

Influence of El Niño–Southern Oscillation (ENSO) events on the evolution of central California’s shoreline

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ABSTRACT

Significant sea-cliff erosion and storm damage occurred along the central coast of California during the 1982–1983 and 1997–1998 El Niño winters. This generated interest among scientists and land-use planners in how historic El Niño–Southern Oscillation (ENSO) winters have affected the coastal climate of central California. A relative ENSO intensity index based on oceanographic and meteorologic data defines the timing and magnitude of ENSO events over the past century. The index suggests that five higher intensity (relative values 4–6) and 17 lower intensity (relative values 1–3) ENSO events took place between 1910 and 1995. The ENSO intensity index correlates with fluctuations in the time series of cyclone activity, precipitation, detrended sea level, wave height, sea-surface temperature, and sea-level barometric pressure. Wave height, sea level, and precipitation, which are the primary external forcing parameters in sea-cliff erosion, increase nonlinearly with increasing relative ENSO event intensity. The number of storms that caused coastal erosion or storm damage and the historic occurrence of large-scale sea-cliff erosion along the central coast also increase nonlinearly with increasing relative event intensity. These correlations and the frequency distribution of relative ENSO event intensities indicate that moderate- to high-intensity ENSO events cause the most sea-cliff erosion and shoreline recession over the course of a century.

INTRODUCTION

California’s shoreline is characterized by coastal mountains, sea cliffs, and small pocket beaches. Sea-cliff erosion along the California coast is permanent and irreversible because eroded bluff material is lost to the littoral system during landward

migration of the sea cliff. In spite of the fact that there are hundreds of kilometers of rocky, cliffed coastline along central California and increasing pressure to develop the shoreline (Griggs, 1995), there are few studies focused on understanding the processes of sea-cliff erosion and the evolution of the coastline. This may be because it is difficult to evaluate the numerous variables that contribute to sea-cliff erosion (Shih and Komar, 1994). Sunamura (1992) identified two main categories: the factors inherent to the cliff material that resist erosion and the external forces that act to erode the sea cliff. The inherent properties include lithology, structure, intact rock strength, permeability, and porosity, as well as cliff height; attributes that tend to be relatively constant over short to intermediate time scales (Sunamura, 1992). The external forces include biologic and seismic activity, which can reduce the resistive forces of sea cliffs (Kuhn and Shepard, 1983; Griggs and Savoy, 1985; Plant and Griggs, 1990); however, fluctuations in the oceanographic and atmospheric climate occur more frequently and are therefore more important to the evolution of sea cliffs over short to intermediate time scales (Griggs and Johnson, 1979; Kuhn and Shepard, 1983; Sunamura, 1992).

Most coastal scientists who have studied the erosion of rocky coasts conclude that the majority of sea-cliff erosion occurs during infrequent, energetic storm events (Griggs and Johnson, 1979; Emery and Kuhn, 1980; Kuhn and Shepard, 1983; Sunamura, 1992; Shih and Komar, 1994). Two of the most recent storm seasons, during which substantial sea-cliff erosion occurred along central California, were the 1982–1983 and 1997–1998 winters (Griggs and Johnson, 1983; Storlazzi and Griggs, 1998; USGS/UCSC/NASA/NOAA Collaborative Research Group, 1998); both of the seasons coincided with severe El Niño–Southern Oscillation (ENSO) climatic anomalies. Even though the impact of ENSO events on productivity in Peruvian coastal waters has been documented for more than four centuries, there has not been a thorough investigation of how the

coastal climate of central California has historically been affected by these large-scale climatic fluctuations.

The goals of this project are to: (1) create a relative intensity ENSO event time series applicable to geomorphic studies along the coastline of central California for the time period from 1910 to 1995; (2) identify the influence of ENSO events on the external forcing parameters that cause sea-cliff erosion; (3) investigate the impact of ENSO events on coastal cliff erosion and storm damage along the shoreline of central California; (4) define what relationships exist between the magnitude of variation in the forcing parameters, the number of damaging coastal storms or occurrences of sea-cliff erosion, and the relative intensity of ENSO events; and (5) define what role ENSO events may play on the evolution of the central coast of California over short to intermediate time scales.

OVERVIEW OF ENSO EVENTS

ENSO events represent one of the two extreme states of the quasiperiodic fluctuation of the large-scale atmospheric circulation systems across the Pacific and Indian Oceans known as the Southern Oscillation. During non-ENSO times when the Darwin, Australia–Tahiti atmospheric pressure anomaly or Southern Oscillation is positive, a region of high atmospheric pressure dominates the eastern equatorial Pacific while the western equatorial Pacific is characterized by a region of low atmospheric pressure. This pressure difference drives the strong easterly equatorial and southeasterly trade winds commonly observed in the low latitudes of the Pacific. These winds, blowing offshore along the west coast of the Americas, cause deep, nutrient-rich, cold water to upwell in the eastern Pacific and push the warm equatorial surface waters westward. This warm water becomes superelevated in the western Pacific, creating an overall west to east downward slope of the sea surface and therefore a pressure gradient across the equatorial Pacific (Wyrtki, 1975).

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With the onset of an ENSO event, an approximate reversal occurs in the Southern Oscillation and in the large-scale atmospheric circulation patterns along the equatorial Pacific. This reversal is marked by the decay of the prevailing easterly winds and the concurrent development of a series of prolonged westerly wind events over the warm pool in the western Pacific. These winds perturb the upper ocean and excite the eastward propagation of large-scale waves in the thermocline that start to suppress the upwelling in the eastern Pacific (Deser and Wallace, 1987; Webster and Palmer, 1997). This reversal in wind direction also allows the potential energy of the sloping sea surface to be released, further inducing the warm waters to propagate eastward along the equator. This disturbance, similar to an equatorially trapped internal Kelvin wave, superelevates the local sea surface at the equator and moves across the Pacific as a wave-like bulge in sea level (Wyrtki, 1975). The Coriolis force not only confines this bulge to low latitudes but also retards its dissipation by expansion into higher latitudes (Komar, 1986). When the superelevated warm water bulge propagating eastward along the equator collides with South America, it splits into two portions that advance north and south to higher latitudes as coastally trapped internal Kelvin waves (Enfield and Allen, 1980). These two propagating shelf waves are pinned to the coast by the inclination of the shelf and slope, increasing sea level along the coastline while retarding dissipation to the opposing eastern boundary currents of the Pacific basin (Wyrtki, 1975; Komar, 1986). This eastward shift of the warm water bulge moves the center of organized cumulonimbus development, which is the principal mechanism for exchanging heat between the ocean's surface and the atmosphere, into the eastern Pacific. This causes atmospheric circulation, which is sensitive to shifts in organized cumulonimbus convection, to be perturbed (Climate Diagnostics Center, 1997).

Although the major vertical convection anomalies are confined to low latitudes, the effects on the circulation of mass and energy in the atmosphere extend to middle and high latitudes. During a typical non-ENSO winter, a region of high pressure is centered over the Gulf of Alaska and Aleutian Islands while southeastern Alaska and western Canada are dominated by a region of low pressure, driving the northwesterly winds and waves common along the west coast of North America (Griggs and Johnson, 1983; Dingler et al., 1985) as shown in Figure 1A. In strong ENSO winters, however, the region of high pressure advances eastward into north-central Canada and is replaced by a region of anomalously low pressure (Seymour et al., 1984; Climate Diagnostics Center, 1997). This causes the jet stream to intensify and split. One section tracks more eastward than dur-

ing non-ENSO time, while the other branch swings south over the Hawaiian Islands before propagating northeast across California (Fig. 1B). This diversion of the jet stream causes the trajectories of cyclones and interanticyclonic systems (fronts) to be redirected. These cyclonic and anticyclonic motions control the daily weather fluctuations at higher latitudes, and their diversion alters the origin, frequency, and strength of storms across the northern Pacific and western North America (Seymour et al., 1984; Climate Diagnostics Center, 1997).

STUDY AREA

This study focuses on the coastline of central California from Bodega Bay (~70 km north of San Francisco) in the north to Point Conception (~95 km south of San Luis Obispo) in the south. This 790 km section of shoreline is sparsely populated, except in the vicinity of San Francisco Bay and Monterey Bay. The coast is dominated by the Coastal Ranges, which are composed of Paleozoic metamorphic rocks, Mesozoic igneous rocks, and Cenozoic sedimentary rocks. These mountains are structurally controlled by the northwest-trending tectonics of the San Andreas fault system and are drained by a number of small, steep perennial streams and a few larger rivers, which are the primary sources of coarse-grained sediment to the littoral environment (Best and Griggs, 1991). The mouths of many of these streams were inundated during the Holocene transgression, forming low-gradient flood plains, coastal lagoons, and marshes in their lower reaches, many of which are backed by dune fields (Griggs and Savoy, 1985; Dingler et al., 1985).

The coastline of central California is characterized by steep, as much as 100 m high, actively eroding coastal bluffs often incised into uplifted marine terraces and commonly fronted by low, wave-cut shore platforms, or very small pocket beaches. These sea cliffs are interrupted at irregular intervals by larger pocket beaches that form at the mouths of coastal streams and by infrequent continuous beaches in sheltered bays. Sea-cliff erosion, with long-term rates ranging from 0 to >30 cm/yr, is episodic and locally variable (Griggs and Savoy, 1985). This erosion typically occurs during the infrequent combination of high tides and extreme storm waves (Griggs and Johnson, 1979).

The offshore wave climate can be characterized by three dominant modes: the Northern Hemisphere swell, the Southern Hemisphere swell, and local wind-driven seas. The Northern Hemisphere swell is typically generated by cyclones in the north Pacific off the Aleutian Islands during the winter months (November–March) and can attain deep-water wave heights exceeding 8 m (Na-

tional Marine Consultants, 1970). The Southern Hemisphere swell is generated by storms off New Zealand, Indonesia, or Central and South America during summer months and, although they generally produce smaller waves than the Northern Hemisphere swell, they often have very long periods (20+ s). The local swells typically develop rapidly when low-pressure systems track near central California in the winter months or when strong sea breezes are generated during the spring and summer (Griggs and Johnson, 1979; Dingler et al., 1985). Storms with deep-water wave heights in excess of 5 m occur five times a year on average (National Marine Consultants, 1970; Dingler et al., 1985).

TEMPORALLY VARIABLE CLIFF EROSION FACTORS

Waves

Wave energy, which is proportional to the square of wave height, is commonly regarded as a dominant physical process leading to coastal erosion and sea-cliff retreat along rocky coastlines (Sunamura, 1992; Shih and Komar, 1994; Griggs and Trenhaile, 1995). Hydraulic action, including compressional, shear, and tensional forces, is exerted on sea cliffs during wave impact (Barnes, 1956; Sunamura, 1977). When sediment or debris are available, waves can also exert mechanical action through abrasion and impact (Sunamura, 1992). Together, hydraulic and mechanical forcing may quarry the sea cliff by prying apart jointed rocks (Baker, 1958; Emery and Kuhn, 1980).

Large waves also facilitate coastal bluff erosion by removing protective beach sediment and allowing the waves to directly attack the cliff toe. This is done by increasing sediment suspension, set-up, and offshore flow as wave heights and periods increase (Holman and Sallenger, 1985). Increased set-up also elevates beach water-table levels, further facilitating beach erosion, as discussed in the next section. Griggs and Johnson (1983), Seymour et al. (1984), Seymour (1998), and Storlazzi and Griggs (1998) discussed the role that large waves may have played on the coastal erosion that occurred along California during the 1982–1983 and 1997–1998 intense ENSO events. Studies by Griggs and Johnson (1979) and Dingler et al. (1985) documented the role of wave action in coastal cliff erosion along central California over longer time periods.

Sea-Surface Elevation

Higher than normal sea-surface elevations played a major role in the damage and erosion that occurred during the 1982–1983 and 1997–1998 ENSO events (Griggs and Johnson, 1983;

Flick and Cayan, 1984; Komar, 1986; Flick, 1998; Storlazzi and Griggs, 1998). Abnormally high sea levels cause flooding in low-lying areas, elevate the level of wave attack relative to the cliff toe, and reduce the amount of wave energy lost to bottom friction during shoaling by increasing the relative water depth (Carter and Guy, 1988; Sunamura, 1992; Griggs and Trenhaile, 1995). Higher than normal sea levels also tend to elevate beach water tables, raising pore pressures and thus increasing sediment mobility, enhancing the beach's susceptibility to both subaerial and subaqueous erosion (Bryant, 1983; Clarke and Eliot, 1988; Mossa et al., 1992). This reduces the effectiveness of the beach as a buffer, and therefore makes the sea cliffs more vulnerable to direct wave attack.

Precipitation and Ground Water

Although most of the terrestrial sediment supplied to the coastline of central California is delivered by rivers and streams during large discharge events, high precipitation generally tends to enhance coastal erosion along cliffed shorelines. Precipitation and runoff tend to elevate the local sea surface in lagoons and estuaries while eroding beaches backed by lagoons or sloughs as the swollen coastal streams breach their barrier spits. The large volume of sediment and debris supplied to the surf zone by the steep streams that drain the Coast Ranges may accelerate sea-cliff erosion through abrasion and impact forces (Griggs and Johnson, 1983; USGS/UCSC/NASA/NOAA Collaborative Research Group, 1998). Episodes of heavy precipitation also tend to raise the ground-water levels of coastal bluffs, increasing their loading and pore-fluid pressures. Increased piezometric pressures along joint surfaces reduce the frictional resistance and effective normal stresses in the bluff material; in conjunction with the increased weight of the bluff due to saturation, this may initiate slope failure (Turner, 1981; Griggs and Johnson, 1983; Kuhn and Shepard, 1983). In addition, ground water can promote the weathering and solution of cementing material, altering the cohesive and frictional properties of the material, thus reducing the strength of the sea cliff (Griggs and Johnson, 1979; Turner, 1981).

DATA ANALYSIS AND RESULTS

Historical Record of ENSO Events

During the past 20 yr, our understanding of the driving mechanisms behind and precursors of ENSO events has made significant progress. By examining the occurrence of diverse biologic, atmospheric, terrestrial, and oceanographic phenomena from South America, Quinn et al. (1987) developed a history of ENSO events and their rel-

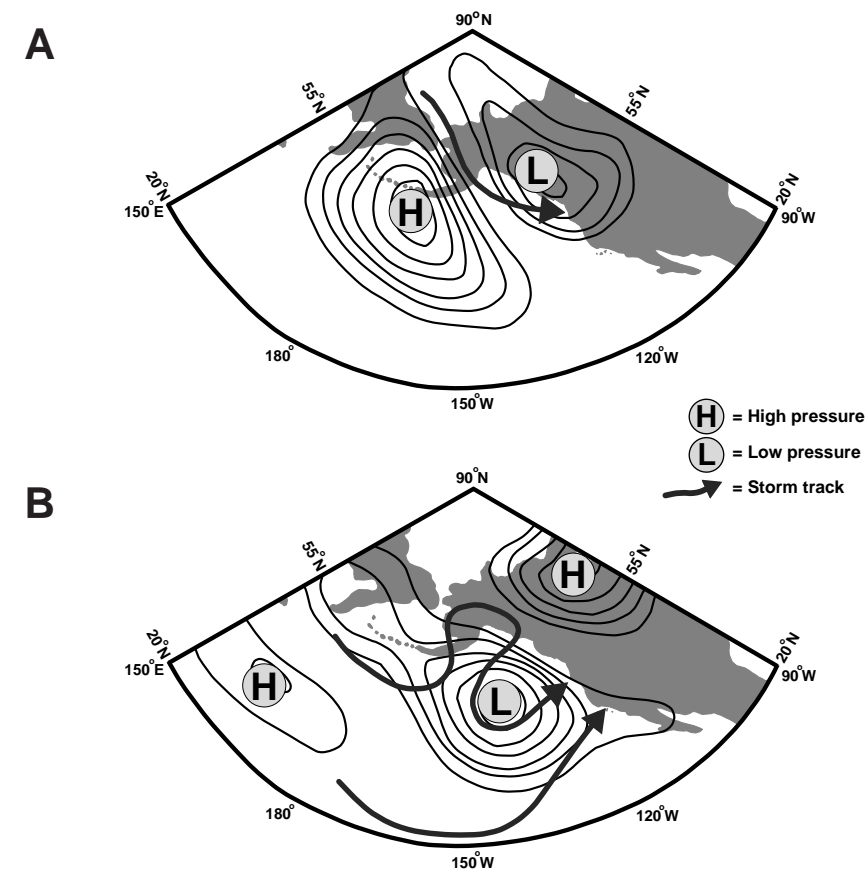


Figure 1. Location of high and low barometric pressure regions in the northern Pacific and North America along with general storm tracks during (A) a typical non-ENSO or La Niña winter, and (B) an intense ENSO winter. Modified after Seymour et al. (1984) and the Climate Diagnostics Center (1997).

ative intensities back to the 1500s. More recently, higher resolution indices using more definitive but shorter records have been developed. Deser and Wallace (1987) and the National Climate Data Center (1997) compiled records of sea-surface temperature anomalies from offshore Puerto Chicama, Peru, and southern California, respectively. A Southern Oscillation index derived from sea-level barometric pressure anomalies at Darwin, Australia, and Tahiti has been generated by the Pacific ENSO Applications Center (1997), and Wolter and Timlin (1997) devised a multivariate index derived from sea-surface temperature, wind stress, barometric pressure, and outgoing long-wave radiation anomalies. Due to the different parameters, locations, and methods utilized by the various researchers, there are some minor discrepancies in the occurrence, timing, and magnitudes of ENSO events during the past nine decades (Fig. 3).

The comprehensive data set of Quinn et al. (1987) incorporated a number of parameters (e.g., storms, flooding, sea-level changes), and because they rated the intensity of each ENSO

event in terms of the occurrence or fluctuation in these parameters, their classification was utilized as the foundation of our ENSO intensity index. Because Quinn et al. (1987) did not evaluate the relative intensity during non-ENSO and La Niña times, the ENSO intensities during these periods were determined by evaluating the fluctuations in the standardized Deser and Wallace (1987), National Climate Data Center (1997), Pacific ENSO Applications Center (1997), and Wolter and Timlin (1997) data sets relative to the Quinn et al. (1987) series.

Owing to the higher resolution and precision of the newer data sets, the relative intensities suggested by Quinn et al. (1987) were modified for a number of ENSO events. The standardized time series were scaled to the maximum relative Quinn et al. (1987) index value, and the geometric mean of these rescaled indices and the Quinn et al. values was computed to develop our modified relative ENSO intensity index. Of note is the fact that the National Climate Data Center (1997) data set was weighed only half as much as the other rescaled data owing to the record's acquisition from



Figure 2. Coastline of California displaying the location of deep-water buoys, precipitation stations, and the two United States tidal gauges utilized in this study.

offshore southern California, where it could affect our correlation with central California coastal phenomena by imposing local bias.

These modifications resulted in a relative ENSO intensity index series that includes 9 single-year and 12 multiyear ENSO events during the period from 1910 to 1995 (Fig. 3). In terms of relative ENSO intensity, the time series developed includes 5 higher intensity (intensity values of 4–6) and 17 lower intensity (intensity values of 1–3) ENSO events. During the early part of the twentieth century to the 1940s, an intense ENSO event occurred on average once every decade-and-a-half. The period from the 1940s through 1970 was marked by a relatively more benign climate with no higher intensity ENSO events and only four events greater than a relative magnitude of 2 occurred; this time span corresponded with a period of intense development along much of the California coast (Kuhn and Shepard, 1983; Griggs, 1995). The past three decades have seen the return to more frequent higher intensity events, similar to the early part of the twentieth century. On average, a high-intensity event transpires once

every 17 yr; however, excluding the 31 yr interval between 1941 and 1972, during which no higher intensity ENSO events occurred, this average is raised to once every 12.3 yr. Lower intensity ENSO events transpire once every 2.6 yr. For our revised intensity index, the normal return interval for ENSO events of all intensities is ~2.1 yr.

Wave Height and Oceanographic Data

Seymour et al. (1984) utilized hindcast information derived from pressure field data for lat 35°N to compile evidence of the correlation between large wave events along California and the Quinn et al. (1987) ENSO time series for Peru for the period between 1900 and 1984. This hindcast series was reevaluated against our revised ENSO index, and the correlation between large waves and ENSO events was found to be statistically significant (Table 1). Although this correlation provides evidence to support the influence of ENSO events on the central coast, we supplemented the Seymour et al. (1984) data with deep-water wave measurements recorded between

1980 and 1995 by three National Data Buoy Center (1997) buoys off central California and one Coastal Data Information Program (1997) buoy located off the Farallon Islands (Fig 2).

All four of the buoys recorded maximum wave heights during the 1982–1983 ENSO event greater than 7.6 m; these heights exceeded one standard deviation from the mean maximum yearly wave heights for all of the buoys during the 16 yr period of observation (Table 2). Buoys 46012 and 23 recorded 8.7 m and 7.6 m waves, respectively, that exceeded two standard deviations from the mean. Buoys 46011 and 23 also recorded wave heights (>6.7 m) exceeding one standard deviation for the 1986–1987 ENSO event while the waves observed at buoys 46011 and 46013 (>7.8 m) exceeded one standard deviation for the 1980 and 1990–1994 events, respectively. Overall, the more recent offshore wave measurements for the central coast appear to support the Seymour et al. (1984) and Seymour (1998) conclusion that ENSO events tend to be marked by the presence of large, damaging waves.

Sea-Surface Elevation Data

Flick and Cayan (1984) provided a comprehensive review of the sea-level fluctuations for San Diego from 1926 to 1984; however, they did not correlate the anomalies with the history of ENSO events. Detrended records of sea-level fluctuations from two stations in Central America and two stations in South America were examined along with records from a station 400 km south of the study area in San Diego and one station in San Francisco (National Ocean Service, 1997). The Central and South American stations were utilized to determine if the fluctuations observed in the sea-level records at North American stations were the result of the ENSO or some other regional phenomenon and not just local conditions. If positive sea-level fluctuations were observed in the Central and South American station records concurrently with positive fluctuations at the North American stations, then the fluctuations seen at the North American stations could confidently be concluded to be of regional origin.

The 1911–1914, 1939–1941, 1957–1958, 1965–1966, 1972–1973, and the 1982–1983 ENSO events stand out in the records for all six stations as fluctuations in maximum annual sea level that exceeded one or two standard deviations from the mean maximum sea levels for the total operational records of the stations. The two Californian stations recorded fluctuations in maximum annual sea levels that exceeded two standard deviations from the mean maximum sea levels for the 1911–1914, 1939–1941, 1957–1958, and the 1982–1983 ENSO events (Fig. 4). The San Francisco station recorded significant positive fluctuations

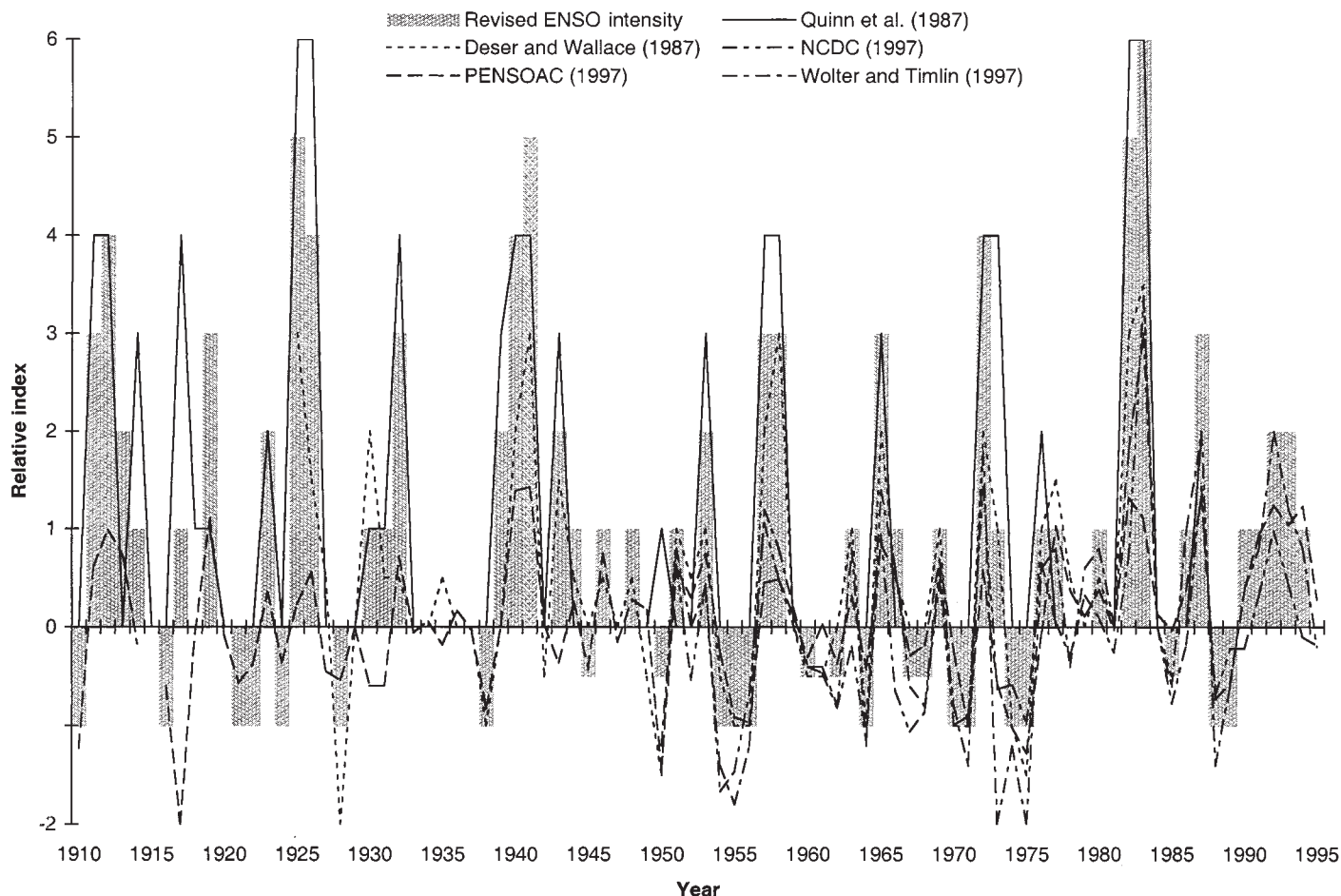


Figure 3. The record of anomalies in different indices used to develop our revised relative ENSO intensity index. The agreement between the different indices clearly increases during the latter half of the twentieth century as the number and quality of instruments used to develop the indices increased.

TABLE 1. CORRELATION BETWEEN ENSO EVENTS AND PARAMETERS

Parameter	ENSO events coinciding with significant deviations in the parameter's records* (%)	Total years/ ENSO years	T-statistic	Correlation significance level (%)
<u>Maximum annual significant wave height</u>				
<u>Buoys</u>				
All intensity (1-6) ENSO events	61	16 / 9	0.171	>50
Higher intensity (4-6) ENSO events	100	16 / 2	4.429	0.1
<u>Hindcasts†</u>				
All intensity (1-6) ENSO events	91	72 / 32	7.228	0.1
Higher intensity (4-6) ENSO events	100	72 / 8	4.518	0.1
<u>Maximum annual de-trended sea level</u>				
All intensity (1-6) ENSO events	59	86 / 41	3.107	1
Higher intensity (4-6) ENSO events	90	86 / 13	8.221	0.1
<u>Annual accumulated precipitation</u>				
All intensity (1-6) ENSO events	26	86 / 40	10.783	0.1
Higher intensity (4-6) ENSO events	79	86 / 13	14.210	0.1
<u>Cyclones impacting California</u>				
All intensity (1-6) ENSO events	37	50 / 23	3.292	1
Higher intensity (4-6) ENSO events	75	50 / 5	15.057	0.1
<u>Cyclones propagating to within 5° of California</u>				
All intensity (1-6) ENSO events	79	50 / 23	2.826	1
Higher intensity (4-6) ENSO events	100	50 / 5	7.799	0.1
<u>Erosive or damaging storms</u>				
All intensity (1-6) ENSO events	76	86 / 41	4.301	0.1
Higher intensity (4-6) ENSO events	100	86 / 13	8.309	0.1

*Deviations greater than one standard deviation from the mean.

†The hindcast wave data is from Seymour et al. (1984).

TABLE 2. CORRELATION BETWEEN ENSO EVENTS AND N.D.B.C. BUOY DATA: 1980–1995

Years	Maximum relative ENSO intensity	Mean number of erosive or damaging storms per year	WHT*	Bodega Number 46013 SST†	SLP‡	WHT	Half Moon Bay Number 46012 SST	SLP	WHT	Santa Maria Number 46011 SST	SLP
1980	1	1.0	N.D.#	N.D.	N.D.	D.N.E.**	D.N.E.	D.N.E.	1††	D.N.E.	D.N.E.
1982–1983	6	3.5	1	2§§	2	2	1	1	1	1	1
1986–1987	3	1.0	D.N.E.	2	D.N.E.	D.N.E.	D.N.E.	1	1	D.N.E.	2
1990–1994	2	0.8	1	D.N.E.	1	1	1	1	D.N.E.	D.N.E.	1
Non-ENSO		0.0									
ENSO events coinciding with significant deviations in parameter's records### (%)											
All intensity (1–6) ENSO events		100	67	67	67	50	50	75	75	25	75
Higher intensity (4–6) ENSO events		100	100	100	100	100	100	100	100	100	100
Non-ENSO events		0	33	0	0	17	0	17	17	17	17
Student's T-test correlation											
All intensity (1–6) ENSO events											
Total years/ENSO years		86 / 41		16 / 19			17 / 10			16 / 9	
Significance level (%)		0.1	>50	0.1	50	>50	>50	50	>50	>50	>50
Higher intensity (4–6) ENSO events											
Total years/ENSO years		86 / 13		16 / 2			17 / 2			16 / 2	
Significance level (%)		0.1	0.1	0.1	0.1	0.1	1	0.1	0.1	1	1

*WHT—maximum significant wave height.

†SST—maximum sea surface temperature.

‡SLP—minimum sea level barometric pressure.

#N.D.—no data.

**D.N.E.—did not exceed one standard deviation from the mean.

††1—exceeded one standard deviation from the mean.

§§2—exceeded two standard deviations from the mean.

###Deviations greater than one standard deviation from the mean.

greater than one standard deviation from the mean for 5 of the 17 lower intensity ENSO events and 4 of the 5 higher intensity events; the San Diego station recorded values greater than one standard deviation than the mean for 8 of the 17 lower intensity ENSO events and all 5 of the higher intensity ENSO events (Table 1). Three of the five higher intensity events were characterized by positive fluctuations that exceeded two standard deviations from the 86 yr mean of the records for both the San Francisco and San Diego stations. Over the same period, 15 of the 17 La Niña or anti-ENSO events (79%) were marked by sea-surface elevations lower than the 86 yr mean.

Overall, the San Diego station tended to correlate better (mean $r \approx 0.63$, significance $\geq 0.1\%$ level) with the Central and South American stations than with the San Francisco station (mean $r \approx 0.52$, significance $\geq 1\%$ level). This may be the result of either (1) the San Francisco station location in the Golden Gate that is influenced by fluvial discharge into San Francisco Bay and tidal flow through the narrow Golden Gate; (2) differences in the propagation of the coastally trapped Kelvin waves; or (3) variations in storm tracks and thus the induced superelevation of the sea surface by decreased barometric pressures or wind and wave forcing.

Historical Precipitation Records

Precipitation data from five sites along the central coast were compiled for the years from 1910 to 1995. The stations, located in San Francisco, Santa Cruz, Watsonville, Salinas, and San Luis

Obispo, are operated by the California Department of Water Resources (California Data Exchange Center, 1997). There is considerable variation between the different station records that may be caused by differences in storm tracks, orographic effects, and local conditions. The 1939–1941, 1972–1973, and 1982–1983 ENSO events, however, clearly stand out in each of the records (Fig. 5). Although only 2 of 17 lower intensity ENSO events (12%) correlated with significant variations in the precipitation records, 4 of 5 of the higher intensity events correlated with episodes of anomalously high precipitation (Table 1). Of the 17 La Niña or anti-ENSO events (53%) during the period of study, 9 corresponded with years that had lower than normal accumulated precipitation.

Recent Sea-Surface Temperatures and Historic Cyclone Activity

In addition to collecting wave height and period data, the three National Data Buoy Center (1997) buoys recorded local sea-surface temperatures and sea-level barometric pressures. Because ENSO events are defined by the presence of anomalously warm water in the eastern Pacific Ocean, sea-surface temperature time series from these buoys were evaluated to identify the historic presence of the warm water anomaly off central California. Although significant positive deviations in maximum sea-surface temperatures were only recorded 47% of the time for ENSO events of all magnitude, the 1982–1983 event stood out as a significant positive deviation in sea-

surface temperatures at all three buoys (Table 2). Although these time series only extend back to 1980, they appear to lend additional support to the conclusion that ENSO-related warm waters historically reached the latitude of central California.

The ENSO-induced warm water increases sensible heating, causing vertical destabilization of the atmosphere and facilitating cyclogenesis (Phinn and Hastings, 1992). High sea-surface temperatures also enhance evaporation and increase latent heating, further destabilizing the atmosphere and intensifying cyclonic vorticity. The low barometric pressures associated with this cyclonic activity cause additional increases in local sea-surface elevation (Robinson, 1964). The counterclockwise rotation of cyclones tends to generate southerly to westerly winds that force the warm surface waters shoreward, further intensifying local sea level along the coast (Saur, 1962). Large waves are usually generated due to the high wind velocities, large fetches, and long durations common to developed cyclonic activity (Seymour et al., 1984; Phinn and Hastings, 1992).

In order to evaluate the connection between ENSO events and the incidence of cyclones that can be enhanced by ENSO conditions, an archive of eastern Pacific tropical cyclone tracks since 1949 (Landsea, 1997) and a record of tropical cyclones that have struck California since 1921 (National Weather Service, 1997) were compared to our relative ENSO intensity time series. Of the 14 cyclones that have struck the coast of California since 1921, 12 (86%) of them coincided with ENSO events. Of 15 low intensity ENSO events (20%), 3 were marked by the impacts of cy-

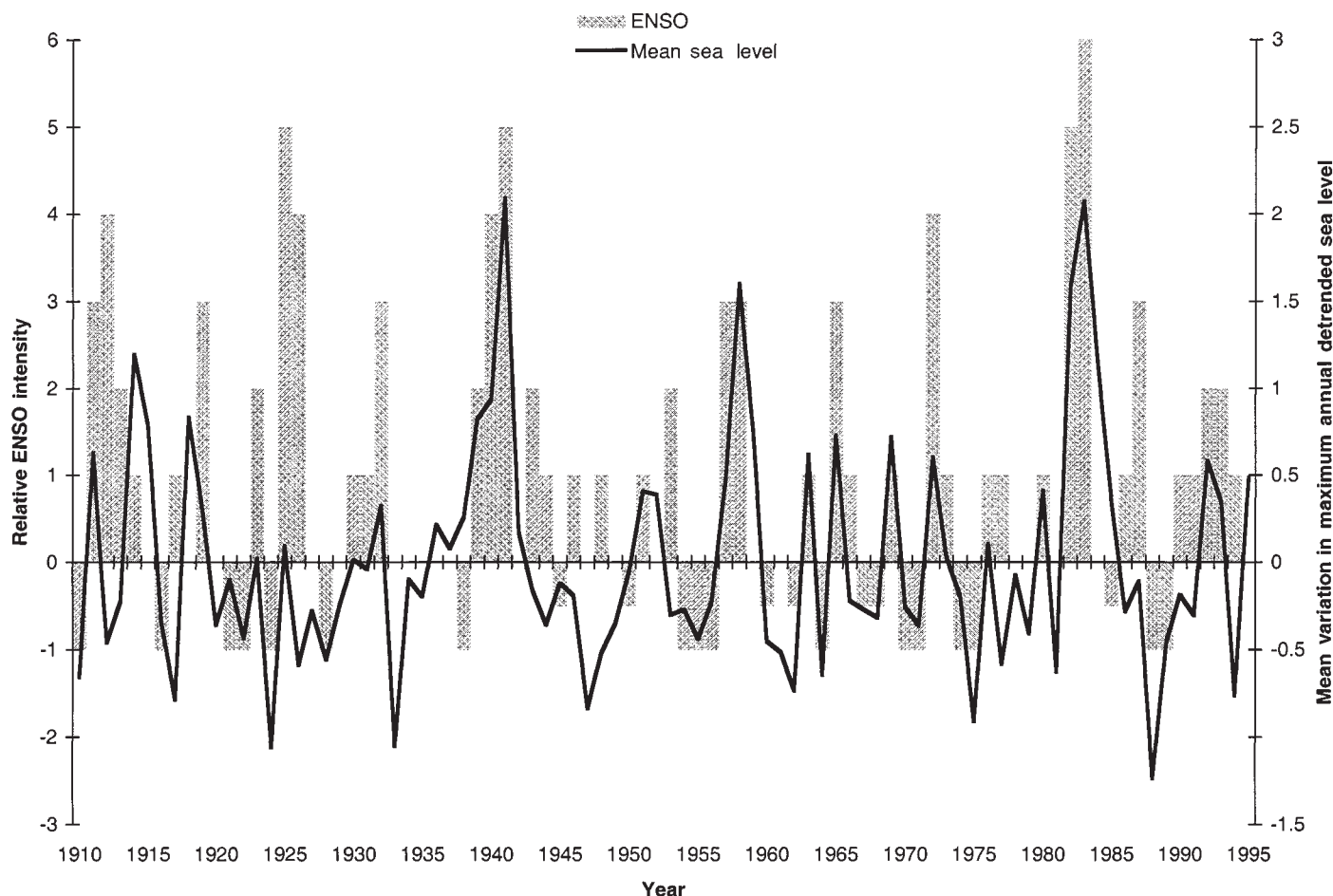


Figure 4. The mean variation in maximum annual detrended sea level for the San Francisco and San Diego tidal gauge records compared with our revised relative ENSO intensity index.

clones, as were 3 of 4 high-intensity ENSO events (Table 1). We also evaluated the incidence of tropical cyclones that propagated to within five degrees of latitude or longitude of the coast that would influence the coastal climate of California by generating large waves and/or lesser storms. Of the 45 cyclones that fit this criteria (62%), 28 took place during ENSO events; 7 of 10 of the lower intensity and both of the higher intensity ENSO events since 1949 were associated with the incidence of tropical cyclones (Table 1).

We believe, however, that the total number of cyclones that have influenced the coast of central California during ENSO events is much higher than the 28 tropical cyclones recorded. During the 1982–1983 ENSO event (Seymour et al., 1984) and the intense 1997–1998 ENSO winter, for example, the majority of the storms that caused coastal erosion and storm damage were generated by extratropical and mid-latitude cyclone activity and thus were not or would not have been incorporated into the Landsea (1997) and the National Weather Service (1997) data sets. In order to determine if this were the case, time series of

sea-level barometric pressure from the three National Data Buoy Center (1997) buoys off central California were evaluated to identify years with anomalously low values that would be the result of cyclonic activity and/or interanticyclonic systems. On average, 72% of the ENSO events recorded by the buoys were marked by significant negative deviations in sea-level barometric pressure (Table 2). All three buoys recorded significant negative deviations during the 1982–1983 higher intensity event. Because the significant drops in barometric pressure recorded off the central coast during the 1986–1987 and 1990–1994 ENSO events were not documented in the Landsea (1997) and National Weather Service (1997) data sets, it appears the buoy data lend support to our hypothesis that the number of cyclones that have influenced the central coast of California is higher than previously recorded.

Coastal Erosion and Storm Damage

With the timing of historical variations in wave height, sea level, precipitation, and cyclonic ac-

tivity in relation to ENSO event intensity during the period from 1910 to 1995 established, an investigation into the response of the central coast of California to these parameters was initiated. Four independent compilations of storm dates (U.S. Army Corps of Engineers, 1958; Bixby, 1962; California Coastal Commission, 1978; Parsons, 1983) provided a basis for investigating the history of coastal storms and the erosion or damage they produced along the central coast from newspaper accounts. These dates were supplemented with unpublished data on the damage to shoreline protection structures along central California since the mid-1920s, a previously published chronicle of historical damage to Sealcliff State Beach in northern Monterey Bay (Griggs and Fulton-Bennett, 1987), and more recent newspaper accounts (Table 3). The information on storm duration and direction from these sources was further augmented by the hindcast wave data compiled by Seymour et al. (1984).

A total of 59 storms that caused significant coastal erosion or reported damage to structures were documented between 1910 and 1995. The

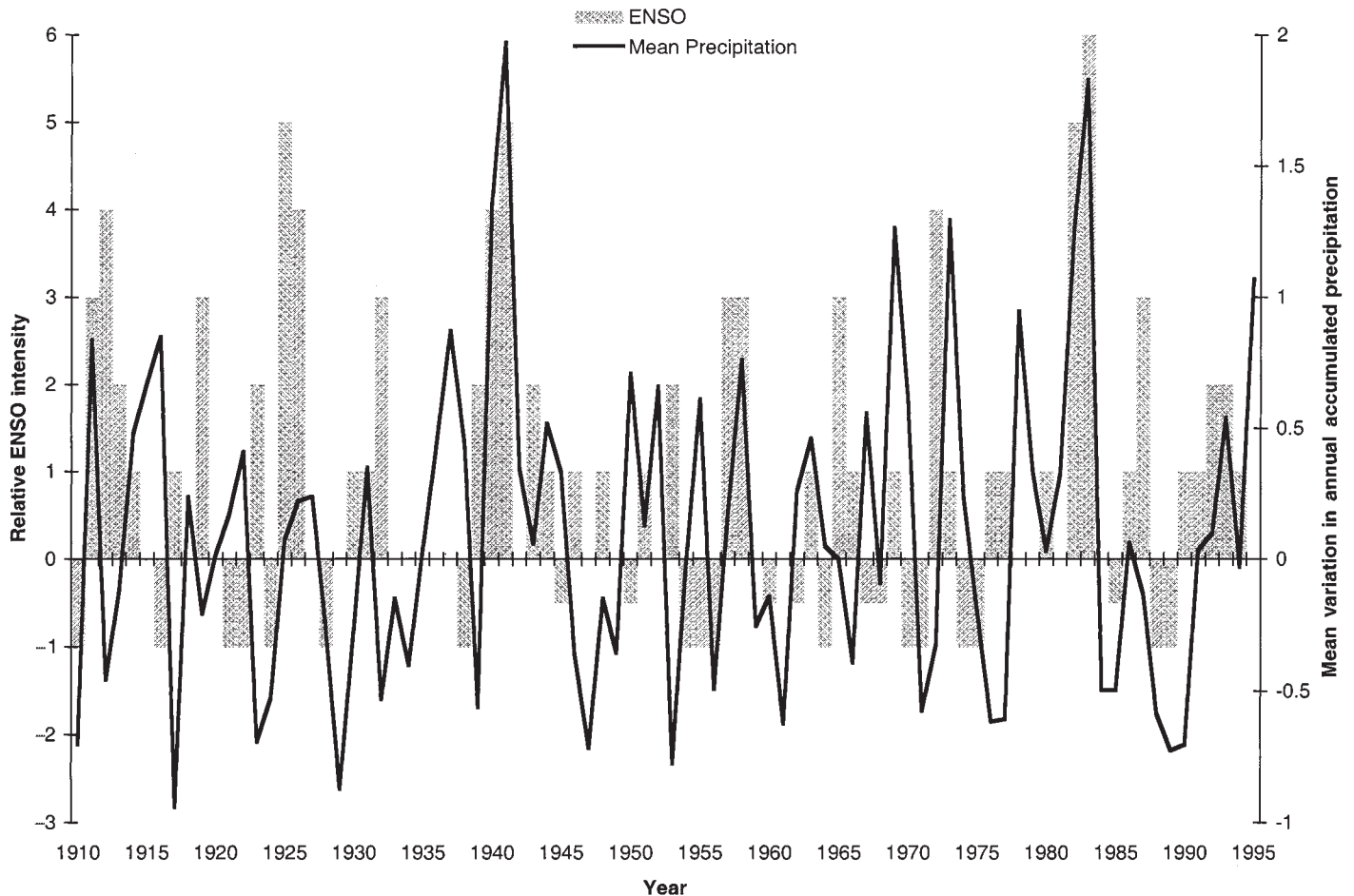


Figure 5. The mean fluctuation in annual accumulated precipitation for the five precipitation stations compared with our revised relative ENSO intensity index. The high variation is a function of many factors such as storm tracks and orographic effects.

storms occurred in 35 different years and all were characterized by larger than normal wave heights. Only during 15 of the 35 yr (43%) was coastal bluff erosion documented in newspaper accounts or county records. This reporting probably underrepresents the true extent of sea-cliff erosion along the central coast due to the (1) aperiodic, instantaneous, and localized nature of coastal bluff failure, and (2) low population density and therefore number of observations for at least half of the time interval analyzed. The documentation of sea-cliff erosion in these records, however, is most likely very accurate for the regions with high population densities such as San Francisco and Monterey Bay, from which the majority of the records originate. If the erosion of a sea cliff was documented, it is highly probable that it was of significant spatial extent to be recorded. The records reinforce this conclusion; many of the erosional events involve the destruction of some structure that was lost during the bluff failure, implying a large, instantaneous event versus the steady, slow erosion of the sea cliff over many years. Thus, while many small, local bluff fail-

ures may have gone unnoticed or unrecorded, it is very likely that the most significant erosional events are in the historical record. This underreporting illustrates the need for sea-cliff erosion data with higher spatial and temporal resolution than has been previously available (aerial photography flights for the central coast were typically flown only once or twice a decade between 1930 and 1980).

Of the 48 storms (81%) that had their direction of origin reported, 39 came out of the southwest and generated large southerly to westerly storm waves not commonly observed along the central coast during the winter months. All 15 yr in which sea-cliff erosion was documented had storms propagating out of the southwest. Storms that have longer durations allow waves to have an impact on the shoreline over multiple tidal cycles, increasing the exposure of beaches and sea cliffs to higher wave energy. In order to better understand the severity of these erosive or damaging storms, and determine if there was a correlation between storm duration and the occurrence of sea-cliff erosion, we assembled the available data

on storm duration. Sea-cliff erosion was documented during 14 of the 26 yr when storms of at least 2 days duration struck the central coast (54%), and 5 of the 7 yr that experienced storms of 4 or more days duration.

Of the storms that caused significant erosion or structural damage along the central coast of California, ~76% (45) occurred during ENSO events (Fig. 6), a correlation that is significant at the 0.1% level (Table 1). Of 17 lower intensity (71%) events, 12 were marked by erosive or damaging coastal storms, as were all 5 higher intensity ENSO events. Only 5 of the 59 storms (8%) occurred during La Niña or anti-ENSO events. For the 86 yr period of study, this amounts to roughly 1.1 erosive or damaging coastal storms per ENSO year versus only 0.3 storms per non-ENSO year. When evaluating the series in terms of ENSO events, central California was struck by an average of roughly 1.4 erosive or damaging coastal storms during every lower intensity event and 3.6 storms during each higher intensity event. It was noted that 3 of 5 of the higher intensity events and 6 of the 17 lower intensity events (35%)

TABLE 3. SUMMARY OF EROSION OR DAMAGING STORM CHARACTERISTICS: 1912–1995

Year	Relative ENSO intensity	Number of storms	Duration of storm (days)	Direction of storm origin*	Large waves	Structures damaged	Structures destroyed	Heavy beach erosion	Seacliff erosion	Flooding
1912	4	2	8, >2 [†]	SW, NW	X [§]	X	N.O.R. [#]	N.O.R.	N.O.R.	X
1915	0	2	2, 1	SW	X	X	N.O.R.	N.O.R.	N.O.R.	N.O.R.
1916	-1	1	1	SW	X	X	X	N.O.R.	N.O.R.	N.O.R.
1923	2	1	3	NW	X	X	N.O.R.	N.O.R.	N.O.R.	N.O.R.
1926	4	3	5, 1, 2	SW	X	X	X	X	X	X
1927	0	2	3, 1	SW, W	X	X	X	X	X	X
1931	1	5	1, 1, 1, 2, 7	SW, NW	X	X	X	X	X	X
1935	0	1	1	W	X	X	X	N.O.R.	N.O.R.	N.O.R.
1937	0	1	2	SW	X	X	X	X	X	X
1939	2	1	2	SW	X	X	X	X	X	X
1940	4	3	3, 2, 6	SW, W	X	X	X	X	X	X
1941	5	3	5, 3, 3	SW, W	X	X	X	X	X	X
1943	2	1	2	N then SW	X	X	X	N.O.R.	N.O.R.	N.O.R.
1947	0	2	1, 1	N, W	X	X	X	N.O.R.	N.O.R.	N.O.R.
1948	1	1	1	N	X	X	X	N.O.R.	N.O.R.	N.O.R.
1950	-0.5	2	3, 1	N, S	X	X	N.O.R.	X	N.O.R.	X
1953	2	2	1, 1	S, N	X	X	N.O.R.	X	N.O.R.	X
1954	-1	1	1	SW	X	N.O.R.	N.O.R.	X	N.O.R.	N.O.R.
1957	3	1	N.D.**	N.D.	X	N.O.R.	N.O.R.	X	N.O.R.	N.O.R.
1958	3	1	>2	W	X	N.O.R.	N.O.R.	X	X	N.O.R.
1959	0	1	1	SW	X	X	N.O.R.	X	X	N.O.R.
1960	-0.5	1	2	SW	X	X	X	X	X	X
1963	1	1	>2	W	X	X	N.O.R.	X	N.O.R.	N.O.R.
1965	3	1	1	W	X	X	N.O.R.	X	N.O.R.	N.O.R.
1969	1	1	>2	SW	X	X	N.O.R.	X	X	N.O.R.
1972	4	1	>2	N.D.	X	N.O.R.	N.O.R.	X	N.O.R.	N.O.R.
1973	1	1	N.D.	NW	X	N.O.R.	N.O.R.	X	N.O.R.	N.O.R.
1977	1	2	>2, >2	SW, NW	X	X	X	X	X	X
1980	1	1	>2	SW	X	X	X	X	X	X
1982	5	2	1, >2	SW, W	X	X	X	X	N.O.R.	X
1983	6	5	3, 7, 3, 4, 2	W, W, W, SW, SW	X	X	X	X	X	X
1986	1	2	3, 2	SW	X	X	N.O.R.	X	X	X
1990	1	1	2	SW	X	N.O.R.	N.O.R.	N.O.R.	N.O.R.	X
1992	2	2	4, 2	W, SW	X	X	X	X	N.O.R.	X
1994	1	1	2	SW	X	N.O.R.	N.O.R.	X	N.O.R.	X

Note: Abbreviations: SW—southwest; NW—northwest; W—west; N—north.

*As noted by wind and/or wave direction.

[†]Unspecified duration greater than 2 days.

[§]X—The characteristic was observed and recorded.

[#]N.O.R.—The characteristic was neither observed nor recorded; see text for further explanation.

**N.D.—no data.

caused sea-cliff erosion, while during only one of the 17 La Niña events (6%) was sea-cliff erosion documented.

DISCUSSION

Relationships Between Frequency and Magnitude of ENSO Events and Sea-Cliff Erosion

Although the correlations between ENSO events and (1) higher than normal wave heights, sea level, and precipitation, and (2) increased cyclone activity were shown to be statistically significant, we have not yet established what, if any, relationships exist between the magnitude of these fluctuations and the relative intensity of ENSO events. This was accomplished by evaluating the average percentage of deviation from the mean for each of the parameters versus our relative ENSO event intensity index (Fig. 7A). A nonlinear increase in wave height, sea level, precipitation, and cyclone activity with increasing relative ENSO intensity is clearly demonstrated. The increase in the magnitude or frequency of

these parameters with increasing ENSO intensity is offset, however, by the lower frequency of the higher intensity events. Because higher than normal waves, sea-surface elevation, and precipitation have been qualitatively shown to increase the erosion of coastal bluffs, it appears evident that the probability of sea-cliff erosion would increase with increasing ENSO intensity.

The increase in the frequency of storms that caused coastal erosion or damage to structures with increasing relative ENSO event intensity is displayed in Figure 7B. The occurrence or documentation of sea-cliff erosion varies similarly with increasing relative ENSO intensity, implying that larger scale sea-cliff erosional events are more likely to occur during higher relative intensity ENSO events than during lower intensity ENSO events (Fig. 7B). The limited sea-cliff erosion data further bolster our hypothesis that coastal bluff recession would increase with increasing relative ENSO intensity based on the increased wave heights, sea-surface elevations, and precipitation that characterize high relative intensity ENSO events. As displayed in Figure 8, the qualitative relationships observed by

many researchers between episodes of sea-cliff erosion and higher wave heights, sea-surface elevations, and precipitation (most likely generated by increased cyclonic activity) are supported by the data compiled for the central coast of California.

Implication of Results to the Temporal Evolution of the Central California Coastline

Our results support the conclusions of others that most sea-cliff erosion and storm damage occur during the infrequent coincidence of higher than normal waves, sea levels, and precipitation. ENSO events, through a number of interactions both at low and high latitudes, cause significant positive fluctuations in the parameters that exert primary external control on sea-cliff erosion over short to intermediate time scales. As demonstrated in Figure 7, the highest waves, heaviest precipitation, highest sea levels, and most cyclone activity tend to occur during the most intense ENSO events. The more intense (relative intensity values of 4–6) events, however, have transpired relatively infrequently during the twentieth century,

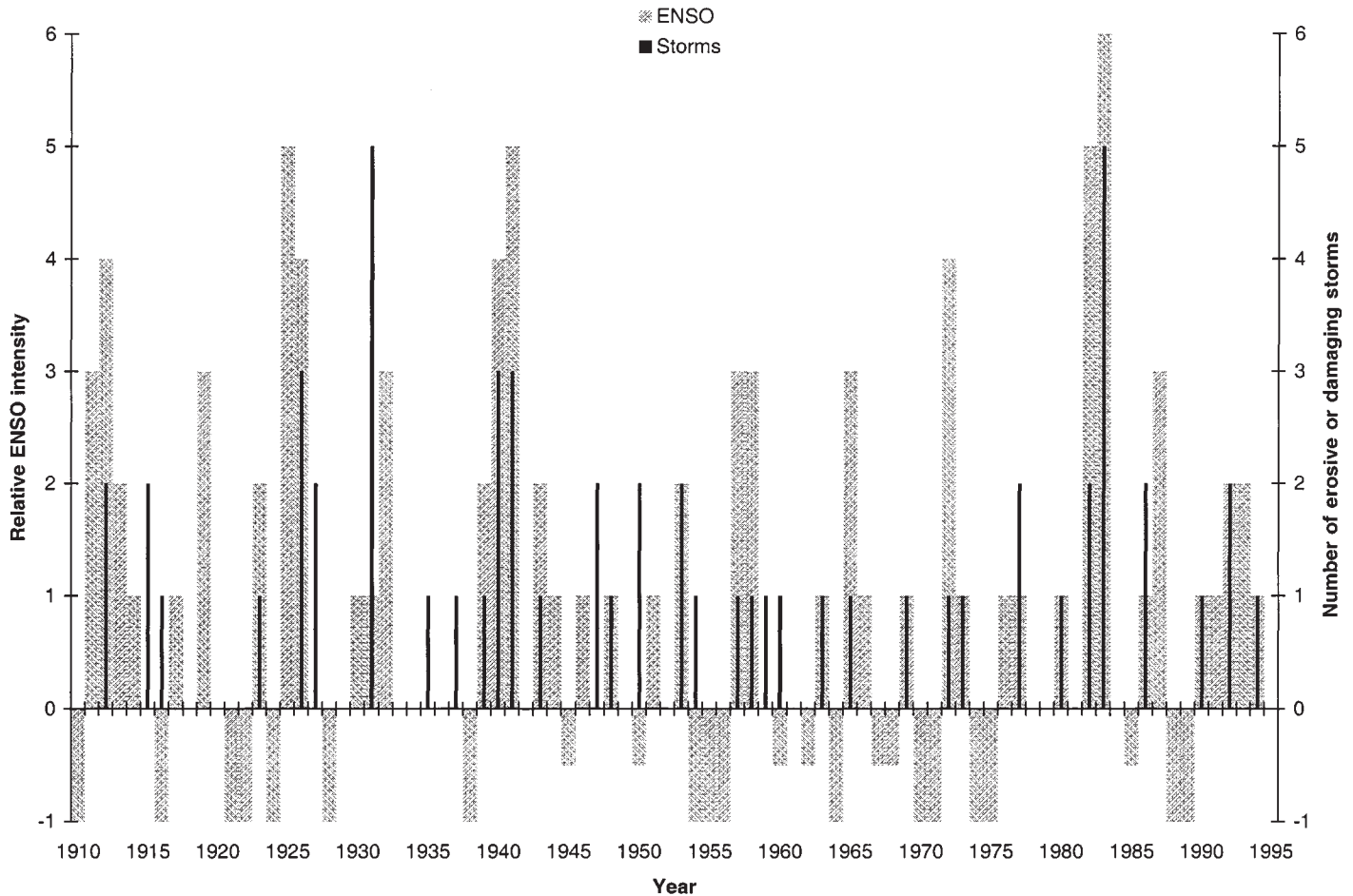


Figure 6. The number of storms that caused coastal erosion or storm damage along central California from 1910 to 1995 and the variation in our revised relative ENSO intensity index. Note that the central coast was struck by storms that caused damage during all four of the intense (relative intensity >3) ENSO events.

only occurring during 8 of the 86 yr (9%) period of study. Thus, the increase in wave height, sea level, precipitation, and cyclone activity with increasing relative ENSO intensity is offset somewhat by the low frequency of these intense events. The product of the magnitude of these parameter records and their frequency demonstrates that, although during any one intense ENSO event more storms affect central California and more sea-cliff erosion occurs, less intense ENSO events may produce more coastal bluff erosion and storm damage over the course of a century (Fig. 9). The maximum of this product (relative intensity values of 1–3 in Fig. 9) would define those relative intensity ENSO events that are the most geomorphically effective over intermediate time scales by producing the most cumulative sea-cliff erosion.

The implications of Figure 9 may be somewhat misleading, however. A specific section of sea cliff may undergo attack for many years and not fail until the cumulative effect of the storms over those years finally causes some intrinsic

threshold of the cliff (i.e., rock strength) to be exceeded. For example, some coastal bluffs that are significantly weakened during intense ENSO events may not fail until the next storm during a less severe ENSO event or La Niña year. The relationship between relative ENSO intensity and sea-cliff erosion may therefore be more nonlinear, the most intense ENSO events contributing a higher percentage of sea-cliff erosion accomplished per event than Figure 9 demonstrates. This conclusion appears to be supported by the much larger spatial extent and magnitude of coastal bluff failure observed during the 1982–1983 and 1997–1998 intense ENSO events than during the less intense events in the intervening years (Griggs and Johnson, 1983; USGS/UCSC/NASA/NOAA Collaborative Research Group, 1998). If the most intense events contribute more sea-cliff erosion, the resulting products of frequency and magnitude shown in Figure 9 would be significantly skewed toward the higher intensity ENSO events. This would imply that higher intensity (relative intensity values of 4–6) events

produce the most cumulative storm damage and sea-cliff erosion over the course of a century and would thus be the most geomorphically effective ENSO events over intermediate time scales.

The timing of ENSO's effects relative to the yearly cycle of normal variations in the coastal climate is also a dominant factor regarding the influence of ENSO events on the coastline of central California. As demonstrated by Griggs and Johnson (1983), Flick and Cayan (1984), Seymour et al. (1984), Komar (1986), Flick (1998), Seymour (1998), Storlazzi and Griggs (1998), and the USGS/UCSC/NASA/NOAA Collaborative Research Group (1998), the occurrence of severe storms, large waves, higher than normal sea levels, and large precipitation events are typically at a maximum during the winter when beach width is at a minimum. The more westerly to southerly direction of the storms and waves during the winter months of ENSO events also contributes to greater than normal erosion and damage along the coast of central California. These large waves and intense

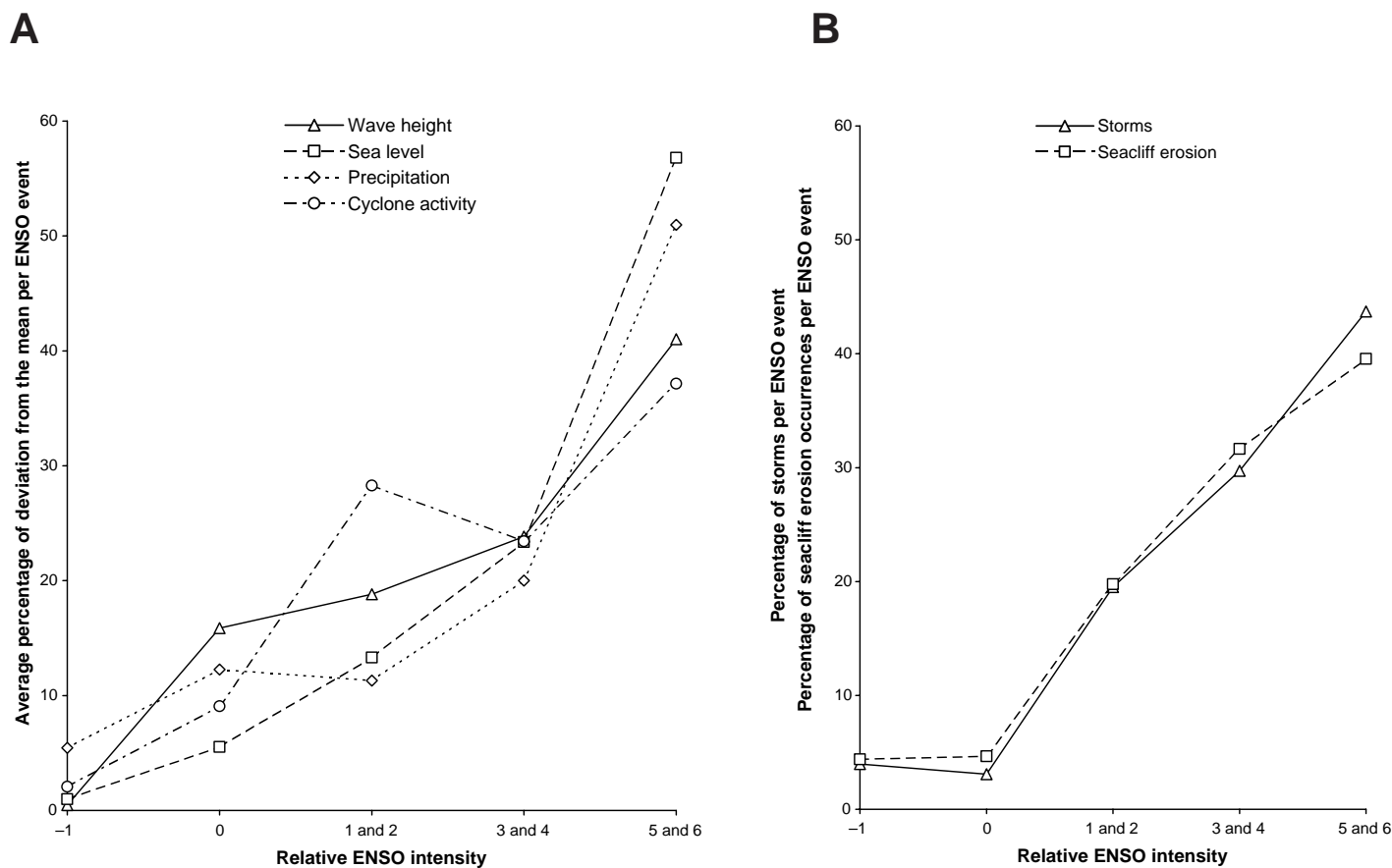


Figure 7. The variation in parameters' magnitude as a function of the relative ENSO intensity along with the frequency or percentage distribution of relative intensity ENSO events from 1910 to 1995. (A) The increase in positive deviation from the mean of the forcing parameters that influence sea-cliff erosion per ENSO event and the increase in the percentage of tropical cyclone activity per event. (B) The increase in the percentage of sea-cliff erosion observed per ENSO event and the increase in the percentage of storms that caused erosion or structural damage per event. The relative ENSO intensities are clustered due to the arbitrary nature of defining the thresholds for the different values during the development of the relative ENSO intensity index.

storms often disproportionately affect southerly and southwesterly facing sections of the central coast (Griggs and Johnson, 1979, 1983). These beaches are protected from the usual northwesterly wave direction and are typically exposed to lower wave conditions than portions of the coast facing the west or northwest. At the same time, however, the sections of the coast that face the northwest and are in quasiequilibrium with the common northwesterly waves tend to undergo substantial modification during ENSO winters, when the waves come out of the southwest, due to changes in the direction of nearshore energy gradients and thus sediment transport (USGS/UCSC/NASA/NOAA Collaborative Research Group, 1998). Combined, these seasonal effects cause the annual effects of ENSO events to be even more influential in coastal cliff erosion along the central coast of California.

Because 52 of the 59 storms (88%) that caused significant damage or erosion along the

coast of central California between 1910 and 1995 coincided with significant deviations in wave height, sea level, precipitation, and cyclone activity, it appears conclusive that ENSO events exert principal control on the frequency and timing of conditions conducive to coastal erosion. The significant correlations between the positive deviation of these parameters and (1) historical damaging or erosive coastal storms, and (2) documented episodes of sea-cliff erosion along the central coast supports the concept that sea-cliff erosion tends to occur during storms when large waves, higher than normal sea levels, and heavy precipitation occur. In conjunction, these two conclusions demonstrate that ENSO events exert primary control on the frequency and magnitude of large-scale cycles of sea-cliff erosion and coastline recession along central California.

Investigations by Thom (1978), Bryant (1983), Clarke and Eliot (1988), and Phinn and

Hastings (1992) described episodes of coastline erosion along Western Australia that they relate to fluctuations in the Southern Oscillation. When the Southern Oscillation is positive (during anti-ENSO or La Niña events), Western Australian beaches undergo periods of erosion due to increased wave heights (Phinn and Hastings, 1992) and sea-surface elevations (Bryant, 1983; Clarke and Eliot, 1988) associated with increased cyclonic activity. This increased cyclonic activity is driven by atmospheric perturbations resulting from the super-elevated warm water in the western Pacific during La Niña events (Thom, 1978; Phinn and Hastings, 1992). These conclusions, together with our results from along the central coast of California, imply that oscillations in the position of the equatorial Pacific's warm water bulge may exert significant control on the temporal evolution of many coastal regions and shorelines across the Pacific Ocean.

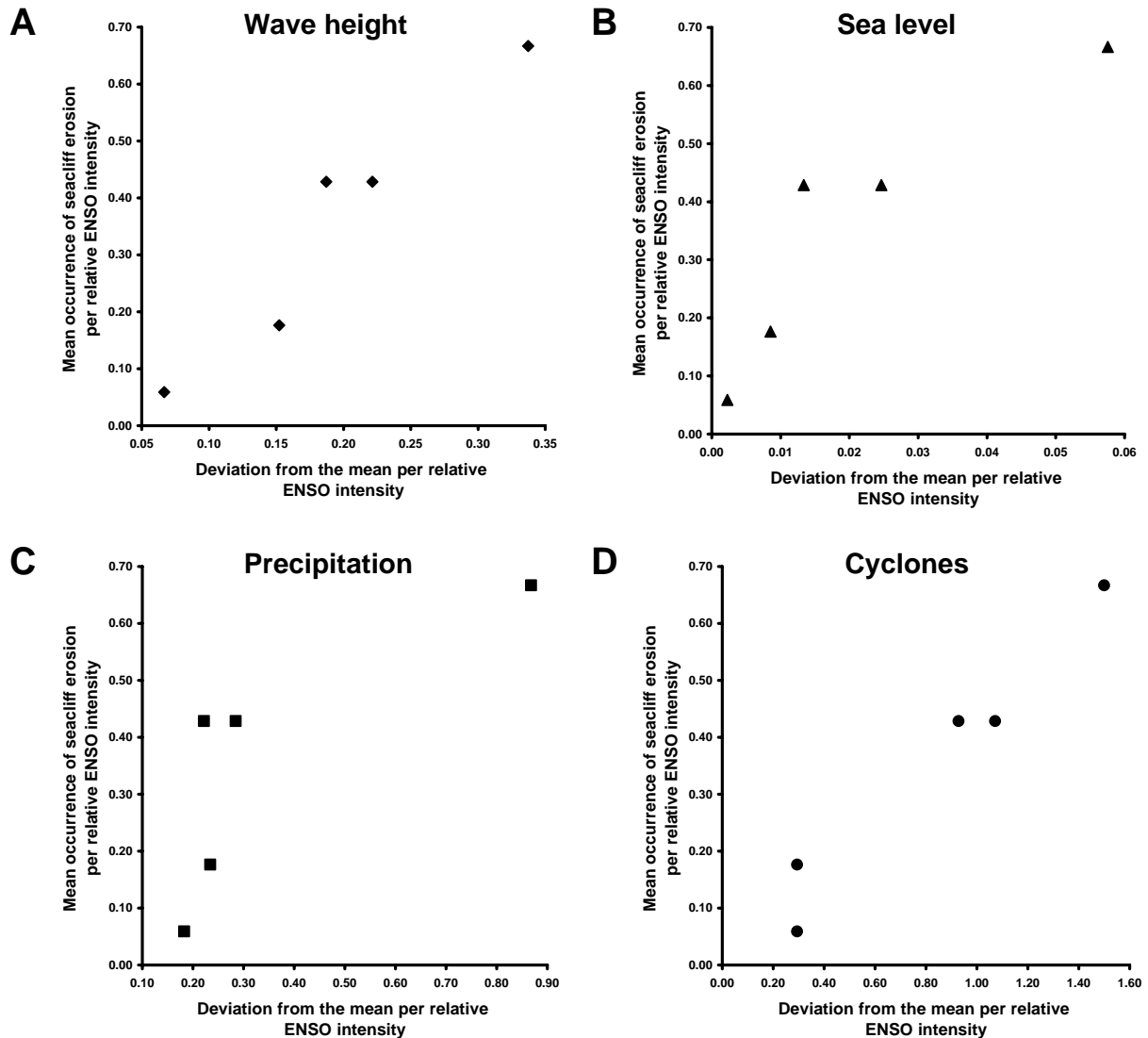


Figure 8. The relationships between the mean deviation from the forcing parameters that influence sea-cliff erosion per relative ENSO event intensity and the mean occurrence of sea-cliff erosion per relative ENSO event intensity. (A) Mean deviation in wave height per relative ENSO event intensity. (B) Mean deviation in sea level per relative ENSO event intensity. (C) Mean deviation in precipitation per relative ENSO event intensity. (D) Mean deviation in cyclone activity per relative ENSO event intensity. All of the relationships display increasing trends, and the correlations are significant at or above the 1% level.

CONCLUSIONS

The following conclusions can be drawn from this study of the relationships between ENSO events and processes responsible for erosion and storm damage along the coast of central California: (1) statistically larger waves, higher than normal sea levels, and heavier than normal precipitation occur during ENSO events, and significant positive fluctuations in these parameter records coincided with more than 88% of the ENSO events from 1910 to 1995; (2) 76% of significant coastal erosion and storm damage along the central coast occurred during ENSO events and was likely caused by increased cyclonic activity re-

sulting from ENSO-related oceanographic and atmospheric shifts in circulation across the Pacific; (3) significant coastal erosion and storm damage is three times as likely to occur during ENSO events than during non-ENSO or La Niña periods; and (4) higher intensity (relative intensity values of 4–6) ENSO events produce the most cumulative erosion and therefore may be the most geomorphically effective events over intermediate time scales. Therefore, because most of the coastal erosion and storm damage transpires during severe storms and the frequency and magnitude of these storms is strongly modulated by ENSO events, it appears that ENSO events exert principal control on the evolution of

the central coast of California. This conclusion, in conjunction with the observations of the cyclic nature of accretion and erosion of beaches in Australia associated with fluctuation in the Southern Oscillation, implies that ENSO events may influence the evolution of many Pacific Ocean coastlines.

This work opens the possibility for better predicting the frequency and magnitude of both episodes of significant beach erosion and storm damage and periods of sea-cliff erosion for many of the coastlines across the Pacific Ocean that are influenced by the atmospheric and oceanographic fluctuations related to the Southern Oscillation. By predicting these patterns of coastal erosion,

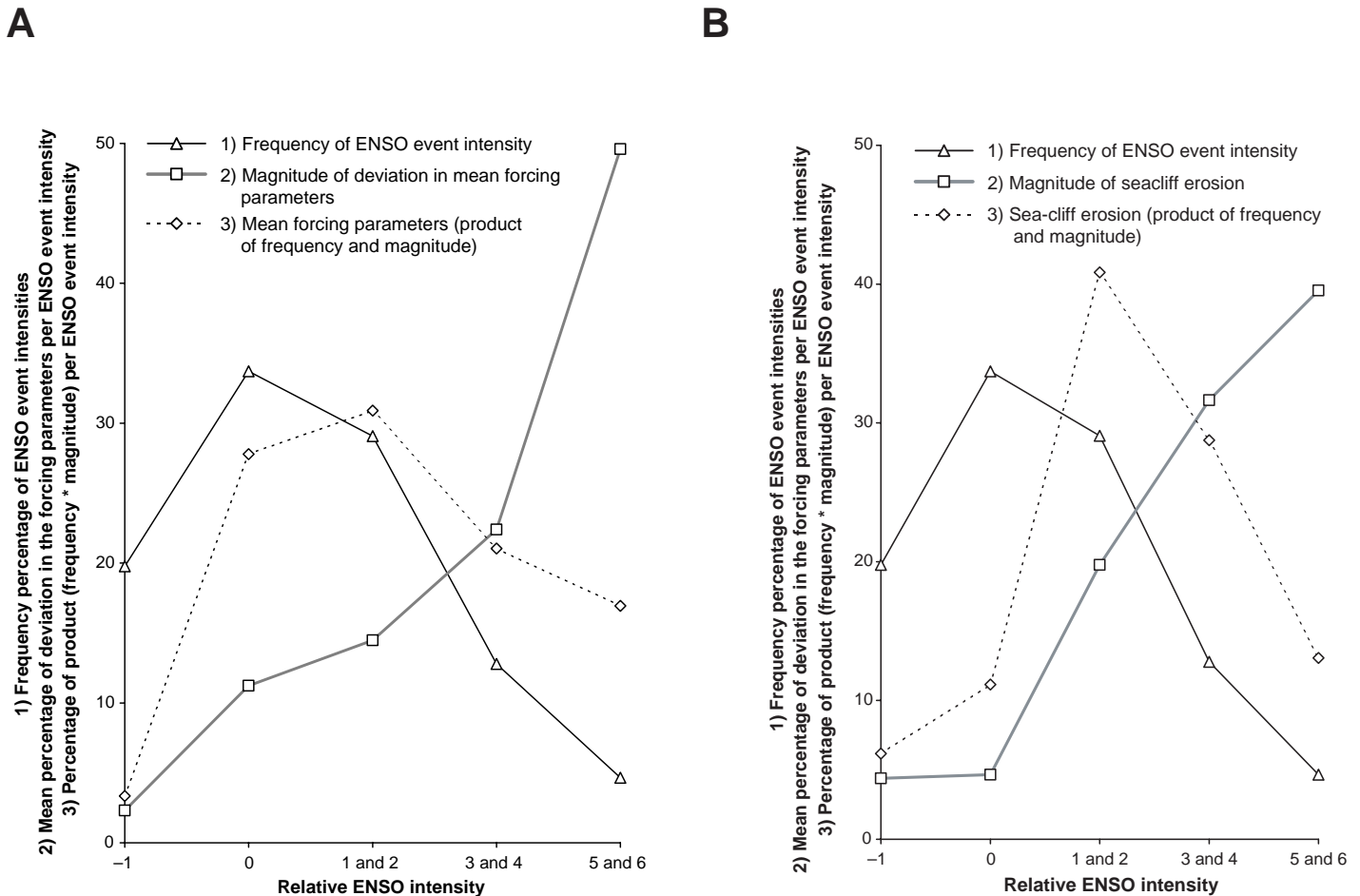


Figure 9. Frequency-magnitude plots relating ENSO intensities and their (A) forcing and (B) geomorphic response. The solid black lines correspond to the frequency of ENSO events of different relative intensities. The thick gray lines correspond to the increase in deviation from the mean forcing parameters (wave height, sea level, and precipitation) that influence sea-cliff erosion observed during ENSO events of different relative intensities, or the percentage of sea-cliff erosion observed during ENSO events of different relative intensities. The dashed lines demonstrate the trade-off between the frequency and magnitude of the forcing parameters or the coastline's response to those parameters. This product of the frequency and magnitude defines during which relative intensity ENSO events most of the positive deviation in a parameter's records or sea-cliff erosion occurs and can be thought of as the comparable effectiveness of ENSO events of a specific relative intensity.

we may be able to better understand the evolution of many of the inadequately documented islands and shorelines in or bordering the Pacific Ocean. More detailed cliff and shoreline erosion studies, with both higher spatial and temporal resolution, would better constrain our conclusions and provide a more definitive understanding of the effects of ENSO-induced oceanographic and atmospheric fluctuations on sea-cliff erosion processes and rocky coastline evolution.

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