CHAPTER SIXTY

EXTREME SEA LEVELS ON THE COAST OF CALIFORNIA

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1. INTRODUCTION

During the winter of 1982-1983, a combination of high tides, higher than normal sea level and storm-induced waves were devastating to the coast of California. Damage estimates for public and private property destruction in the coastal counties of California total over $100,000,000.

Much higher than average sea levels played a very important contributory role in the flooding damage. This report describes and examines the oceanographic and meteorological conditions prevailing during winter 1982-1983, and attempts to put them into perspective using historical information at San Diego. Emphasis is placed on the processes and forces that contribute to extreme sea levels in the hope that better understanding of these and more complete information on historical extremes will help the engineer in design and in assessment of risk.

The unusually high sea levels were due to a combination of higher than normal mixed layer temperature associated with a strong, 2-year El Nino, storm surge due to low atmospheric pressure and persistent onshore winds, and the cumulative effect of steady, "global" rise in relative sea level. Higher than average high tides coincided to an unusual extent with the peak sea levels reached during the numerous storms between November 1982 and March 1983. Important cyclical variations occur in California's tide regime and the consequences of these on extreme tides have not been considered previously.

2. ASTRONOMICAL TIDES

During the time of the winter 1982-1983 storms, newspaper accounts of the damage referred to predictions of much higher astronomical tides in the early part of the next decade and led to increased public concern as to the future safety of many coastal structures. These concerns are unfounded since studies have shown that there are crucial differences in the California tide regime compared with those that were used as the basis for the alarming forecasts (Zetler and Flick, 1985).

Tides along the coast of California are of the "mixed" type meaning that the diurnal constituents are of the same order of magnitude as the semidiurnal components. This is crucial for explaining the

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nature of the extreme ranges of tides. Different criteria determine the time of occurrence of maximum mixed tides as opposed to semidiurnal tides, which dominate, for example, the east coast of the U.S.

"Spring tides" are large semidiurnal tides that occur twice each month around the time of full and new moon. Spring tides tend to be larger than average twice each year during the equinoxes, that is, during the spring and autumn seasons. In contrast, "tropic tides" are large diurnal tides that also occur twice each month, but around the times of maximum lunar declination. Solar declination has a similar influence, and as a consequence, the tropic tides occurring in winter and summer (during maximum solar declination) are larger than average. In addition, the earth's yearly closest approach to the sun (perihelion) occurs during the northern hemisphere winter, thus increasing yet further the magnitude of the tropic tides that occur around December and January.

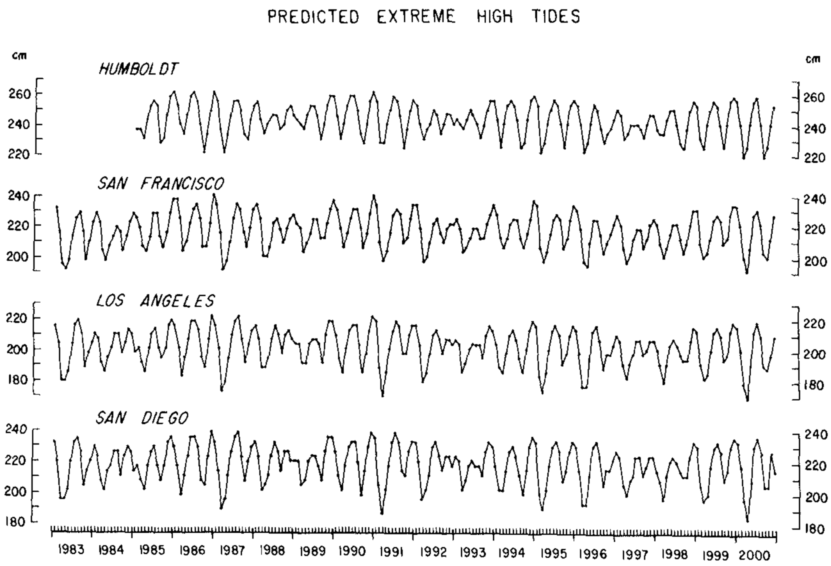

Figure 1. Predicted extreme high astronomical tide for four California ports through 2000. The extremes are dominated by the mixed tidal regime (Zetler and Flick, 1985).

Because of the complexities in the mixed tide regimes, the best way of forecasting times and heights of extreme tides is to prepare standard harmonic predictions and extract the desired extremes for tabulation. This has been done for the monthly extreme high tides at four California ports through the year 2000, and is shown in Figure 1 (from Zetler and Flick, 1985). The details of the interactions governing the variability of extreme predicted tides as well as tables of data corresponding to Figure 1 are given in Zetler and Flick (1985) and Zetler and Flick (in prep).

The effect of tropic tides dominates the extremes so that maximum tides occur in summer and winter. This maximizes the likelihood of coincidence of high tide levels with storm-induced sea level extremes. A second feature evident in Figure 1 is the regular 4.4 year beat which raises high tides about 0.5 foot every 4.4 years compared with times in between. This cycle peaked in 1982-1983 and contributed to the high levels observed.

3. MEAN SEA LEVEL

Recent studies of global mean sea level rise indicate a most probable value of about 0.5 foot/century (Hicks et al, 1983; Aubrey and Emery, 1983; Barnett, 1983; and many others). These estimates have a great deal of uncertainty and variability depending on how the analysis is done and due to a large number of other factors: errors in measurement, poor spacial distribution of stations around the world, wide variations in record length, wide variability of ground motions relative to sea level, etc.

Yearly mean values are likely contaminated very little by tidal errors and are very useful for displaying secular trends and longer term departures from the trends. Figure 2 shows annual average sea level at San Diego relative to MLLW computed over the 1960-1978 epoch, also shown in the figure. The light line is a least squares fit to all the data points and indicates an upward trend of 0.7 foot/century between 1906-1983. This is comparable to the global rate of rise and is typical of all long-term California stations, except for a few where

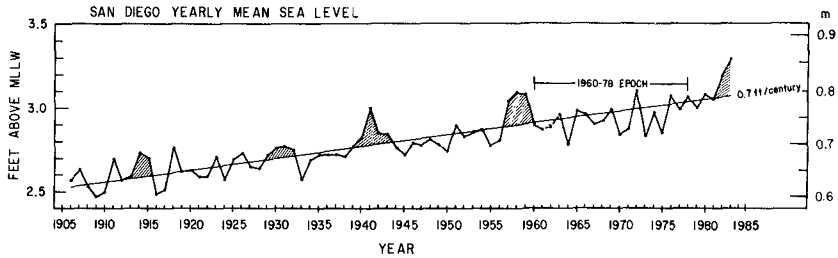

Figure 2. Secular increase in relative sea level at San Diego is close to global "average" of around 0.5 foot/century. Large positive departures are associated with major El Nino events.

local uplift or subsidence effects dominate the relative sea level signal.

Extreme estimates of rapidly accelerating rise in future mean sea levels have been published, and expressed as a mean rate, range as high as 10 feet/century to the year 2100 (Hoffman, 1983). These estimates depend upon a widely varying range of assumptions, or "scenarios," involving global warming and subsequent ice cap retreat and thermal expansion of the oceans. In our opinion, it is very difficult to know how much weight to assign to such extreme predictions and therefore how much to allow for them in design. On the other hand, it seems prudent to allow for at least the current rise of between 0.6-0.7 foot/century over the life of any particular planned coastal improvement.

Another feature of annual mean sea levels displayed in Figure 2 are the episodic (2-4 year) positive departures from the linear trend. These are shown shaded and are very pronounced in 1914, 1930-1931, 1941, 1957-1959 and 1982-1983, comprising 5 episodes in about 70 years of record. All these periods coincide with or are near in time to strong El Nino events. While there is no ability to forecast the year of onset, duration, and intensity of future El Nino occurrences, the historical record suggests that for engineering purposes, it would be sensible to design for the prolonged high sea level stands that occur during major episodes. The data in Figure 2 suggests these major events have an average return period of 14 years with departures from the trend on the order of 0.2 foot for durations of 2-3 years.

Seasonal variations in mean sea level are often displayed using monthly mean sea levels. The extremely unusual and persistent sea level heights reached during the 1982-1983 El Nino off San Diego are illustrated in Figure 3. The solid line shows the "average" seasonal cycle of sea level computed over the 19-year tidal epoch from 1960-1978. The light vertical bars around each average monthly data point show +/-1 standard deviation, indicating the typical variability of the fluctuations. The amplitude of the seasonal cycle is about 0.5 foot, with a variability of about 0.1-0.2 foot. This seasonal sea level cycle in San Diego is clearly related to seasonal heating and cooling of the ocean (Reid and Mantyla, 1976). On average, the water temperature is coolest in spring, leading to lower levels, and warmest in autumn, leading to higher levels. The light dashed line in Figure 3 shows the monthly averages for 1982. Until about July, observed sea level was close to normal, but by fall and early winter it exceeded the 1960-1978 average by up to 0.5 foot, or about 3 standard deviations. This condition persisted through 1983, illustrated in Figure 3 with the light solid line. Sea level finally returned to near normal in December 1983. The small vertical arrow labelled "trend" shows the increase in yearly mean sea level between 1969 (middle of the 1960-1978 epoch) and 1983. The magnitude of this increase is 0.1-0.2 foot or about 0.5 of a typical standard deviation. This shows that the unusually large deviations in 1982-1983 from the 1960-1978 mean were only due in small part to the cumulative secular increase.

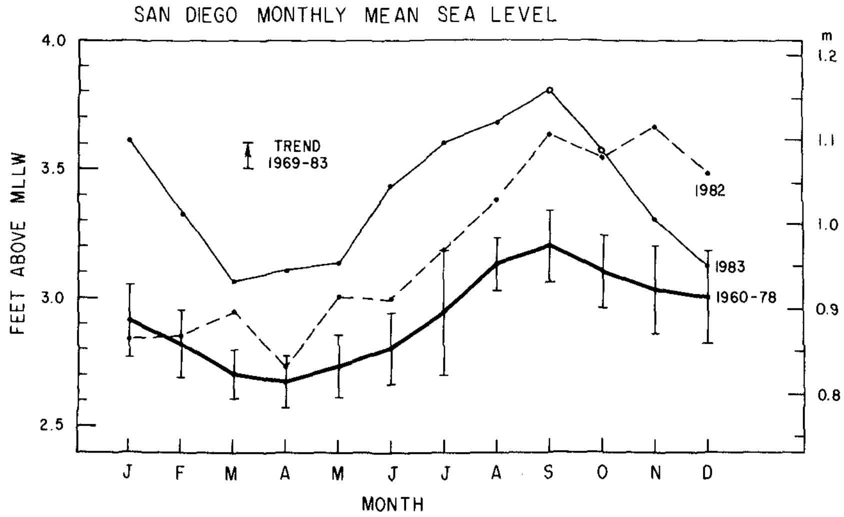

Figure 3. Seasonal cycle of sea level at San Diego associated with cooling in spring and warming in autumn. Curves for 1982 and 1983 show large departure from 1960-1978 average.

4. METEOROLOGICAL INFLUENCES

The winter of 1982-1983, now commonly known as "El Nino Winter," was in many repsects the most severe storm season in several decades along the North American Pacific Coast (Quiroz, 1983). The unusually active North Pacific storm conditions were associated with anomalously warm water in the eastern tropical Pacific that had its beginnings in the Summer of 1982 and by northern Winter, 1982-1983, had developed into the most intense such warmings of any within about a century of quantitatively recorded data.

Winter atmospheric conditions during El Nino events show a tendency for anomalously low barometric pressure in the region south of the Aleutian Islands, extending into the Gulf of Alaska, and higher than normal pressure in the North Pacific subtropics (Namias, 1976; Dickson and Livezey, 1984). This pressure distribution is associated with heightened storm activity across the central North Pacific. However, the pattern is not clear-cut along the West Coast: in some winters the storms take a northward course into British Columbia and Alaska, while in others they take a southward trajectory into Oregon and California (Namias and Cayan, 1984). As a measure of this activity during the winter of 1982-1983, the average westerly winds across the North Pacific subtropics were almost twice their normal speed. The high winds and long fetch produced by these conditions during 1982-1983, caused the unusually long and high waves that pounded the California coastline (Seymour et al, 1984). The influence of atmospheric pressure and high winds during the winter 1982-1983 season on sea level is illustrated in Figure 4. The upper curve shows daily maximum observed sea level with each monthly maximum, shown circled. The second curve shows the anomaly, or the difference between the observed daily maximum and the predicted highest tide each day. This curve is very close to the daily mean sea level (curve 3) implying that the exceedence over the predicted tide is more or less constant over time scales of 1 day. The dashed line under the daily mean sea level shows the long-term (1960-1978) monthly mean sea levels and illustrates the approximate 0.5 foot excess due to the large-scale El Nino condition.

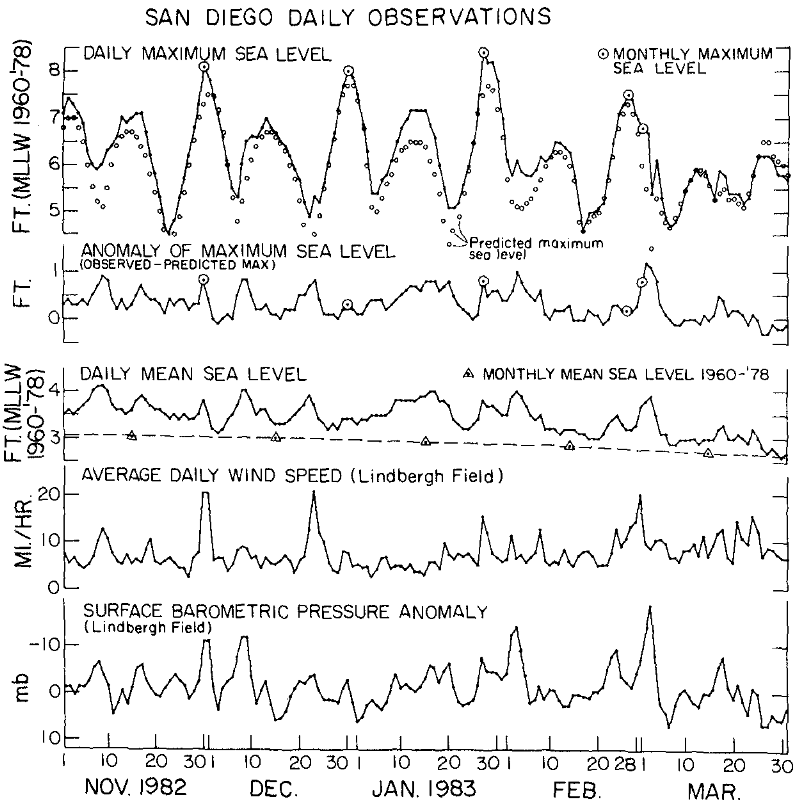

Figure 4. Daily observations at San Diego during winter 1982-1983. Storm episodes are marked with increased wind speed and anomalously low barometric pressure (bottom two curves).

The lowest 2 curves in Figure 4 show average daily wind speed and surface barometric pressure anomaly at San Diego. The storm episodes stand out clearly (9-10, 16-19, 29-30 Nov; 7-9, 22-23, 29 Dec; 17-19, 27-29 Jan; 2-4, 7-8, 24-27 Feb; 1-5, 17-18, 21-24 Mar) and these are highly correlated with the sea level anomalies. In general, the direct influence of lowered atmospheric pressure in the winter's storm events through the inverse barometer effect contributed about 1/3 of the observed anomalies of sea level. The average of surface pressure anomalies during the storms is in the range of 7-10 mb, with a maximum of 18 mb below normal on 3 March 1983.

Maximum winds recorded at San Diego during this time period were 39 mph on 1 December 1982. The wind direction (not shown) associated with high sea level anomalies varies from one event to the next. High sea level events were found under conditions of east, south, southwest and northwest wind. The largest anomalies (2-3 Mar 1983) occurred under southerly winds at San Diego. It is not known how open ocean wind conditions may differ from those measured at San Diego's Lindbergh Field.

In the five month winter 1982-1983 period shown, three of the five monthly high predicted tides (30 November 1982, 27 January 1983, and 1 March 1983) were coincident with unusually large anomalous daily average sea level (0.8, 0.7, 0.9, respectively). For any given month, with about 6 days of large sea level anomalies and only about 3 days of near monthly maximum predicted tide, the probability of these coinciding (assuming the two phenomena are independent) is about 6/30 x 3/30 = 1/50. The fact that this coincidence was realized in 3 out of 5 chances between November and March is even more unusual, and illustrates the extraordinary nature of this winter. This suggests a very small likelihood that such a concentrated run of severe winter months having high tides amplified by large non-tidal anomalies will recur with great frequency, even given sympathetic large-scale conditions.

5. MONTHLY EXTREME SEA LEVELS

Many published studies describe changes in mean sea level and their possible causes, but very few have concentrated on the extremes of sea level (Disney, 1955; Smith and Leffler, 1980). From an engineering viewpoint, the rationale behind such investigation is simple: the extreme sea level dictates design since it is what floods property and causes damage. Monthly sea level extreme values are routinely tabulated as one of the products of the National Ocean Service, NOAA. Plots have been prepared (Figures 5, 6, 7) each showing (at San Diego) observed monthly extreme sea level, maximum predicted tide on the date of the observed extreme, and two versions of the anomaly defined as the difference between the observed level and predicted tide. Movement of the tide station, installed in 1906, and other complications causes the analysis of the anomalies to be limited to the period 1940-1983.

The highest value of sea level recorded at San Diego is 8.35 feet above MLLW on 27 January 1983. The largest contribution to this level was from the extreme tide (7.6 feet) with the remainder due to the processes discussed above. Analysis in this study was limited to the statistics of the monthly anomalies at the time of maximum monthly sea level. In this sense, the statistics should not be expected to follow extreme value form since they are not the extremes drawn from the population of all (hourly or daily, say) exceedence values. Instead, they form a conditional sample from this population, the condition being that the total sea level be the monthly maximum.

The two versions of the anomaly plotted in Figures 5, 6, 7 are the "raw" anomaly, which is simply the difference between the observed sea level and the tide, and the "adjusted" anomaly which was corrected for a linear fit to the trend in sea level (shown in Figure 2). The raw anomaly figures show a secular increase which reflects the trend in the observed monthly extremes and the fact that the tide predictions do not include any trend. In effect, the "adjusted" anomalies represent the exceedence of the maximum sea level over the tide and the secular trend. To derive statistical estimates of future absolute

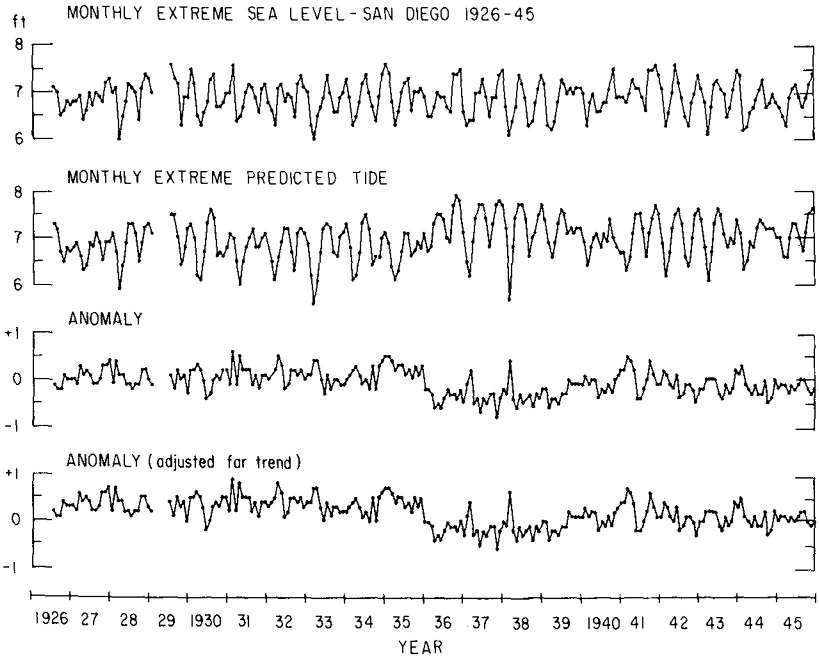

Figure 5. Monthly extreme sea level at San Diego 1926-1945 showing predicted tide on day of observed monthly maximum. Anomaly is difference between observed and predicted. Lower trace is anomaly adjusted for secular trend shown in Figure 2.

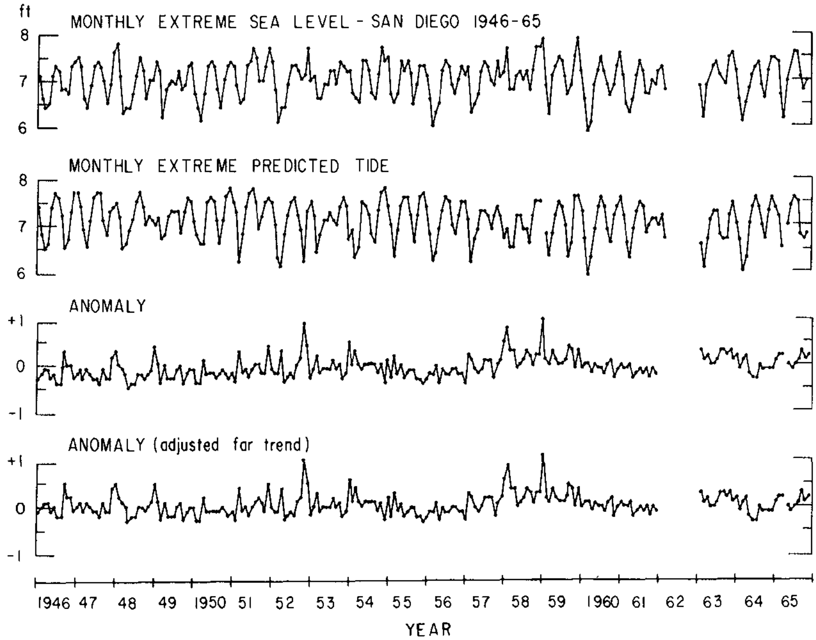

Figure 6. Monthly extreme sea level at San Diego 1946-1965. See Figure 5.

sea level heights, the estimate of exceedence must be added to the tide prediction plus an estimate of the increase due to the trend in mean sea level.

Several statistical analyses of the adjusted anomaly data have been carried out. First, Figure 8 shows the median anomaly as a function of month of year for the period 1940-1983. There is a clear seasonal variation with larger than normal anomalies in December through April, with median values around 0.1 to 0.15 foot. During the summer and in October and November, the median of the highest monthly sea levels are very close to the predicted tides with median anomalies not significantly different from zero. In September, there is a significant peak, with median anomalies over 0.1 foot higher than predicted tides at maximum sea level. This is apparently attributable to extra-tropical low pressure systems that are frequently observed west of San Diego in September. These systems cause depressions in atmospheric pressure of about 5-10 millibars compared with seasonal normals, roughly accounting for the magnitude of the anomalies.

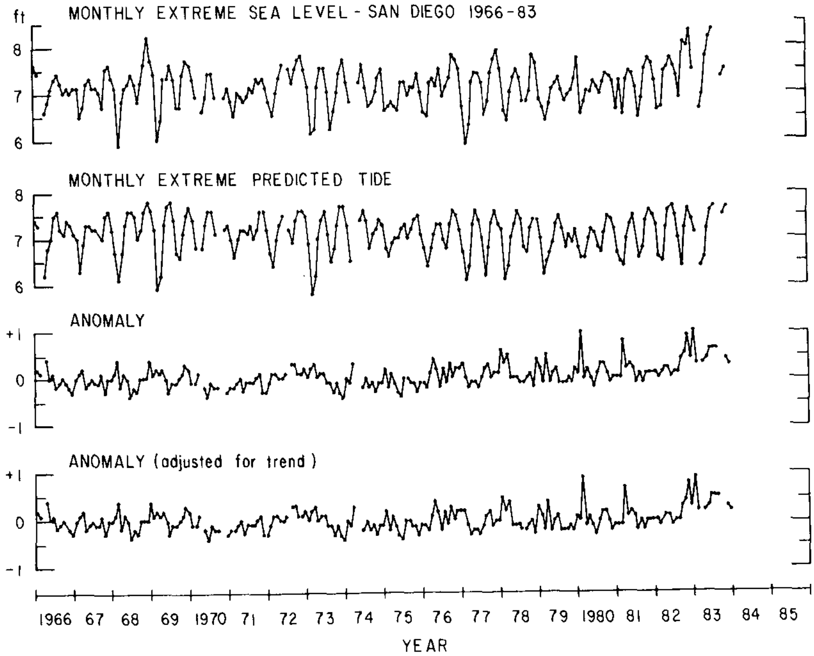

Figure 7. Monthly extreme sea level at San Diego 1966-1983. See Figure 5.

A return period statistic has been computed, and the results are shown in Table 1. The return period of any particular anomaly size can be defined as T where T = R/N, and R is the record length in months and N is the number of occurrences of that size in the record. Table 1 shows that the return period for 0.3 foot anomalies is about 20 months, or just under 2 years. Anomalies of 0.5 foot occur on average about every 50 months (4 years). The longer interval, larger anomalies have not recurred often enough to derive stable statistics, and not too much faith should be put in their return period. On the other hand, anomalies on the order of 1 foot are certainly possible, since they have been observed at San Diego, and at other stations on the California coast.

An added complication in the recurrence of the largest anomalies exists because their occurrence is not independent. Examination of the dates of occurrence of the 12 largest adjusted anomalies (greater than or equal to 0.6 foot) shows that 3 groups, containing 9 events cluster together (March, April and October 1941; January, February 1958, January 1959; and November 1982, January 1983). This is consistent with the observations that a large portion of the exceedence is related to the sympathetic, large-scale and persistent El Nino conditions.

Table 1

San Diego Sea Level Anomalies, 1940-1983

Adjusted Anomaly (ft)	Number of Occurrences	Return Period (mo.)
-0.4	4	132.0
-0.3	32	16.5
-0.2	58	9.1
-0.1	100	5.3
0.0	103	5.1
0.1	99	5.3
0.2	59	8.9
0.3	28	18.9
0.4	22	24.0
0.5	11	48.0
0.6	4	132.0
0.7	2	264.0
0.8	1	528.0
0.9	3	176.0
1.0	1	528.0
1.1	1	528.0

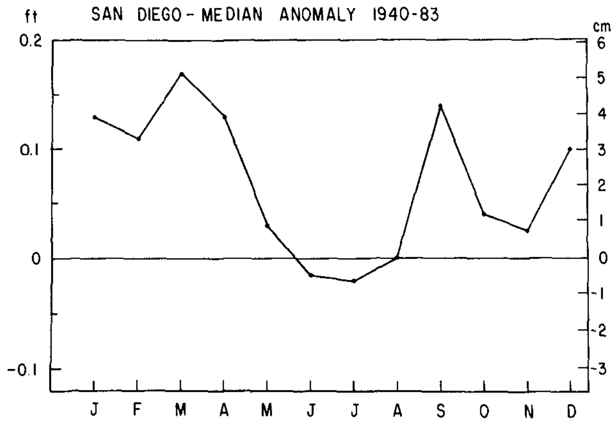

Figure 8. Median adjusted anomaly statistics, San Diego 1940-1983. Peak in September is associated with extra-tropical low pressure systems.

6. CONCLUSIONS

This investigation confirms the unusual nature of the 1982-1983 winter. Although individual months with relatively high sea level anomalies can be isolated, and some years exist with clusters of such anomalies, the concentrated run of extreme events that occurred in 1982-1983 is virtually unprecedented in the California sea level record. That is not to say that winters such as 1982-1983 won't happen again, but such recurrence should be quite rare.

Unusually high tides coincided with storm events to cause coastal flooding. The mixed tide regime in California predictably causes peak tides in summer and in winter. This maximizes the chances for such coincidences.

Sea levels in excess of predicted high tides during Winter 1982-1983 were the result of 1) large-scale meteorological and oceanic influences broadly known as "El Nino" that produced (among other effects) a tendency for anomalously high sea levels along the West Coast, probably contributing in the neighborhood of 0.1 to 0.4 foot in excess of normal. 2) Frequent vigorous North Pacific storms affected hundreds of miles of the West Coast over durations of 1-4 days. These heightened sea level by lowering surface barometric pressure via the "inverse barometer effect" (as much as 0.6 foot, but usually about 0.2 to 0.3 foot), and strong winds that piled up coastal waters.

ACKNOWLEDGEMENTS

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