flow from the Sacramento—San Joaquin rivers through the Delta. Global, regional, and local mechanisms that force sea level in the Bay occur at a variety of temporal scales and can affect long-term fluxes of dissolved material into and out of the Bay. This in turn has important implications for the determination of the health of the Bay with respect to factors such as salt-water intrusion, pollutant transport, and phytoplankton and benthic filter feeder populations. Ultimately, subtidal flow controls the long-term transport and fate of suspended and dissolved matter in the Bay. In addition, water resource managers for the state of California need to make decisions as to how much water can be released into San Francisco Bay to control flooding. However, there has been only limited knowledge available to them on how the coastal ocean forcing of sea level within the entire Bay potentially would impact large reservoir releases.

Delta flow, which is calculated from discharge into the Bay from the Sacramento and San Joaquin rivers adjusted for agricultural diversion, has been reduced by about 50% of its 1850
volume (Peterson et al., 1995). Increasing withdrawal capacity combined with an increase in demand has resulted in further decreases in freshwater from the system (Knowles, 2002). Recent studies of changes in climatic forcing since the late 1940s suggest the potential for an increase in Bay salinity, including an increased contribution from interactions of the Bay with higher salinity coastal waters. A long-term trend of more rain and less snow in the California Sierra Nevada mountain range will also have an impact on salinity in the Bay by affecting the timing and magnitude of freshwater discharge into the Bay (Dettinger and Cayan, 1995, 2003). In a study of potential impacts to San Francisco Bay as the result of global and/or regional warming, Knowles and Cayan (2002) predict an increase in spring—summer salinity of 9 psu by the year 2090 based on a projected increase in temperature of 2.1 °C.

Factors that influence the height of sea level include the tides, atmospheric pressure, temperature, winds, river discharge, eustatic (thermal expansion and ocean mass changes), and tectonic effects. We are particularly interested in those factors that result in an increase in sea level in the coastal ocean that could, in turn, influence sea level in the Bay. For example, an intensification of the Aleutian Low Pressure System (Bograd et al., 2002) or increased storminess in the Pacific Ocean (Graham and Diaz, 2001; Bromirski et al., 2003) could result in increases in coastal sea level. Both local and remote forcing of sea level during El Niño events generally result in higher sea level off California (e.g. Ryan and Noble, 2002). A prediction of increased El Niño activity with global warming (Timmermann et al., 1999; Boer et al., 2004) could result in the dominant wind pattern coming out of the south and west during the winter off California (Schwing et al., 2002b), which would result in an increased set-up of sea level at the coast.

Previous studies of sea level in San Francisco Bay have shown that over 90% of the variance in the subtidal sea level signal is related to non-local forcing by set-up of the coastal ocean at the mouth of the Bay (Walters, 1982; Wang et al., 1997). In this paper, we analyze the 100-plus year tide gauge record at San Francisco combined with 7 years of tide gauge records at additional sites within San Francisco Bay to determine how sea level in the Bay is impacted by: (1) long-term eustatic changes in sea level; (2) El Niño and other climatic events; (3) forcing by both the local and regional wind stress in the synoptic wind band (2–30 days); (4) discharge from the Sacramento—San Joaquin River Delta; and (5) interactions of tidal constituents at subtidal time scales.

2. Data processing

About 100 years of sea level elevations were obtained for coastal tide gauge stations at Fort Point near the mouth of San Francisco Bay (1900–2003) and San Diego (1906–2003) (NOAA, 2003). These data were supplemented with over 6 years (1996–2003) of tide gauge data from three stations from within San Francisco Bay: Port Chicago in Suisun Bay, Alameda, and at the Dumbarton Bridge and Redwood City Wharf in the South Bay (Fig. 1), and an additional coastal tide gauge at Monterey, about 140 km south of San Francisco (NOAA, 2003). Hourly sea level elevation data were low-pass filtered to remove the tides (Limeberner, 1985), averaged to daily values, and adjusted for barometric pressure effects by adding 1 cm/mbar barometric pressure to the sea level data and removing the mean. The tide gauge station at the Dumbarton Bridge was moved to the Redwood City Wharf in April 1998. To create the South Bay record, we merged the records by applying a static shift to the station datum at Redwood City Wharf to correspond to the station datum at the Dumbarton Bridge. An east—west gradient of sea level in the Bay was calculated by subtracting San Francisco data from the Port Chicago sea level data, and the north—south gradient was calculated by subtracting the San Francisco data from the Redwood City sea level data. There is a strong annual cycle in the sea level data that dominates statistics at periods of a year and greater. To determine the annual cycle for the long-term sea level records at San Francisco and San Diego, we calculated monthly means that were then averaged over the entire data set for each site. We then used a spline interpolation to convert the monthly values to daily values, and then removed the daily values from both of the long-term sea level records (see Ryan and Noble, 2002).

Hourly wind speed and direction data were obtained in the coastal ocean for NOAA buoy 46012 (1981–2002), and within San Francisco Bay for San Francisco International Airport (SFO) (1964–2003) and Travis Air Force Base (1998–2003). Wind vectors were created, low-pass filtered (Limeberner, 1985), rotated to be aligned along their principal axes as determined from the subtidal data, and alongshore wind stress (AWS) was calculated (Wu, 1980); AWS data were then averaged to create records of daily values. Buoy 46012 wind stress data were rotated to their principal axis 330° (alongshore direction); SFO wind stress data were rotated to the along-Bay direction of 300°; Travis Air Force Base winds were rotated along their principal axis of 235. Buoy 46012 failed in 9/97. Therefore it was necessary to derive AWS from buoy 46026 through 2/98, and buoy 46013 from 2/98 to 6/98, when buoy 46012 became operational again. The directional AWS data from buoys 46026 and 46013 were highly correlated with buoy 46012, although the amplitudes differed. We adjusted the amplitudes using the linear regression coefficient between the AWS data sets. Because the cross-shelf wind stress at buoy 46012 was not well correlated with buoy 46026 owing to orographic effects, we were only able to create a long record for the alongshore wind stress.

Discharge into San Francisco Bay from the San Joaquin and Sacramento River Delta, which is based on Delta inflow and estimates for agricultural diversions within the Delta, was obtained from the California Department of Water Resources (2003) for the time period 1955–2003.

3. Results

3.1. Sea level fluctuations at very low frequencies

Long-term rates of sea level change in the coastal ocean are related to a combination of eustatic and tectonic induced water
level changes through time. Over the past century, sea level in central California, as measured at the Fort Point, San Francisco tide gauge station, has been steadily rising. A linear regression calculated on adjusted monthly sea level anomalies at San Francisco for the time period of 1900–2003 shows an increase in sea level of 1.85 ± 0.09 mm/yr (Fig. 2A). Although the sea level data have been low-pass filtered and adjusted sea level for barometric pressure effects and the annual cycle, there are still pronounced fluctuations in the monthly sea level signal that may be obscuring changes in the rate of long-term sea level rise (Fig. 2A).

In order to try to remove the strong fluctuations in monthly sea level at San Francisco, a principal component analysis was computed between monthly sea level anomalies at San Francisco and San Diego from 1906–2003 (Fig. 3). The principal components are the eigenvectors of the covariance matrix. The first mode of the principal component analysis, representing the greatest variance in the data set, explains 73% of the variance between the two signals. We removed the first mode, which by definition has no slope, from the monthly sea level anomalies at San Francisco. The removal of the first mode results in a significant reduction in the variance of the sea level signal, and shows that the long-term trend in sea level at San Francisco has been relatively constant over the past century at 1.92 ± 0.04 mm/yr (Fig. 2B).

Many of the subtidal fluctuations in the first principal component of sea level (Fig. 3) are related to large-scale oceanographic processes such as ENSO events and the Pacific Decadal Oscillation (PDO). Most of the strong positive (El Niño) and negative (La Niña) peaks in the mode 1 signal correspond to the times of the strongest El Niño and La Niña events of the last century (Fig. 3; Wolter and Timlin, 1998). We compare the first mode of sea level anomalies at San Francisco and San Diego (Fig. 3) to several climate indices: the Multivariate ENSO Index (MEI), the PDO Index and the Northern Oscillation Index (NOI). The MEI represents the first principal components of six oceanographic variables observed over the tropical Pacific Ocean (Wolter and Timlin, 1998) for the time period 1955–2003. The PDO is the first principal component of Sea Surface Temperature (SST) anomalies in the Pacific Ocean north of 20°N (Mantua et al., 1997). The NOI is based on differences in sea level pressure anomalies between the North Pacific High at 35°N, 130°W and that at Darwin, Australia (Schwing et al., 2002a); it is similar to the Southern Oscillation Index (difference in sea level pressure between Tahiti and Darwin), but with a direct physical link to the northeast Pacific region. At periods greater than 2 years, the coherences between the MEI and NOI are high (about 0.9) (Fig. 4), which is not surprising since ENSO events strongly influence the location and intensity of the Aleutian low. However, the MEI and PDO indices are generally not coherent at the 95% confidence level (Fig. 4). The linear correlation coefficient between the MEI and the San Francisco–San Diego sea level mode 1 is 0.63. However, if only periods between 2 and

![Fig. 1. Location map for tide gauge and wind stations. The Monterey Bay tide gauge station (not shown on figure) is located ~140 km south of San Francisco.](image_url)
10 years are considered, the signals are significantly coherent at about 0.8 and in phase (Fig. 4). Since the coherences between the PDO and sea level mode are lower than between ENSO and the sea level mode, the long period fluctuations in sea level that are common to both the San Diego and San Francisco sites are most likely dominated by ENSO.

In order to study sea level fluctuations on shorter time scales, we calculated individual records of daily-adjusted sea level anomalies at both San Francisco and San Diego. Coherencies calculated between these two signals, show three distinct frequency bands with different coherencies (Fig. 5). At periods less than 30 days, the mean coherence between the signals is 0.4. At periods between 40 and 90 days, within the intraseasonal frequency band, the mean coherence increases to 0.6. Finally, at very long periods (2–30 years), the mean coherence is 0.8. The very long period signal is related to ENSO events as discussed above. For periods between 40 and 90 days the sea level signal is likely forced primarily by a combination of remote (equatorial) and regionally forced coastally trapped waves (Ryan and Noble, 2002; Strub and James, 2002). Fluctuations in subtidal sea level for periods less than 30 days are described in the following sections.

3.2. Fluctuations in the synoptic weather band (2–30 days)

Previous studies have shown that over 90% of the variance in the sea level signal in San Francisco Bay is forced by the coastal ocean signal (Walters, 1982; Wang et al., 1997). In this paper, we determined those factors that directly force subtidal coastal sea level fluctuations and thus indirectly forced sea level in the Bay. Subtidal coastal sea level fluctuations were determined primarily by the tide gauge stations at San Francisco (SFSL) and Monterey, which have the most direct connection to the coastal ocean. Subtidal Bay sea level data were analyzed for stations at Port Chicago (PCSL), Alameda (ASL), and Redwood City (RCSL). In order to differentiate between the different forcing mechanisms in the synoptic weather band, we analyzed the relationships between coastal and Bay sea level, alongshore wind stress, and river discharge to San Francisco Bay for the time period 1996–2002 (Fig. 6).
This time period included the La Niña of 1996–1997 during which one of the largest recorded discharge events occurred around January 1, 1997, and the very strong 1997–1998 El Niño with its attendant elevated sea levels and prolonged winter storm season.

3.2.1. Sea level

All of the subtidal sea level fluctuations at sites in San Francisco Bay are similar (e.g. Fig. 6), particularly at longer periods. The coherences between the coastal sea level measured at the mouth of the estuary (SFSL) and the sea level signals observed at other sites in the Bay are above 0.9 at periods greater than 40 days (Fig. 7). At periods less than 6 days, the coherences fall off rapidly. Coherences are slightly higher between SFSL and ASL than SFSL and PCSL at periods between 6 and 40 days. At periods centered about 14 and 28 days, however, coherences between the sea level signals drop off significantly owing to the very large signal at the $O_1/K_1$, $M_2/S_2$, and $M_2/N_2$ beat frequencies (see below), particularly as observed at PCSL. All of the sea level signals are in phase at periods greater than 6 days with the following exceptions: at periods between 6 and 10 days, SFSL leads RCSL by about 20° (7–8 h), and at periods between 8 and 12 days, SFSL leads PCSL by 10–25° (5–20 h).

In order to be able to identify spatially and temporally varying patterns in sea level fluctuations, we ran a principal component analysis of subtidal sea level at the three bay stations (ASL, RCSL and PCSL) plus two coastal stations (SFSL and adjusted sea level at Monterey). The first principal component (mode 1) accounts for 87% of sea level fluctuations, with the second component (mode 2) accounting for 9% and the third mode only 3%. Over 95% of the sea level fluctuations at RCSL and ASL are described by the first mode. The spatial amplitude of the first mode is similar at all of the stations, except at PCSL where the amplitude is about 30% higher. A time series of the temporally varying amplitude of the first and second principal components of sea level is shown in Fig. 8. Mode 1 is highly correlated with the observed sea level signals (see Fig. 6) and is influenced primarily by the remote forcing of coastal sea level at the estuary entrance. The coastal sea level signal propagates across the entire Bay in phase and with similar amplitudes.

![Fig. 4. Coherences between MEI Index and (1) NOI (diamonds), (2) PDO index (circles), and (3) the first principal component of sea level fluctuations between San Francisco and San Diego (squares) for the years 1955–2003; the maximum period resolved is 10 years. The gray line shows the 95% confidence limit for coherence.](image)

![Fig. 5. Coherences between daily sea level anomalies at San Francisco and San Diego for the time period 1906 and 2003. The gray line shows the 95% confidence limit for coherence.](image)
Fig. 6. Daily anomalies (annual cycle removed) for delta discharge, alongshore wind stress at buoy 46012, and adjusted sea level at Fort Point (black) and Port Chicago (gray).

Fig. 7. Coherences between adjusted sea level at Fort Point and (1) Alameda (circles), (2) Redwood City (squares), and (3) Port Chicago (diamonds) for the time period 1996–2002 using a 140-day piece length, Hanning filter, and overlap of 70 days.
Energetically, the signal at PCSL was stronger than at SFSL, ASL, or RCSL (Fig. 9). Prominent peaks in energy in the sea level signal occur at periods of \( \sim 14 \) days, and to a lesser extent at \( \sim 28 \) days, and correspond to the beat frequencies between tidal components \( O_1 \) (principal lunar diurnal) and \( K_1 \) (luni-solar diurnal), \( M_2 \) (principal lunar semi-diurnal) and \( S_2 \) (principal solar semi-diurnal), and \( M_2 \) and \( N_2 \) (larger lunar elliptic semi-diurnal). An autospectrum of the square of the predicted tidal signal generated by the primary diurnal (\( O_1 \) and \( K_1 \)) and semi-diurnal (\( M_2, S_2, \) and \( N_2 \))

![Graphs showing normalized amplitudes, frequencies, and power spectra for different tide gauge stations.](image)

Fig. 8. Normalized amplitudes of first and second principal components of five tide gauge stations: San Francisco, Redwood City, Port Chicago, Alameda and Monterey. Mode 1 is very similar to the daily sea level anomalies shown in Fig. 6.

![Graphs showing variance conserving autospectra.](image)

Fig. 9. Variance conserving autospectra of subtidal sea level using a 532-day piece length and Boxcar filter with no overlap. The beat frequencies between tidal constituents \( O_1 \) and \( K_1 \) (13.66 days), \( M_2 \) and \( S_2 \) (14.77 days), and \( M_2 \) and \( N_2 \) (27.55 days) are labeled. Note that the energy at Port Chicago is about five times higher than at the other stations. A piece length of 532 days was used to separate energy in the peaks centered about 13.66 and 14.77 days.
tidal constituents at PCSL shows peaks at periods corresponding to the O1/K1 (13.66 days), M2/S2 (14.77 days), and M2/N2 (27.55 days) beat frequencies.

A peak in energy at the O1/K1 beat frequency is observed at all of the sites, but is much higher at PCSL; the peaks at SFSL, RCSL, and ALSL are similar, with a slightly greater amplitude observed at RCSL (Fig. 9). The M2/S2 beat frequency only shows a large peak in energy at PCSL, although there is also a smaller peak at SFSL that is also significant at the 95% confidence level (Fig. 9). The M2/N2 beat frequency at PCSL, although there is also a smaller peak at SFSL, is similar to the aforementioned beat frequencies.

A sharp peak in energy at the O1/K1 beat frequency is also evident in the first mode of the sea level signal, with a lesser peak at the M2/S2 beat frequency (Fig. 10). Mode 2, which is primarily manifest in SFSL and PCSL signals, shows significant energy at periods around 14 days (M2/S2 and O1/K1 beat frequencies, Fig. 10). In contrast to mode 1, the semi-diurnal beat frequencies (M2/S2 and M2/N2) are more prominent in mode 2; the M2/S2 peak is the most dominant in this mode. The autospectrum of the east–west sea level gradient (PCSL – SFSL) is similar to the mode 2 autospectrum (Fig. 10). Coherences between mode 2 and the east–west gradient are very high and near 1.0 at the beat frequencies (Fig. 11). Thus the diurnal beat frequency (O1/K1) affects the entire Bay, whereas the semi-diurnal beat frequency (M2/S2) is primarily manifest in the northern reaches of the Bay.

3.2.2. Wind stress and sea level

Previous studies of wind forcing of sea level in San Francisco Bay have relied on wind stress measured at San Francisco International Airport (SFO) (e.g. Walters, 1982). However, since late 1980, coastal AWS has been available (NOAA buoy 46012, Fig. 1). For the time period 1980–1998, it is evident that the buoy wind stress is much stronger and more polarized in the alongshore direction (330°) than the wind stress calculated at SFO (Fig. 12). Fluctuations of the along-Bay wind stress at SFO only account for 27% of the variance observed in alongshore wind stress at buoy 46012. Both the SFO and Travis Air Force Base (data not shown) have wind signals that are not strongly polarized and are influenced by local topography. This suggests that whereas these winds may locally influence sea level set-up in some areas of the Bay, they are most likely not driving large-scale set-up of Bay sea level.

At periods greater than 2.5 days, AWS at buoy 46012 is significantly coherent at the 95% confidence level with all of the tidal constituents at PCSL.
ASL stations in the Bay (Fig. 13). All stations share a similar pattern with AWS coherence highest with SFSL and lowest with PCSL. The coherences tend to increase with period for periods up to about 4 days. Overall, there is a decrease in coherency between AWS and all of the sea level signals centered about 14 days, similar to the decrease in coherence observed between coastal and Bay sea level. For periods between 3 and 30 days, the phase and frequency response function (response of sea level to a unit AWS forcing at a given frequency) between coastal AWS and all sea level stations are similar. At periods greater than 40 days, fluctuations of AWS account for about 75% of the sea level signal at all stations (Fig. 13). The coastal alongshore wind stress forces sea level fluctuations in the coastal ocean that, in turn, propagate into the Bay at San Francisco, and set-up or set-down sea level in the Bay in phase and with a similar amplitude.

In order to differentiate between sea level forced by AWS that sets up coastal sea level, which then propagates into the Bay, and local, direct wind forcing of sea level in the Bay, we ran coherences between the along-Bay wind stress at SFO and RCSL. RCSL is the sea level station most likely to be locally set-up by winds at SFO. At periods greater than 5 days, the coherences between offshore winds at buoy 46012 and RCSL are higher than those between SFO and RCSL (Fig. 14). Although SFO and RCSL are significantly coherent at the 95% confidence level at periods greater than 5 days, these coherences can be explained by the fact that the winds at buoy 46012 and SFO are themselves coherent with each other (Fig. 14). It is only at periods of less than 5 days that the coherencies between SFO and RCSL are large enough that they cannot simply be related to the covariance of buoy 46012 and SFO winds. This suggests that local, direct, along-Bay set-up of sea level independent of the coastal wind field occurs primarily at higher frequencies. We also tried to determine whether local winds measured at Travis Air Force Base were also locally forcing sea level in the northern reaches of the Bay. However, the coherences between the Travis winds and sea level were not significant at the 95% confidence level, although the Travis winds may not be representative of cross-Bay winds in the area owing to complicated orographic effects.

In order to separate the local coastal wind field (e.g. winds from buoy 46012) from larger-scale regional wind signals, we calculated the first principal component between alongshore wind stress at buoy 46012 and the C-man station at Point Conception (370 km southeast of buoy 46012) to represent the

![Fig. 12. Scatter plot of subtidal wind stress at (A) San Francisco International airport and (B) buoy 46012 for the time period 1981–2002.](image-url)

![Fig. 13. Coherences between alongshore wind stress at buoy 46012 and adjusted sea level at: (1) Fort Point (triangles); (2) Redwood City (circles); and (3) Port Chicago (squares) for the time period 1996–2002 using a 140-day piece length, Hanning filter, and overlap of 70 days.](image-url)
regional coastal wind stress field. The coherences between the regional AWS and mode 1 of sea level are similar to those calculated between AWS at buoy 46012 and SFSL (compare Figs. 14 and 15). At periods greater than 16 days, over 60% of the mode 1 sea level signal in the Bay is forced by the regional AWS (Fig. 15), with the regional winds leading sea level by a constant phase of about 40°. Thus the longer period sea level signals observed in San Francisco Bay are forced to a large degree by the regional-scale wind systems, which have spatial scales on the order of 100s of km.

3.2.3. Delta discharge and sea level

The highest coherences between discharge from the San Joaquin/Sacramento rivers into the Delta and sea level in San Francisco Bay occur between discharge and PCSL (Fig. 16); discharge and PCSL are in phase, except for periods less than 25 days, when PCSL lags discharge by 0.5 to 1 day. The higher coherences between PCSL and discharge are as expected since PCSL is the closest station to the Delta. However, what is somewhat more surprising is that the sea level and discharge are more highly coherent at periods longer than 20 days, with little coherence at shorter periods. The lack of coherence at shorter periods is most likely owing to the observation that there is low coherent energy in the discharge signal at periods less than about 40 days that would force a response in the sea level signal (Fig. 17). It should be noted, however, that discharge tends to occur as events that only occur during certain times of the year (winter and spring) and thus are not regular fluctuations amenable to time series analyses. Linear regression analyses between discharge and PCSL demonstrates the seasonality of the impact of discharge on sea level with the following calculated correlation coefficients: winter 0.76, spring, 0.68, summer 0.47 and fall 0.20.

4. Discussion

The primary mode that explains over 90% of the subtidal variance in sea level in San Francisco Bay is the coastal ocean (Walters, 1982; Wang et al., 1997). Because San Francisco Bay is a comparatively small estuary, it is not surprising that water elevations in the Bay are forced primarily by the coastal sea level of the Pacific Ocean. Subtidal sea level signals at the estuary
mouth propagate into the Bay largely unattenuated, especially at longer periods. The coastal ocean impacts sea level in the Bay at a variety of time scales as shown by the over 100-year record of sea level from the Fort Point tide gauge station in San Francisco. There is an observed rise in eustatic sea level at San Francisco of about 2 mm/yr, similar to that observed elsewhere around the world (Cazenave and Nerem, 2004). Since the rate of sea level rise is similar to global rates, there does not appear to be a tectonic influence on this long-term rate, nor is there an indication that the rate of sea level rise has changed over this time period. However, predictions of an acceleration of global sea level rise could have a significant impact on water levels in the Bay in the future (e.g. Hayhoe et al., 2004).

Superimposed on the long-term trend of rising sea level observed at San Francisco are interannual to decadal changes in coastal sea level linked to climatic processes such as ENSO and PDO. Climatic signals result in a Pacific basin-wide response to large-scale wind forcing (e.g. Chelton and Davis, 1982). Schwing et al. (2002b) show atmospheric teleconnection patterns during ENSO events that affect sea surface height anomalies along the entire west coast of North America. The intensification of the Aleutian Low Pressure System that is associated with a positive ENSO event is linked to warmer coastal waters and thus higher sea level in the northeast Pacific. During a strong El Niño event, sea level as measured at both the coast and the Bay is less coherent with regional AWS than at other times suggesting that remote forcing exerts a strong influence on the sea level signal (Ryan and Noble, 2005). The poleward propagation of remotely forced coastally trapped waves with periods of 40–90 days, which are generated in the equatorial Pacific during El Niño events, can result in downwelling along the coast with an associated rise in sea level and increase in temperature above the seasonal thermocline (Ryan and Noble, 2002; Strub and James, 2002). Although there may be a modulation of the ENSO signal at decadal time scales, the PDO does not appear to be as important a factor in sea level elevations in central California.

As has been observed elsewhere, the Ekman effect of AWS forcing sea level at the coast and hence at the mouth of an estuary dominates over direct wind forcing of the estuary surface at subtidal frequencies; AWS forcing over the shelf is generally far more effective than in an estuary (e.g. Garvine, 1985; Wong and Moses-Hall, 1998). In addition, regional-scale AWS is as effective as locally generated coastal AWS in setting up coastal sea level, owing to the large spatial scales of the wind (Ryan and Noble, 2006). Forty to seventy percent of the first principal component of sea level in the Bay is forced by the regional AWS at periods greater than 5 days. Conversely, the combination of orographic effects and the complicated geometry of San Francisco Bay suggest that local, direct wind set-up is not as important in setting up sea level in the Bay. Wang et al. (1997) indicate that about 3% of sea level

![Fig. 16. Coherences between delta discharge and adjusted sea level at: (1) Fort Point (triangles); (2) Redwood City (circles); and (3) Port Chicago (squares) for the time period 1996–2002 using a 140-day piece length, Hanning filter, and overlap of 70 days.](image1)

![Fig. 17. Variance conserving plot of autospectrum of discharge into the Delta using an 1800 day (about 5 years) piece length with Hanning filter and overlap of 900 days.](image2)
fluctuations in San Francisco Bay are related to local wind set-up in both the north–south and east–west directions. We observe that local, direct set-up of subtidal sea level in the South Bay may be important at periods less than 4 days. This is similar to what was observed in Chesapeake Bay where local winds only force sea level in that estuary at periods less than 4 days (Wang, 1979).

Tidally induced forcing of sea level at subtidal periods around 14 and 28 days is evident at all the sea level stations in the Bay, but is especially evident in the northern reaches as measured at Port Chicago. The amplitude of the O1/K1 tidal beat frequency (13.66 days) is about 2.5 times larger at PC than the other stations. In contrast, there is no spike in the sea level signal at 13.66 days at Monterey, and SFSL and Monterey sea level are not significantly correlated at this period. We suggest that the strong 13.66-day signal is related to enhanced diurnal tidal currents, with amplitudes greater than the generally dominant M2 tidal currents, that have been observed on the nearby Farallones shelf (Noble, 2001). The propagation of the enhanced diurnal currents from the shelf into the Bay at the Golden Gate could result in the generation of a sea level signal at the O1/K1 beat frequency owing to frictionally induced non-linear interaction of these currents within the Bay. The increased response to a standing wave at the boundaries combined with multiple constrictions and decreasing depth inherent to the northern reaches of the Bay could act to increase this response at Port Chicago.

Although the dominant mode of sea level in the Bay is correlated with coastal ocean sea level as measured at the Golden Gate, 9% of the subtidal sea level signal is related to an E–W sea level gradient in the Bay. This second mode of sea level variability is observed at San Francisco and Port Chicago. Walters and Gartner (1985) noted a fortnightly variation in sea level between the landward and seaward ends of the northern reach, which they attribute to tidal stress as the primary mechanism. We expand upon their observations and suggest that the E–W surface slope is predominantly produced by a combination of non-linear tidal processes and discharge into the Bay at its' far eastern end. After removing the first principal component of sea level from PCSL, the resultant autospectrum shows that the dominant peak in energy is at the M2/S2 (14.77 days) beat frequency and the O1/K1 signal is reduced in amplitude. The M2/S2 beat frequency signal is only evident in the signals at SF and PC. Stacey et al. (2001) observed a tidally induced residual flow in the currents in Suisun Bay at a period of about 14.6 days. They ascribe this signal to barotropic forcing of a periodically stratified water column whereby changes in freshwater discharges intensifies flow as the result of increases in the salinity gradient. The east–west sea level gradient may also be enhanced by a larger delta discharge signal at Port Chicago during times of large delta discharge anomalies such as observed in January 1997 and February 1998 (Fig. 6).

5. Conclusion

Increases in sea level at San Francisco Bay have long-term implications for the Bay, particularly in terms of increased Bay salinity and the exacerbation of flooding during winter storm events. Changes in sea level occur at a variety of temporal scales with the long-term eustatic rise in sea level and interannual fluctuations in sea level related primarily to climatic conditions such as global warming and ENSO. At subtidal time scales within the synoptic wind band, over 40% of the fluctuations in sea level of the Bay are tied to the large-scale regional wind field that force sea level in the coastal ocean with the coastal sea level signal propagating into the Bay. Of secondary importance, subtidal variations of sea level in the Bay occur as the result of tidally induced fluctuations in the northern reaches of the Bay at fortnightly and monthly time scales, and discharge into the Bay at the Sacramento–San Joaquin River Delta.

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References


