Title
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Journal
The Science of the Total Environment, 55

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Publication Date
1986

Peer reviewed

The Science of the Total Environment, 55 (1986) 251—259
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

A Review of Conditions Associated with High Sea Levels in Southern California

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1. INTRODUCTION

Southern California is often considered immune from the catastrophic flooding that periodically inundates the Atlantic and Gulf coasts of the United States. The generally mild weather and relatively sheltered coast (Figure 1-1) supports this popular conception. However a series of severe winters (1977-78 and 1979-80) and the popular "El Niño" winter of 1982-83 have shaken the idea that this highly developed region is beyond threat. This report briefly reviews the large-scale and short-term conditions that lead to anomalously high sea levels in southern California.

Section 2 reviews recent work on the mixed tide regime which governs the occurrence of peak tides on the west coast of the U.S. Section 3 outlines the cumulative effect of the secular, global sea level rise. Section 4 discusses seasonal and interannual effects and the causes of departures from the mean on these time scales. Finally, Section 5 describes the detailed correlations of regional weather forcing and sea level anomaly, defined as the departure from predicted astronomical tides.

2. THE TIDES

Of all the variables that contribute to sea level changes along California, the astronomical tides are responsible for the largest signal. About 90% of the tidal fluctuations occur near 1 and 2 cpd. The diurnal constituents amount to about 70% of the semidiurnal constituents, resulting in a mixed tide regime. This is crucial to understanding the occurrence of extremes of tide height. The remaining 10% of "tidal" variation is associated mainly with seasonal changes in solar heating which are lumped with the other constituents for purposes of prediction.

Relatively few studies have considered the processes and statistics associated with extreme tides in California (Disney, 1955; Smith and Leffler, 1980; Zetler and Flick, 1985a). Most published studies of extreme astronomical high tides have concentrated on the criteria that produce large semidiurnal responses (Wood, 1978; Amin, 1979; Cartwright, 1974). Zetler and Flick (1985a, b) suggest that the most useful approach for prediction of (at least short term) maxima is to use the standard harmonic predictions and extract the (monthly, say) peaks over the desired period. This has been done for the California coast, and peak monthly tides are tabulated in Zetler and Flick (1983b) for the years 1983-2000.

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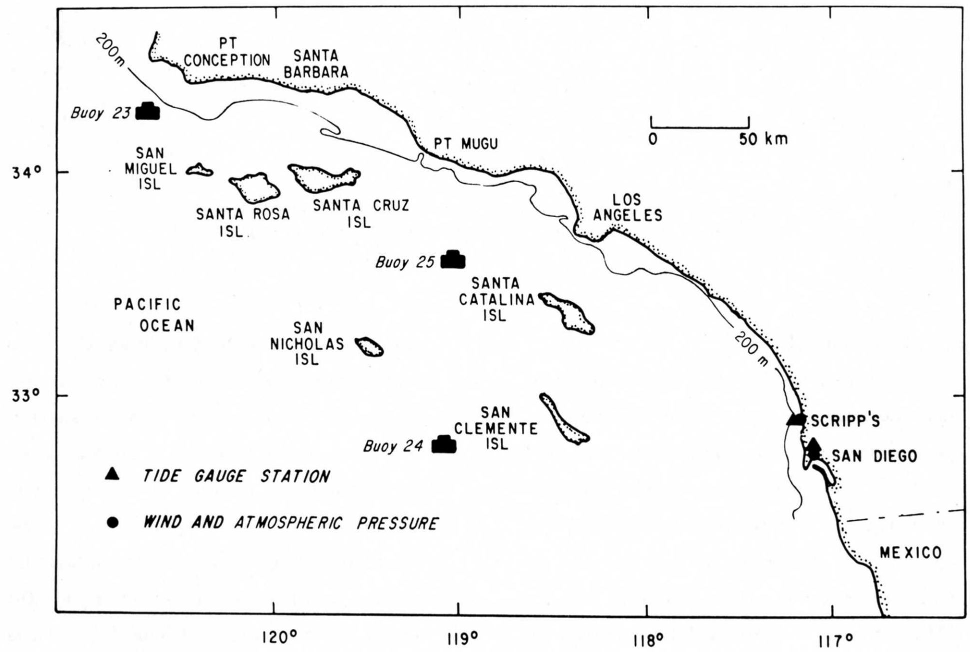

Fig. 1-1. Location map showing Southern California Bight and locations of data sources discussed in the text.

These predictions point out three interesting features of the California tide that are confirmed by observations (Flick and Cayan, 1984). First, the peak tides always occur in summer and winter, with lower extremes in spring and fall. Second, there is a distinct 4.4 year beating which raises the extremes about 15 cm, for example in 1982-83, 1986-87 and 1990-91, compared with years in between. Finally, the 18.6 year lunar node cycle causes enhancement of tides, for example in 1986-90, by about 8 cm compared with 9 years later.

The coincidence of storm induced sea level changes and high astronomical tides is the dominant factor in determining the extent of coastal flooding in southern California. Figure 2-1 shows storm related sea level anomalies exceeding 30 cm in height

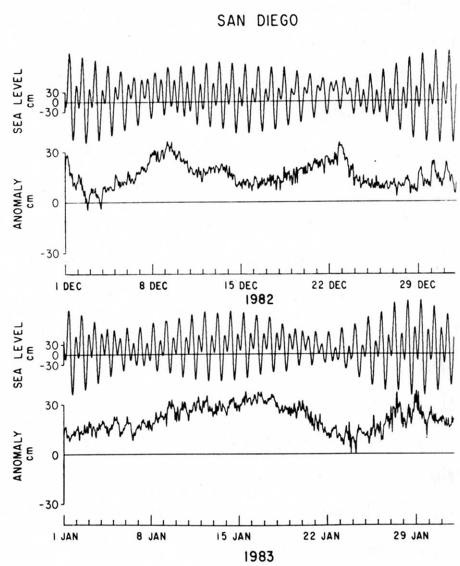

Fig. 2-1. Hourly measured sea level (upper trace) and anomaly (lower) for December 1982 and January 1983. Note episodes of large anomaly coinciding with neap tide in December, but occurring at spring tide at the end of January.

(7-9 December 1982, 8-20 and 27-29 January 1983). Higher tides but lower anomalies occurred during 29-30 December 1982. Serious flooding, erosion and wave damage to beaches, facilities and structures occurred during the late January 1983 episode of peak spring-tropic tides and severe sea level anomalies. Approximately half, or 15 cm of the anomaly was attributable to long-term interannual effects discussed in Section 4, while the remainder could be attributed to atmospheric forcing described in Section 5.

3. SECULAR TRENDS

Much recent attention has been focused on long-term, secular trends in sea level because of increased awareness and concern over the "greenhouse effect." In general, tide gauge records in California show a secular rise in relative sea level comparable or slightly larger than the global "average" of 15 cm/century over the past 80-100 years. The cumulative effect of this slow rise is beginning to be felt on this shore (Figure 3-1) where massive coastal development has accelerated in the past 40 years since World War II (Cayan and Flick, 1985).

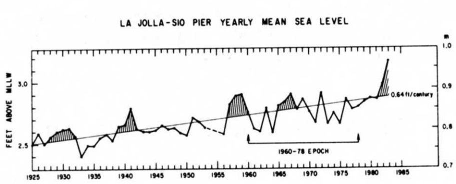

Fig. 3-1. Illustration of secular trend of sea level increase at La Jolla. Slow increase over long periods has a cumulative detrimental effect on coastal improvements. Episodic high water events (shaded) are associated with large-scale El Niño effects.

The importance of the problem of extracting a global trend, if it exists, from regional patterns and the "noise" demands highly sophisticated analysis procedures. Aubrey and Emery (1983) and Barnett (1983, 1984) have used modern normal mode methods to more objectively separate spacial and temporal patterns. However, fundamental problems (such as poor spacial coverage and short records) remain with the tide gauge data. This emphasizes the need for better understanding of the meteorological and oceanographic processes that contribute to the noise.

4. LARGE-SCALE EVENTS

Large, Pacific Ocean scale meteorological and oceanographic events have been shown to be strongly correlated with anomalous sea levels along the west coast of North America (Wyrtki, 1985; Emery and Hamilton, 1985; Chelton and Davis, 1982; Reid and Mantyla, 1976 to cite only a few of the most recent references). In particular, the basin-wide, tropical El Niño-Southern Oscillation (ENSO) phenomena much more often than not are associated with elevated coastal sea levels in California on time scales of months to years (Simpson, 1984; Cayan and Flick, 1985).

Figure 4-1 shows monthly average sea level plotted for data from La Jolla-SIO Pier (Figure 1-1). The curves for 1982-83 show that the 1960-78 mean elevation was exceeded by an average 15 cm beginning in late 1982 through 1983. The exceedence was on the order of 3 standard deviations (shown in the figure with vertical bars). Sea level did not return to normal until late 1984 (not shown) consistent with the long

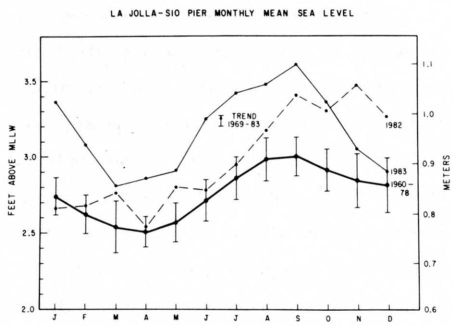

Fig. 4-1. Monthly average sea level at La Jolla shows large departure during 1982-83 El Niño compared with 1960-78 mean value (dark).

time required for readjustment observed in the entire Pacific (Wyrtki, 1985).

Several causes of the anomalous mean sea level have been suggested: poleward propagating long, coastally trapped Kelvin waves (see Chelton and Davis, 1982 for references); advection of warm water onshore due to changing wind patterns (Simpson, 1983, 1984) and direct meteorological effects such as lower than normal barometric pressure and anomalous wind (Namias, 1976; Cayan and Flick, 1985).

Observations of surface and subsurface oceanic temperatures strongly suggest that steric height changes contributed to anomalous sea levels during the 1982-83 winter (Simpson, 1983, 1984). Figure 4-2 shows monthly anomalous sea surface temperature for 1982 and 1983 relative to the 1927-1983 mean. Simpson (1983, 1984) shows that subsurface anomalous warming greatly exceeded even the surface warming, and along with depression of the thermocline, the upper 250 m of the coastal ocean were an average of about 2 ° C warmer than long-term normal. This is consistent with a steric height increase of about 10 cm. An additional increase in sea level is associated with the large negative atmospheric pressure anomalies (relative to 1948-83 means) shown in Figure 4-3, particularly in late 1982 and early 1983.

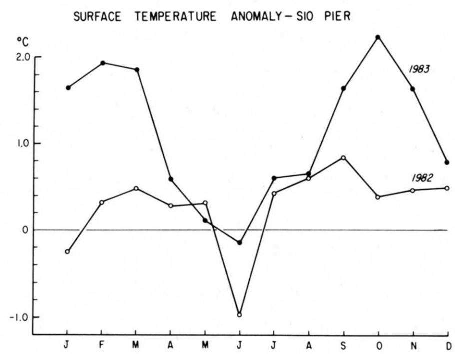

Fig. 4-2. Monthly average surface temperature anomaly 1982-83 relative to 1927-83 long-term mean at La Jolla, SIO pier.

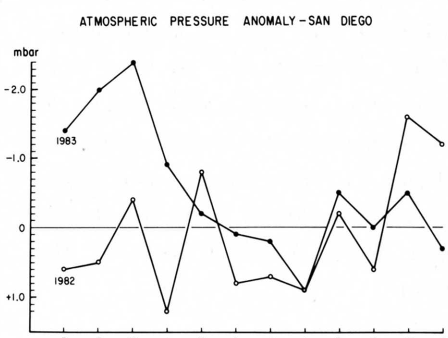

Fig. 4-3. Monthly average barometric pressure anomaly 1982-83 relative to 1948-83 mean values at San Diego.

5. REGIONAL ATMOSPHERIC FORCING

For coastal engineering purposes it is highly desirable to have a direct, predictive relationship between coastal sea level response and the atmospheric forcing variables. This could be viewed as a statement of the storm surge problem. Unfortunately,

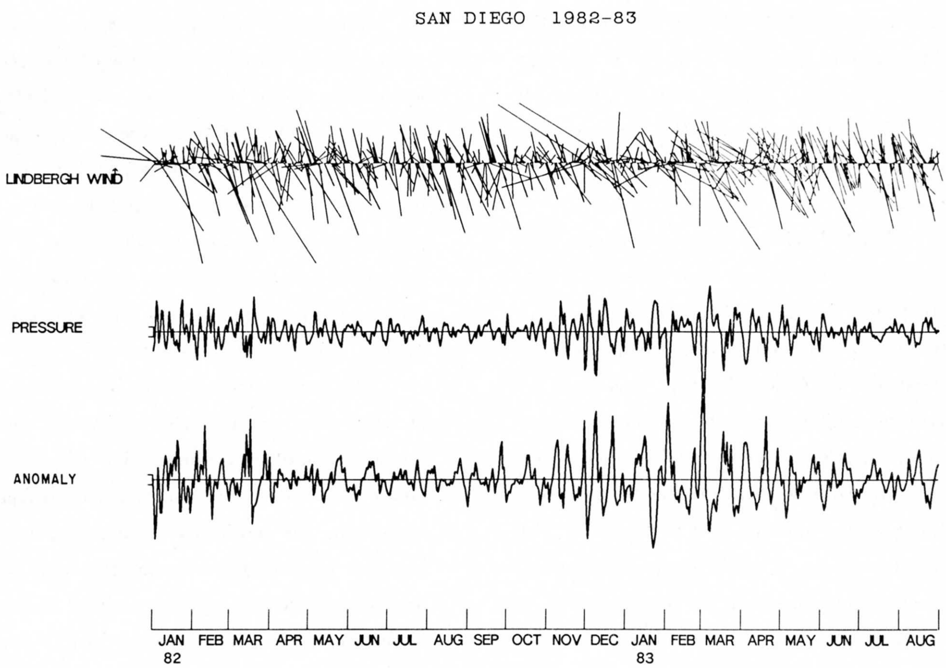

Fig. 5-1. Time series of daily wind vector (upper), atmospheric pressure (middle) and sea level anomaly (bottom). Wind direction follows compass heading, i.e., sticks from upper left indicate wind from north-west. Maximum length sticks indicate speed about 15 m/sec. Ticks on pressure and anomaly axis show ± 1 mbar and cm, respectively.

the relationship between coastal sea level fluctuations and the atmospheric forcing by pressure and wind in the band between seasonal and inertial/tidal frequencies is very complex.

Figure 2-1 shows that moderate to large sea level anomalies occur during storm periods on the southern California coast and have time scales of 3 days (7-9 December 1982) to 12 days (8-20 January 1983). A detailed investigation of these fluctuations has recently begun using long time series of observations available from southern California coastal tide stations, weather stations and offshore buoys (Figure 1-1). Correlation, spectral and multiple linear regression analysis methods are being applied to the data in an attempt to quantitatively relate the variability in sea level to the atmospheric driving in the 2-30 day period band (Flick and O'Reilly, 1985).

Notwithstanding the complexities, many investigators have attempted development of both statistical and dynamical relationships of sea level and atmospheric forcing (Noble and Butman, 1979; Groves and Hannan, 1968; Wunsch, 1972; Palumbo and Mazzarella, 1982; Garrett and Toulany, 1981, 1982; Garrett and Petrie, 1981). The present investigation seeks to apply similar, advanced methods to the southern California data set.

Hourly tide gauge data is available in digital form from San Diego Bay since 1950 and from La Jolla (SIO pier) since 1955. Atmospheric pressure and wind velocity data from San Diego's Lindbergh Field are available digitized since 1948. Long periods of hourly and 3-hourly sampled data alternate.

Tidal fluctuations were substantially removed from the sea level records by subtracting a standard 27-component harmonic prediction based on tidal constituents calculated directly from the data. Residual tidal noise and all other higher frequency signals in the sea level and atmospheric data were removed by digitally filtering to pass only the 2-30 day band (0.0333 to 0.5 cpd). This (arbitrary) band was chosen to eliminate seasonal changes and to avoid inevitable contamination by tidal residuals at 1 cpd and higher. Spectra of unfiltered signals revealed no substantial fluctuations other than harmonics of 1 cpd up to 5 cpd. Filtered signals were decimated to 1 sample per day, and the 608-day time period 1 January 1982 to 31 August 1983 separated for further study (Figure 5-1). A shorter time series (304 days) of atmospheric variables from NOAA Buoy #46024, designated "Buoy 24" in Figure 1-1, were also examined, as well as 180 days of data starting on 1 November 1982 from La Jolla.

Inspection of the time series shown in Figure 5-1 shows large fluctuations of sea level anomaly during the November 1982 to April 1983 winter. Peak values range up to 20 cm. Storms occurred an average of about 3 times per month with peak wind speeds on the order of 15 m/s, atmospheric pressure anomalies over -10 mbars and usual durations of 3-5 days (Cayan and Flick, 1985).

Correlation and spectral analysis suggests that the primary response of sea level anomaly is to the barometric pressure in the 2-30 day band. Simple cross-correlation functions have been computed between anomaly, a, and pressure, p, and both components of wind, v and u, where v denotes the north-south component positive from the south, and u denotes the east-west component, positive to the east.

The correlation ap peaks at about -0.8 at zero lag, qualitatively consistent with inverse barometer response. The regression factor is found to be about -1.2 cm/mbar, suggesting an additional minor sea level response to forcing itself coherent with the pressure, or some shelf wave activity leading to increased response due to weak resonances.

The av correlation peaks at about +0.35 with wind leading sea level by less than 1 day. Positive anomalies are associated with south wind, qualitatively consistent with cross-shelf geostrophic balance. The au correlation is relatively weak.

Multiple linear regression analysis of the (hourly) La Jolla winter data shows that over 60% of the variance in sea level anomaly can be related to pressure and wind with significant skill. A "predicted" anomaly can be written in the form

$$\hat{a}(t) = \alpha p(t) + \beta u(t) + \delta v(t-18)$$

where α,β,δ are regression coefficients, and t is time in hours. The resulting correlations $\hat{a}p$ = -0.9, $\hat{a}u$ = 0.2 and $\hat{a}v$ = 0.5 suggest that pressure is the primary agent, followed by longshore wind and finally on-offshore wind. It is common for longshore winds to be more effective than on-offshore winds at

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