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Comparative Impacts of the 1982–83 and 1997–98 El Niño Winters on the Central California Coast

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ABSTRACT

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Although most indices suggest the 1997–98 El Niño-Southern Oscillation (ENSO) was more intense than the 1982–83 ENSO event, the coastline of central California sustained approximately $14 million in damages during the 1982–83 winter, more than double the economic impact experienced during the 1997–98 winter. We attribute the difference in coastal response to a combination of oceanographic and anthropogenic factors. During 1982–83, the large wave events tended to coincide with more southerly and higher velocity winds, increasing set-up along the shoreline and beach erosion due to offshore-directed flow. These large wave events also occurred during very high tides, causing the waves to break closer to shore and to strike the coast with more energy, increasing their impact on coastal structures and property. During the 1997–98 winter, however, the largest waves arrived during lower tides and coincided with lower wind velocities. The northwesterly winds reduced set-up along the shoreline and caused net onshore flow, decreasing wave impact. Another important factor contributing to the disproportionate damage between the winters was the higher percentage of shoreline that had been armored by 1997. Most areas significantly damaged in 1982–83 winter were protected by more substantial seawalls or revetments during the 1997–98 ENSO event. Improving the understanding of variations in coastal response to extreme storm events is essential to bolstering the resiliency of our coastal communities.

ADDITIONAL INDEX WORDS: *ENSO, waves, sea level, storm damage, seawalls, coastal erosion.*

INTRODUCTION

While the impact of El Niño-Southern Oscillation (ENSO) events on productivity in Peruvian coastal waters has been well documented for over four centuries, the effect of ENSO events on the coastal climate of central California has not been fully understood or appreciated. The El Niño winters storms of 1978 and 1983 inflicted major damage to many of the developed and heavily populated portions of California's shoreline, bringing an end to the relatively benign wave and storm climate in California over the previous three decades. As an ENSO anomaly of similar magnitude to the 1982–83 winter developed over 1997 and persisted into 1998, considerable interest arose to assess the impacts of the 1997–98 ENSO winter on the coast and to compare the responses to the 1982–83 and 1997–98 winters so that coastal communities can properly prepare in order to avoid or reduce public and private losses in the future. The severity of impacts over both of these ENSO events has also prompted other studies to understand the role of ENSO events in the long-term geomorphic evolution of the central California coast (STORLAZZI and GRIGGS, 2000).

Coastal erosion and storm damage along rocky coastlines is usually influenced by the interplay of many dynamic but often intermittent processes that typically occur during times of intense weather when certain physical thresholds such as the strength of seacliffs or coastal structures are exceeded. Recent research has shown that approximately 76% of the storms between 1910 and 1995 that caused significant erosion or structural damage along the central coast of California occurred during ENSO events, a correlation which is significant at the 0.1% level (STORLAZZI and GRIGGS, 2000). Some of the factors that contributed to the heavy coastal damage that occurred during the 1982–83 ENSO event included the combination of high astronomical tides, higher than normal sea levels, and large storm-induced waves (GRIGGS and JOHNSON, 1983; FLICK and CAYAN, 1984; SEYMOUR *et al.,* 1984). The 1982–83 coastal damages, adjusted for inflation, totaled over $160 million along all of California and approximately $14 million in central California from San Francisco to Monterey (SWISHER, 1983; GRIGGS and JOHNSON, 1983).

With the onset of another major ENSO winter in 1997–98, the stage seemed to be set for coastal damages potentially equivalent to or exceeding the damages sustained in 1982–83. However, when the ENSO spawned storms of January and March 1998 passed, coastal damages along central Cal-

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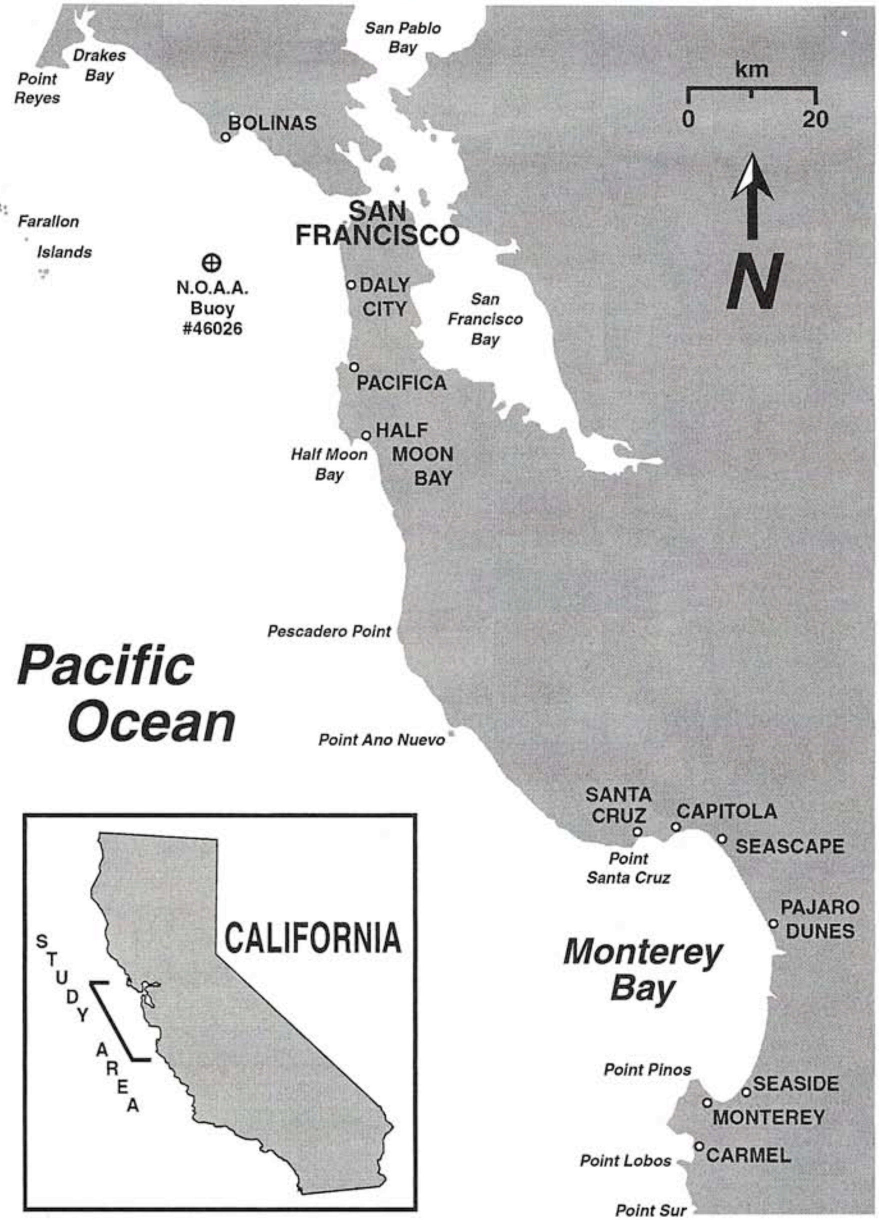

Figure 1. Map of the study area showing the major coastal population centers and prominent features of the central California coast.

ifornia amounted only to $6 million. While significant wave heights during the 1997–98 storms met or even exceeded those in 1982–83, the 1997–98 winter storms struck the coast during significantly lower tidal conditions and coincided with more northerly waves and winds that reduced set-up along the coast. Moreover, the communities constructed along the back-beach in northern Monterey Bay severely damaged in 1982–83 invested heavily in coastal protection structures, engineered according to new design criteria provided by the 1982–83 storms. The coupling of waves, winds, and spring tides, along with the increase in armoring and the redesign and/or reconstruction of much existing armoring decreased the overall damage to coastal structures during the 1997–98 winter. These factors are likely largely responsible for reducing the economic impacts of the 1997–98 winter storms by more than 50% of the damage costs incurred during the 1982–83 winter.

STUDY AREA

This study focuses on the coastline of central California from San Francisco in the north to the Carmel River in Monterey County in the south (Figure 1). This 147 km section of shoreline is characterized by population centers in San Francisco, Pacifica, Half Moon Bay, Santa Cruz, and along Monterey Bay, but with approximately 103 km (71%) of undeveloped shoreline interspersed between these cities. The primary sources of coarse-grained sediment to the littoral environment are sand discharged through the Golden Gate and the numerous small, steep perennial streams and less frequent rivers that drain the coastal mountains (BEST and GRIGGS, 1991). The mouths of many of these streams were inundated during the Holocene transgression, forming low-gradient floodplains, coastal lagoons, and marshes in their lower reaches, many of which are backed by dune fields (GRIGGS and SAVOY, 1985; DINGLER *et al.,* 1985).

Steep, up to 100 m high, actively eroding coastal bluffs bound the central coast; these are often incised into uplifted marine terraces and, in northern Santa Cruz County, are commonly fronted by low, wave-cut shore platforms. The seacliffs are interrupted at irregular intervals by pocket beaches that form at the mouths of coastal streams or in joint-bounded coves and by infrequent continuous beaches in sheltered bays. Seacliff erosion, with long-term rates ranging from essentially zero to greater than 30 cm/year, 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 8m (NATIONAL MARINE CONSULTANTS, 1970). The southern hemisphere swell is generated by storms off of 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 sec). The local seas 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).

THE 1982–83 ENSO WINTER

The role that the 1982–83 ENSO event played on the west coast's shoreline and the central coast of California has been well documented. During the months of January, February, and March, eight major storms struck the coast (SEYMOUR, 1983). These storms were associated with offshore maximum significant wave heights between 5 m and 7 m, with the largest waves recorded in northern Monterey Bay (SEYMOUR, 1983). The elevated sea levels and large waves damaged breakwaters, piers, park facilities, seawalls, coastal infrastructure and private and public structures. The January 1983 storms alone destroyed 27 homes and 12 businesses along the state's coastline.

On the central coast, wave impact, flooding, seacliff erosion, and undermining of coastal structures occurred from Pacifica to Monterey Bay. Over 20 m of bluff recession in Pacifica forced the removal of an entire row of mobile homes in a large oceanfront mobile home park. Significant damage to cliff top roads occurred in Santa Cruz, destroying one home. The interior of Monterey Bay provided the best example of the problems associated with building permanent structures on the beach. The common wave approach along the central coast of California is from the northwest and thus the beaches in the northeast corner of Monterey Bay tend to be protected because of the high degree of energy loss incurred by waves refracting around Point Santa Cruz. A wide sandy beach, which is typically in quasi-equilibrium with the predominant northwesterly waves, normally protects this stretch of coast. During January and February of 1983, however, the central coast was struck by a series of storms that approached from the west and southwest. This more southerly approach caused the large waves to strike southerly and southwesterly-facing sections of the coast relatively unimpeded by refraction, resulting little to no energy loss.

For a distance of 4.5 km from Pot Belly Beach to Aptos Seascape, private homes, a state recreational vehicle campground, a county road, restrooms, and a major sewer line have been built on or buried beneath the beach. Damage during early 1983 was extensive and a look at the historic records reveals that past damage has been frequent in this area, particularly during past El Niño events (1925–27, 1929–32, 1939–41, 1977–78, 1982–83). Damage to a timber bulkhead and other facilities at Seacliff State Beach, which had just been rebuilt for the eighth time several months earlier at a cost of $2.75 million, received $1.2 million in damage (GRIGGS and FULTON-BENNETT, 1987). Just downcoast, along Beach Drive, waves and large logs damaged or destroyed virtually every protective structure which had been built to protect homes and a parking lot. Pilings were exposed as sand was scoured from behind the damaged seawalls. Two houses collapsed onto the beach as their pilings were undermined, and other houses lost decks, windows, doors, and stairways (Figure 2). Damage along the adjacent beach front development at Aptos-Seascape was similar, as waves overtopped a revetment and broke through the windows, sliding glass doors, and walls. Further south, waves caused up to 12 m of bluff recession at the Pajaro Dunes development in central Monterey Bay, threatening a number of expensive homes before emergency rip-rap was emplaced (Figure 3). The wharf and restaurants in downtown Capitola were heavily damaged as the waves broke through seaward facing doors and windows.

Due to the severe damages experienced along the majority of the California coast, a systematic inventory of damages and cost estimates was undertaken by the state's coastal zone management agency, the California Coastal Commission (SWISHER, 1983). Our cost estimates were primarily taken from this report and were augmented by other damage inventories published shortly after the 1983 winter storms (GRIGGS and JOHNSON, 1983). To make the cost of damages directly comparable to the 1997–98 damages, we adjusted the 1982–83 cost estimates for inflation using the consumer price index. Table 1 shows the distribution of the approximately $14 million in damages along the central coast in 1982–83.

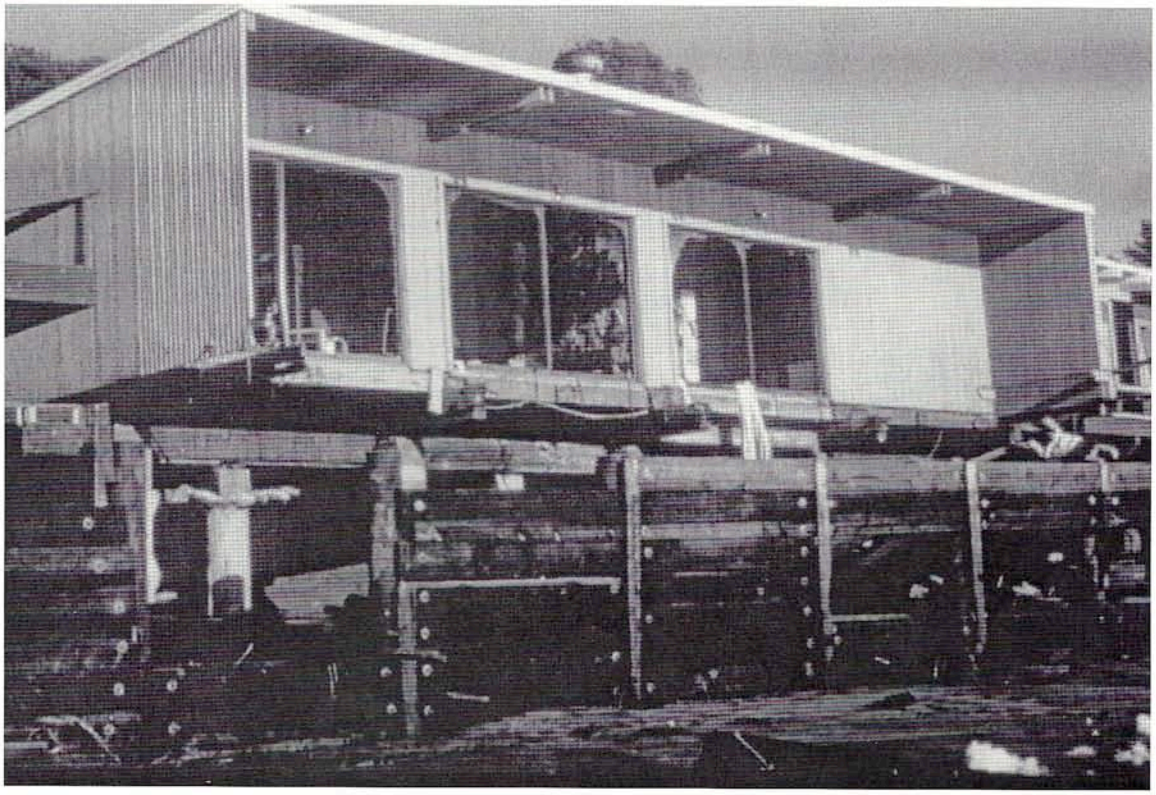

Figure 2. Damage to a house and timber seawall along Beach Drive in northern Monterey Bay resulting from the storms of early 1983. The seawall was battered and breached by waves and debris, allowing over 2 m of fill behind the wall to be scoured, undercutting the structure and threatening the structural support system.

THE 1997–98 ENSO WINTER

The development of a large positive sea surface temperature anomaly in the equatorial Pacific was observed at least as early as June of 1997. The decline of the easterly trade winds in conjunction with the development of persistent westerly onshore winds caused higher than normal sea surface temperatures along the central coast of California during most of the summer and fall. The effect of the decline in offshore wind strength, in conjunction with the propagation of the warm water bulge across the Pacific and up the west coast of the Americas, was first observed in June as the mean monthly sea surface elevation exceeded the maximum monthly elevation recorded in San Francisco during the previous eleven years. By November, strong positive sea level anomalies along the central coast were identified by NASA satellites while the sea surface temperature anomalies had reached +1°C to +2°C along California and greater than +4°C in the eastern equatorial Pacific, surpassing the 28°C threshold necessary for deep tropical convection and precipitation.

The latter half of December, 1997 and the first week of January, 1998 was marked by a rather mild wave climate, with nearshore significant wave heights in northern Monterey Bay never exceeding 1.5 m. In northern Monterey Bay, the first nearshore significant wave heights in excess of 2 m arrived in the second week of January that again coincided with higher than normal sea levels and onshore winds. The waves continued to come out of a more westerly to southwesterly direction than normal and steadily increased in height until the end of the month which was marked by a wave event with nearshore significant wave heights exceeding 2.5 m for the first time since the winter of 1995–96 (STORLAZZI and GRIGGS, 1998). This storm was felt all across the Pacific, generating greater than 10 m waves off Baja California, Mexico, the Hawai'ian Islands, and in Half Moon Bay, California.

The first two weeks of February were marked by the largest waves of the winter in northern Monterey Bay, with nearshore significant wave heights exceeding 4.2 m, higher than any waves in the previous 10 years (STORLAZZI and GRIGGS, 1998). These storms also came out of the southwest and coincided with higher than normal wind velocities and sea level elevations while sea level barometric pressures dropped below 985 mBar, a level not observed in offshore buoy records since the storms of early 1983. The end of February was less energetic than the first half of the month, with one storm producing waves with nearshore significant heights greater than 2.5 m and a second storm with significant wave heights just over 2 m. March was marked by the passing of only three storms that generated abnormally high waves or wind veloc-

Figure 3. Beach and dune erosion at the Pajaro Dunes development in early 1983. Over 15 m of the dunes were eroded during the storms of early 1983, undermining the foundations of many structures. The rip-rap was emplaced at the height of the storms to stop further erosion and the possible collapse of structures.

ities. While all three storms produced significant wave heights greater than 1.5 m, only one of these storms came out of the southwest. Overall, the oceanographic conditions were relatively benign compared to those encountered between mid-January and mid-February.

The coastal areas of central California fared much better during the 1997–98 winter storms, experiencing roughly $6 million in property damages. The most visibly damaged area along the central coast was in Pacifica, where a segment of poorly cemented bluffs retreated over 10 m. In immediate danger of falling over the bluff edge, ten homes were condemned and eventually removed (Figure 4). The Federal Emergency Management Agency (FEMA) bought out the homeowners for approximately $2 million and provided the local government with $1.5 million to reconstruct a large riprap revetment along the toe of the bluff, even though a re-

Table 1. *Central California coastal damages from 1982–83 and 1997–98 winter storms.*

Winter	Location	Description of Damage	Cost Estimate ($)*
1982–1983	Pacifica: Pacific Skies Trailer Park	13–26 m of bluff retreat	93,150
	Pacifica: Beach Boulevard	2–4 m of bluff retreat	291,600
	Santa Cruz County	Road and utility damages	3,137,940
	Capitola: Esplanade & Wharf	Wave impact and innundation	2,106,000
	Seacliff State Park	Damage to bulkhead and facilities	1,198,800
	Aptos: Las Olas Drive	Damage to beachfront homes	648,000
	Rio Del Mar: Beach Drive	Damage to beachfront homes	3,240,000
	Seascape: Via Gaviota	Damage to beachfront homes	3,240,000
	Pajaro Dunes	6–13 m of dune retreat	270,000
			Total: 13,955,490
1997–1998	Pacifica: Esplanade Drive	10 m of bluff retreat	2,000,000
	Santa Cruz: East and West Cliff Drive	Road and bikepath damage	3,300,000
	Santa Cruz: municipal wharf	Structural damage to pilings	500,000
	Capitola: wharf	Structural damage to pilings	35,000
			Total: 5,835,000

*All 1982–1983 coast estimates have been adjusted for inflation using the Consumer Price Index.

Figure 4. Erosion of the seacliff and undercutting of houses along the Esplanade at Pacifica in March of 1998. Rip-rap on the beach marks the location of the cliff toe before the winter storms. The scatter of these several-ton boulders testifies to the wave energies encountered along this section of the central coast during the 1997–98 ENSO storms. Photograph courtesy of Monty Hampton, U.S. Geological Survey.

vetment failed to protect the bluff during the 1997–98 winter. The second area to receive major damage was the city of Santa Cruz, 86 km to the south. Wave damages to the municipal pier and public roads totaled \$3.8 million. The back-beach communities in northern Monterey Bay, which were heavily damaged in 1982–83, survived the winter unharmed. While most coastal structures were spared, large amounts of precipitation triggered landslides and flash floods throughout the central coast, damaging crops, washing out roads and bridges, and flooding homes (Figure 5). If all damages are considered, not just coastal damages, the total property damages in the central coast region reach levels comparable to 1982–83, nearly \$15 million. Similarly, this pattern of precipitation induced damages—flooding, landslides, and debris flows—dominated over marine driven impacts throughout the state, with overall damages for California reaching \$550 million for the 1997–98 winter.

CAUSES FOR DIFFERENTIAL RESPONSE BETWEEN WINTERS

Winds

During the 1982–83 winter, the two largest storms struck the coastline of central California on January 25th and February 27th. Both of these storms were associated with strong, sustained southerly winds (Figure 6a). These winds caused net onshore movement of surface water due to enhanced set-up along many sections of the coast that face the southwest, increasing sea level at the shoreline. This flux of surface water induced downwelling along the coast and near-bed offshore flow, likely increasing beach profile deflation and the susceptibility of structures to wave damage. As shown in Figure 7a, sea surface temperature remained high and fluctuated very little along central California, demonstrating that most strong wind events tended to coincide with more southerly directions by the lack of any significant wind-induced upwelling episodes.

In contrast, the two dominant storms during the 1997–98 winter, which reached the central coast on January 31st and February 15th, were associated with lower sustained wind velocities and more westerly directions (Figure 6b). This caused relatively less wind-induced set-up along the coastline, suppressing nearshore downwelling and near-bed offshore flow. Figure 7b displays the response of the thermocline to these strong northwesterly wind events as sea surface temperatures typically dropped significantly. These differences most likely resulted in less subaqueous beach profile deflation and thus reduced the susceptibility of the coastline to large, damaging waves during the 1997–98 winter.

Sea Surface Elevations

The monthly mean sea surface elevations recorded in San Francisco during the 1997–98 winter were, on average, slightly greater than those observed during the 1982–83 ENSO event. Between June and December, the 1997–98 event was marked by monthly mean sea surface elevations that were on average 4 cm higher than those observed over the same time span in 1982–83. Both winters, however, exceeded the 1984–1995 mean sea surface elevation by more

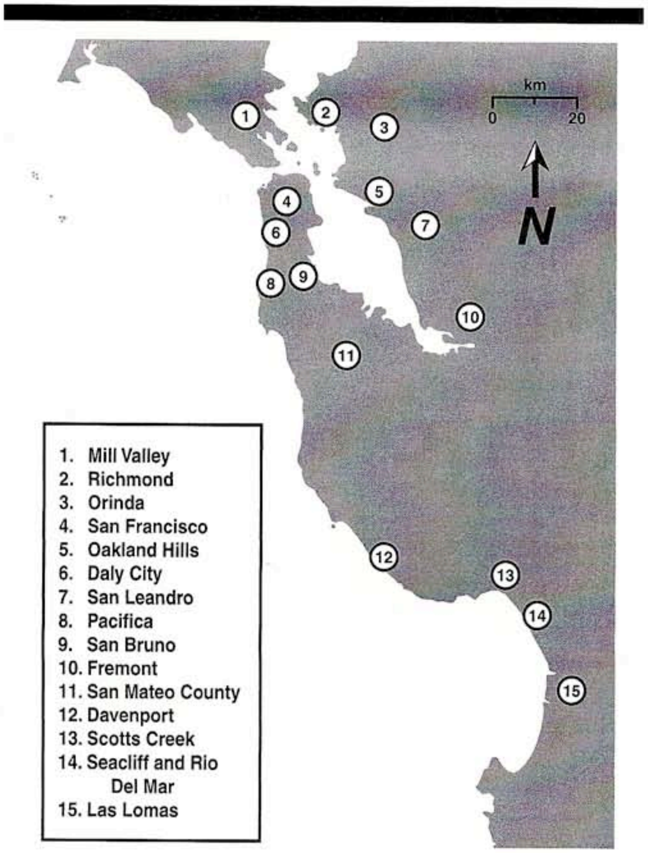

Figure 5. Location of major landslides along the central coast during the 1997–98 ENSO winter. All of the landslides were a result of the high precipitation during the 1997–98 winter; wave erosion played a part in the failure of the coastal bluffs only in Pacifica. Data from the California Department of Conservation's Division of Mines and Geology (http://www.consrv.ca.gov/dmg/).

than 25 cm on average during the more energetic months between November and February (STORLAZZI and GRIGGS, 1998). As discussed by FLICK (1998), the peak astronomical tides were lower and occurred earlier in the 1997–98 winter than in 1982–83 due to the different phases of cycles of the 4.4 year lunar perigee and 18.6 year lunar nodal cycles. Most importantly, however, was simultaneous occurrence of higher than normal sea levels with the impact of large waves as discussed in the next section.

Waves

Although the 1997–98 winter did have nearshore waves approximately 20% higher than any observed in northern Monterey Bay during the 1982–83 winter, the latter was marked by larger waves over a longer span of time. As of May 1998 significant wave heights greater than 2.5 m only occurred during two months while northern Monterey Bay endured five months that were marked by significant wave heights greater than 2.5 m during the 1982–83 winter (STORLAZZI and GRIGGS, 1998).

As shown in Figure 8, while comparable wave heights were observed during the 1982–83 and 1997–98 ENSO winters, the major storms struck the central coast during distinctly different periods of the monthly tidal cycle. During the 1982–83 winter, the two largest storms struck the central coast during spring tides. The high tides elevated the level of wave attack relative to the protective beach, decreased wave energy loss to bottom friction, and increased beach pore fluid pressures, all of which increased beach erosion and the susceptibility of structures to wave-induced damage. During the 1997–98 ENSO winter, the largest storms hit during lower periods of the monthly tidal cycle, significantly reducing the impact of waves upon the shoreline. Since wave impact upon coastal structures is strongly dependent upon tidal elevation along meso-tidal coastlines, we defined a relative wave power (P_r) to describe the influence of this interaction:

$$P_r = P\frac{d}{\min(d)}$$

where: $P = ECn$ and d is the instantaneous water depth or tidal elevation. Thus, the relative wave power increases fourfold for waves with similar heights and celerities but which strike the coast during a +2 m high tide than during a +0.5 m low tide assuming the minimum tidal elevation is +0.5 m. As demonstrated in Figure 9, the relative wave power was shown to have been substantially higher during the 1982–83 winter than in 1997–98, most likely contributing to the much higher wave damage that occurred in 1982–83. These differences in relative wave power are supported by the storm surge data presented by FLICK (1998).

Duration of Exposure to Anomalous Conditions

Another contributing factor to the disparity in winter damages between 1982–83 and 1997–98 was the difference in the length of time that the central coast was impacted by severe weather (Table 2). Although the 1997–98 winter experienced a slightly longer duration of larger than normal deep-water waves, the 1982–83 ENSO event was marked by a longer duration of higher wind velocities and lower sea level barometric pressures and thus wind-induced set-up, most likely increasing the damage to coastal structures. However, when the tidal elevation is included into the wave height data as defined by relative wave power, the 1982–83 ENSO event caused the central coast to be exposed to large waves at higher tidal elevations over a much longer period of time than during the 1997–98 winter.

As discussed earlier, the dominant direction of wave approach for the central coast is from the northwest and therefore northern Monterey Bay, where much of the damage occurred in 1982–83, is largely sheltered from large waves. Thus, nearshore wave heights in northern Monterey Bay are a proxy for the combination of deep-water waves and westerly to southwesterly directions of wave approach with which the central coast is typically not in equilibrium. During the 1982–83 winter, northern Monterey Bay was struck by abnormally large (>2.5 m) waves in the nearshore as early as November which, except for March, persisted every month through April. During the 1997–98 winter, however, the northern Monterey Bay was struck by waves higher than 2.5 m only during January and February (STORLAZZI and GRIGGS,

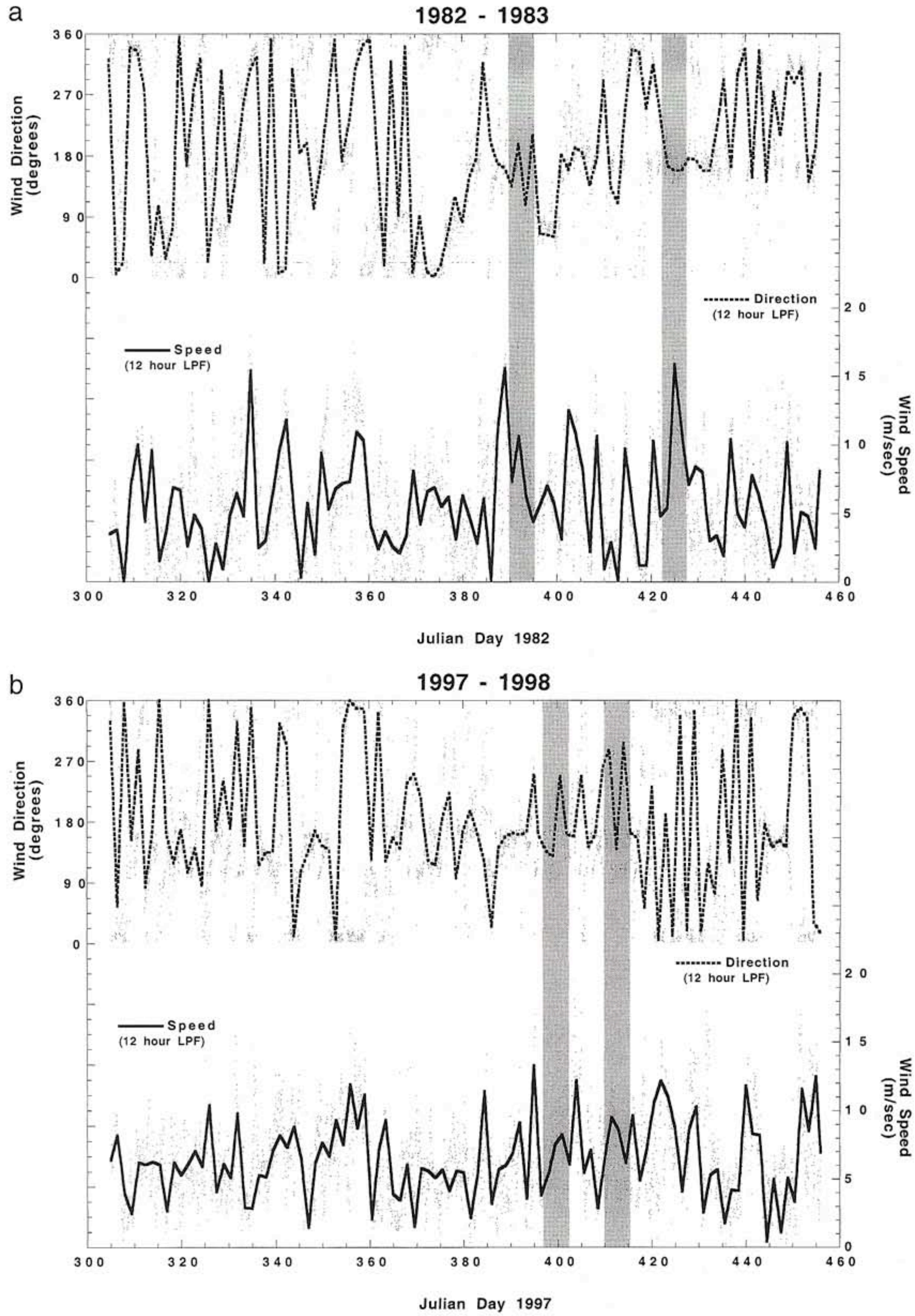

Figure 6. Fluctuations in wind direction and velocity from N.O.A.A. buoy #46026 during the (a) 1982–83 ENSO event, and (b) the 1997–98 ENSO event. The grey bands denote the periods when the most intense storms struck the central coast. Note the correlation between the higher wind velocities and the more southwesterly directions during the major 1982–83 storms as compared to the 1997–98 storms.

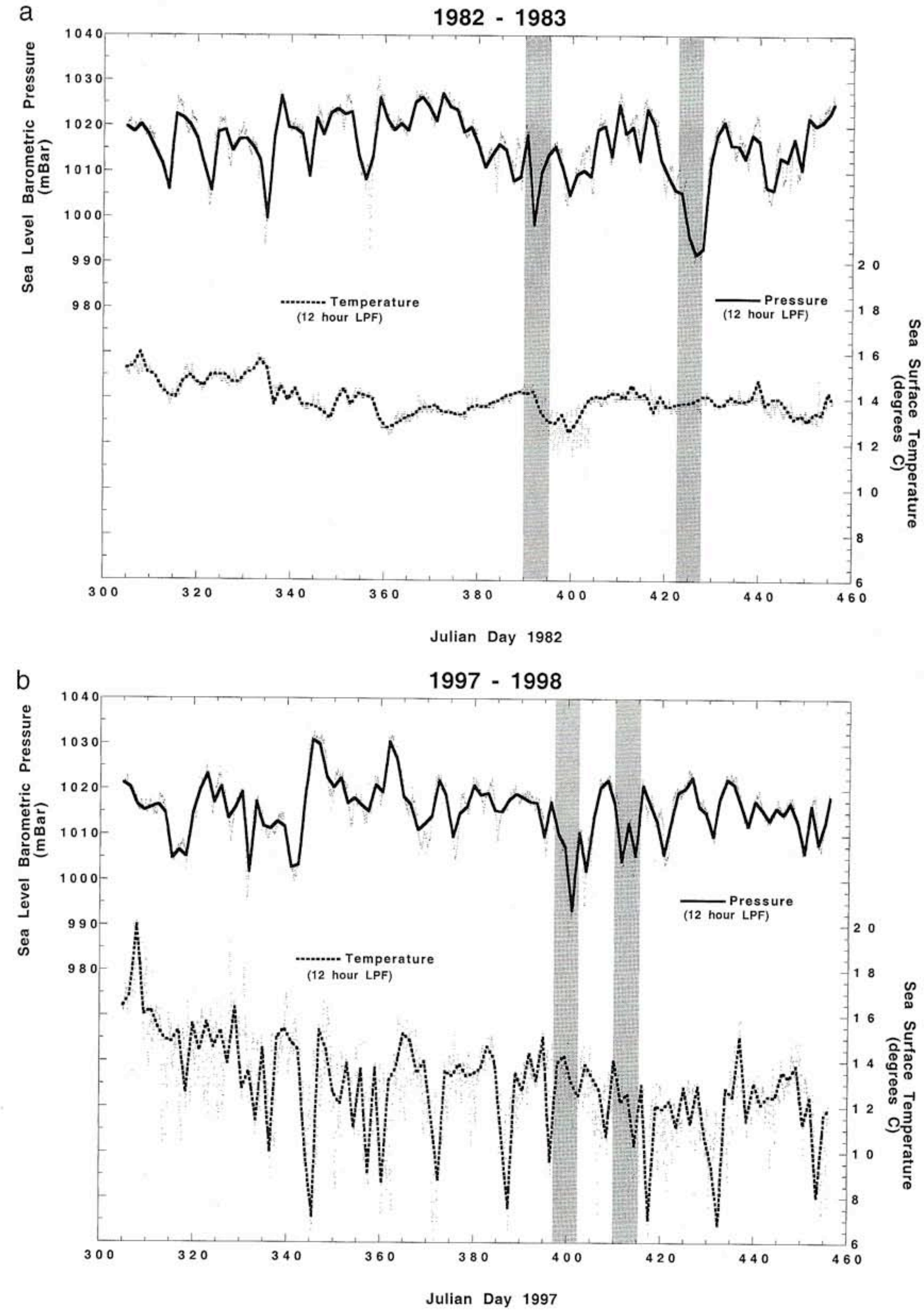

Figure 7. Fluctuations in sea level barometric pressure and sea surface temperature from NOAA buoy #46026 during the (a) 1982–83 ENSO event, and (b) the 1997–98 ENSO event. The dark lines represent 12-hour low-pass-filtered signals while the dots represent hourly data values. The grey bands denote the periods when the most intense storms struck the central coast. The sharp drops in sea surface temperature during the 1997–98 winter typically follow storms incident from the northwest with high sustained wind velocities.

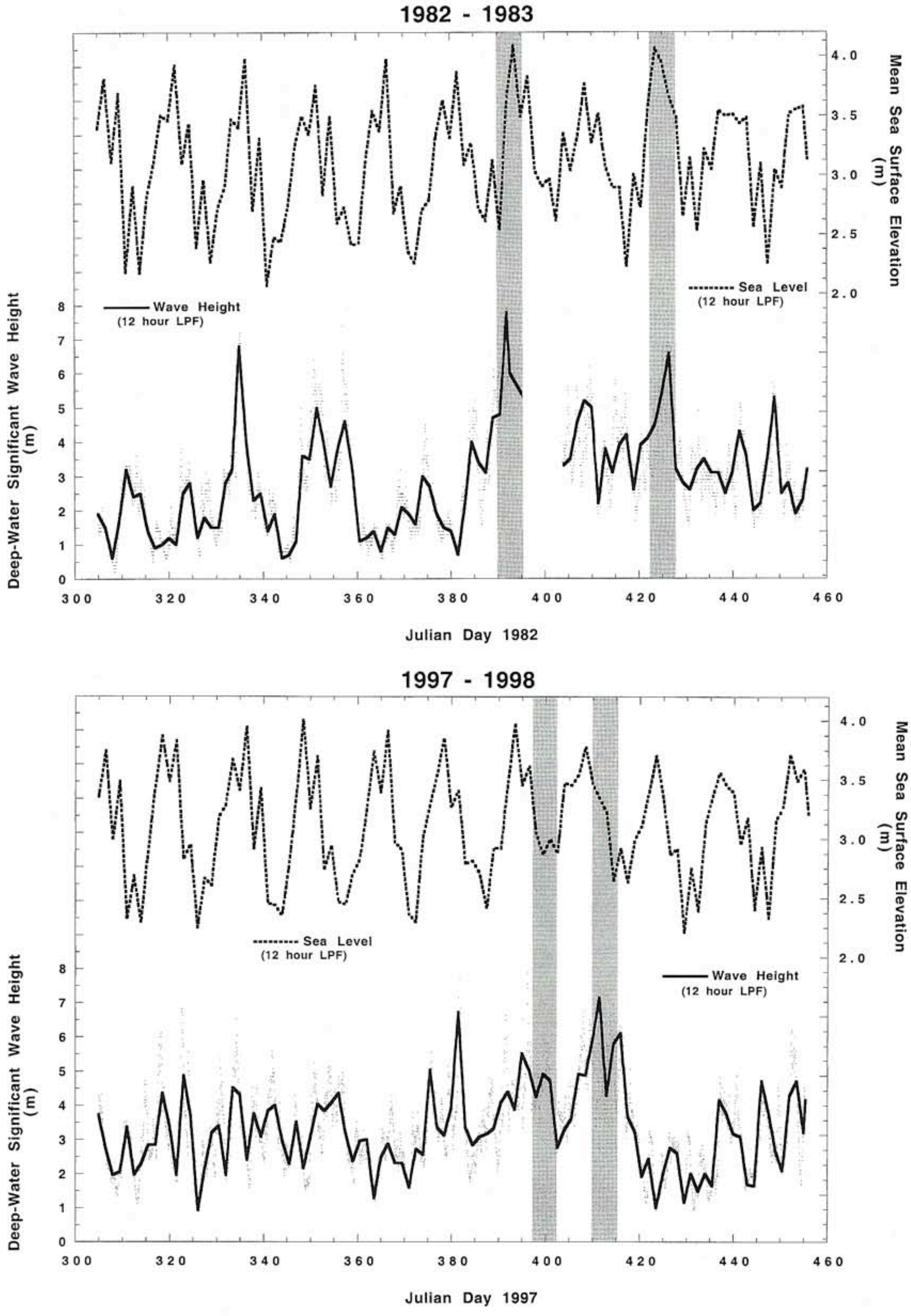

Figure 8. Fluctuations in the sea surface elevation at Monterey Harbor and wave height from N.O.A.A. buoy #46026 during the (a) 1982–83 ENSO event, and (b) the 1997–98 ENSO event. The dark lines represent 12-hour low-pass-filtered signals while the dots represent hourly data values. The grey bands denote the periods when the most intense storms struck the central coast. Note the coincidence of large waves and spring tides in 1982–83, while the largest waves in 1997–98 struck the central coast during neap tides.

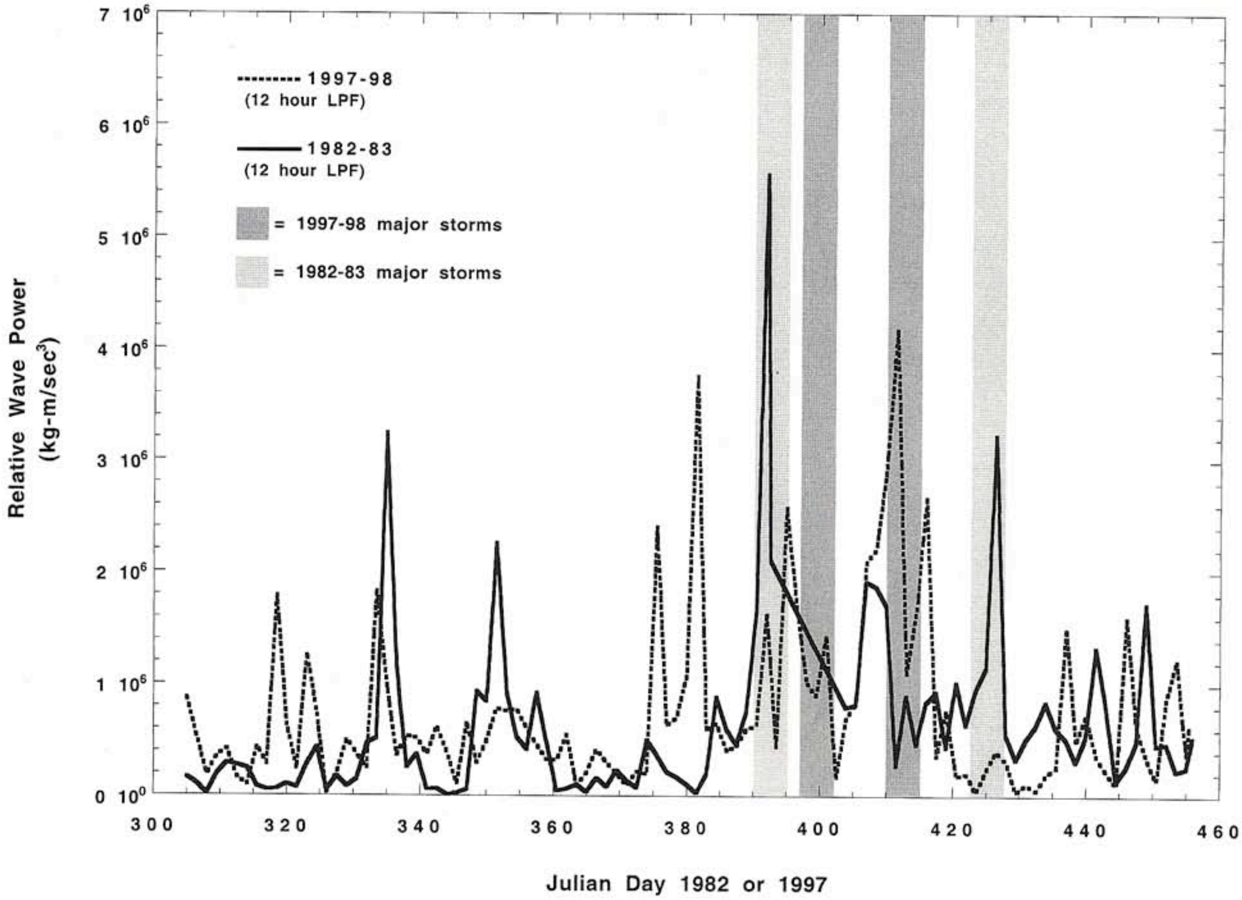

Figure 9. Fluctuations in the relative wave power data for the 1982–83 and 1997–98 ENSO events. The dark lines represent 12-hour low-pass-filtered signals while the dots represent hourly data values. The grey bands denote the periods when the most intense storms struck the central coast.

Table 2. *Duration of exposure to anomalous conditions during 1982–83 and 1997–98 ENSO events as recorded by N.O.A.A. buoy #46026.*

Parameter	Level Exceeded	1982–1983 Hours Exceeded		1997–1998 Hours Exceeded	
Deep-Water Significant Wave Height (m)					
	>7	11		13	
	>6	66		93	
	>5	269		352	
Wind Speed (m/sec)					
	>17	9		6	
	>15	48		30	
	>10	525		422	
Sea Level Barometric Pressure (mBar)					
	<990	0		9	
	<995	77		27	
	<1000	116		57	
Relative Wave Power (kg-m/sec³)					
	$>6 \times 10^6$	1		0	
	$>5 \times 10^6$	7	2,5*	0	
	$>4 \times 10^6$	12	3,9*	8	1,2,2,3*
	$>3 \times 10^6$	37		52	

* Number of consecutive hours the relative wave power was exceeded.

1998). The longer duration of higher than normal wave heights during the 1982–83 winter caused beaches sheltered from the dominant northwesterly wave approach to be eroded earlier in the winter which hampered their recovery through the winter by the sustained high energies. Beach erosion therefore allowed the large winter waves to attack coastal bluffs, structures and infrastructure relatively unimpeded, causing considerable erosion and damage. During the 1997–98 winter, however, the central coast experienced a narrower window with abnormally high nearshore waves, and thus the amount of time that coastal cliffs and human structures were unprotected by fronting beaches and directly exposed to wave energy was substantially less, reducing the amount of erosion and damage.

Antecedent Conditions

Another factor that may have caused the greater damage that occurred during the 1982–83 ENSO event was that it followed a distinctly more energetic winter than the 1996–97 winter. The 1981–82 winter was marked by two storms that caused coastal erosion and damage to the central coast of California while no damaging or erosive storms were record-

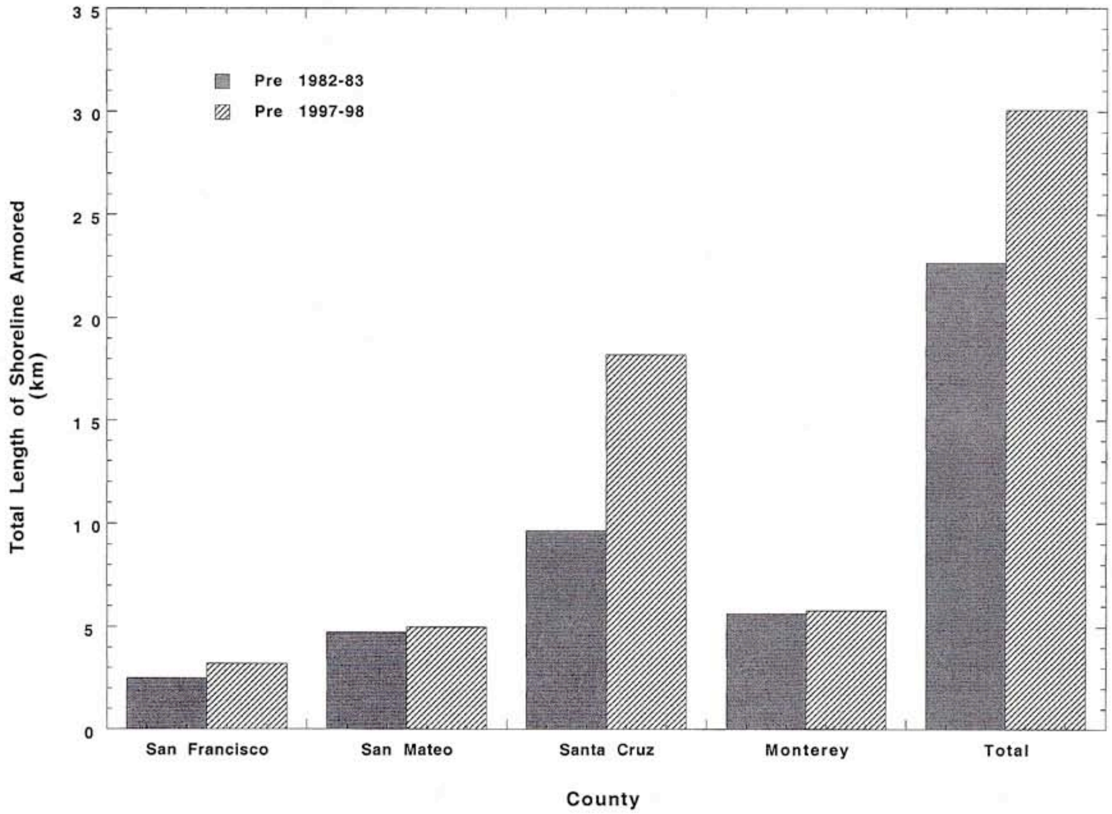

Figure 10. Distribution of coastline protection structures along central California and the increase in the number of structures between the 1982–83 and 1997–98 ENSO winters. Overall, there was a 30% increase in armoring along the central coast following the 1982–83 ENSO event.

ed during the relatively benign 1996–97 winter. The storms and erosion that occurred during 1981–82 may have caused the beaches to erode to a degree that they were not able to completely recover before the following winter. This would have made the shoreline more vulnerable to the high-energy conditions encountered during the 1982–83 winter. While there are no beach erosion data for the 1982–83 winter to substantiate this hypothesis, it does remain a distinct possibility.

Precipitation

The 1997–98 ENSO winter was marked by much higher levels of precipitation than those observed in 1982–83. Between November and March, the 1997–98 winter's mean monthly accumulated precipitation exceeded the 1982–83 event by 9 cm on average, and during February of 1998, the mean accumulated precipitation recorded was roughly three times the precipitation observed during February of 1983 (Storlazzi and Griggs, 1998). The significantly higher levels of precipitation during the 1997–98 ENSO event caused large volumes of sediment to be supplied to the coastline during the energetic winter months, helping to buffer wave impact. This buffering was a result of the deposition of sediment across the beaches' subaqueous profiles downcoast of streams and rivers, resupplying sediment to the bed that had been lost to offshore-directed flow resulting from increased wave heights and infragravity motions. Numerous bars formed offshore many of the river and stream mouths, causing waves to break further offshore, dissipating much of their energy before reaching the shoreline (USGS/UCSC/NASA/NOAA Collaborative Research Group, 1998). The high sediment concentrations in the nearshore also dampened turbulence by increasing stratification of the water column, reducing sediment suspension from the bed and thus bed erosion, reducing subaqueous beach profile deflation. The higher level of precipitation during the 1997–98 ENSO event was the primary cause for the larger number of both coastal (Figure 4) and inland (Figure 5) bluff and slope failures than during the 1982–83 winter.

Armoring

A final factor that contributed to the higher amount of coastal damage caused by the 1982–83 winter was the higher degree of shoreline armoring at the time of the 1997–98 winter compared to 1982–83. Between the 1982–83 and the 1997–98 ENSO events, roughly 7 km of coastal protective structures were built along the central coast (Figure 10). In Santa Cruz County, for example, the proportion of coastline protected by seawalls, revetments, bulkheads, or other types of structures prior to 1982–83 was approximately 17%. By

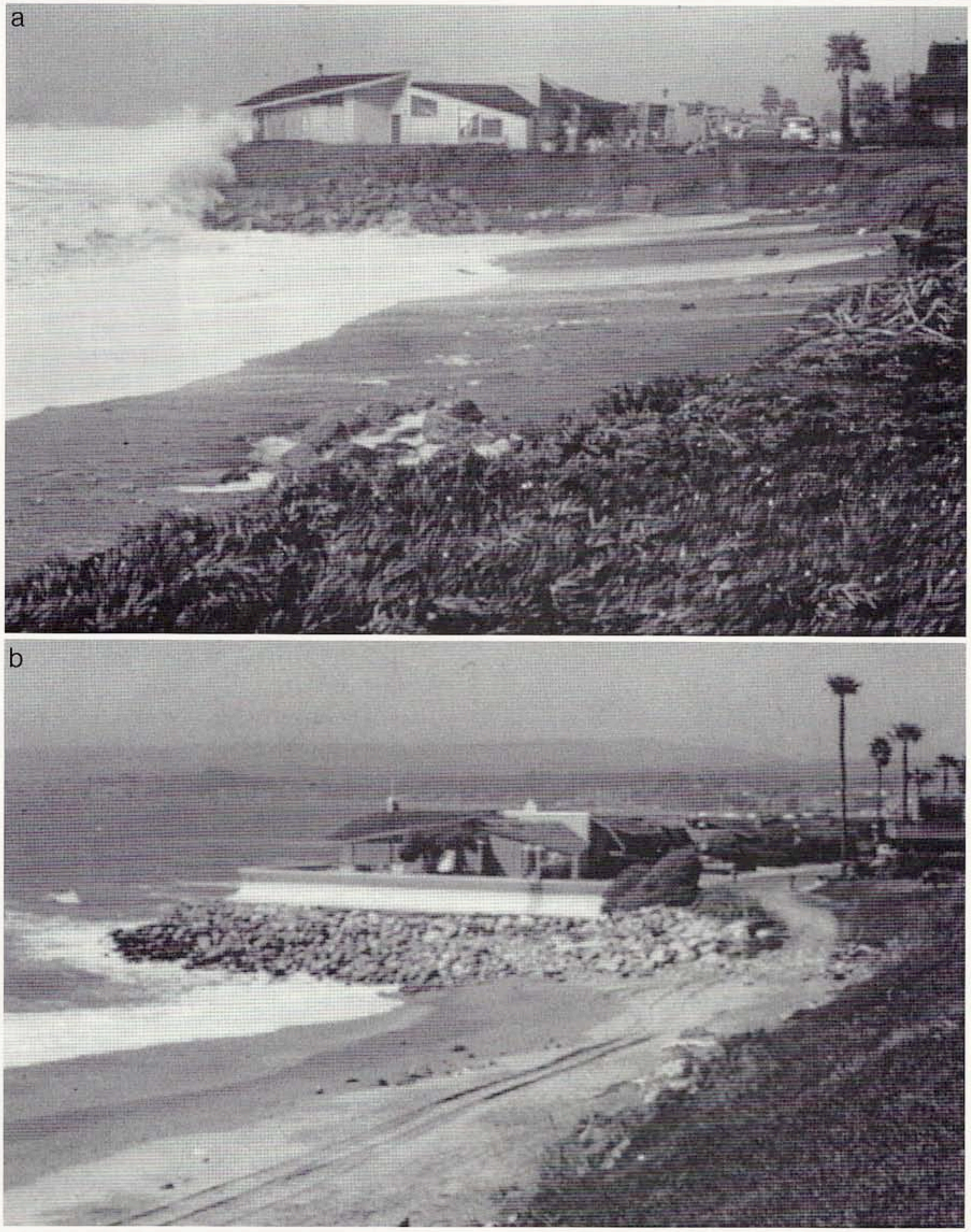

Figure 11. Changes in the construction and the effectiveness of coastal protection structures along Via Gaviota in Aptos-Seascape during early (a) 1983, and (b) 1998. Following the storms of early 1983, the rip-rap revetment was removed, a new curved-face concrete seawall was placed upon steel piles driven to refusal, and the rip-rap was then placed back at the toe of the seawall to provide additional protection. None of the houses along Via Gaviota reported wave-induced damage during the 1997–98 winter.

the latter half of the 1990s, the percentage of shoreline armored rose to more than 65%, nearly a threefold increase. The majority of this increase in armoring can be attributed directly to the 1982–83 storms: 50% of all armoring approved by the California Coastal Commission between 1978 and 1994 occurred in the months following the 1982–83 winter (CALIFORNIA COASTAL COMMISSION, 1995). Of the unprotected regions along northern Monterey Bay that were hard hit during the 1982–83 winter, almost all of them were armored or rearmored before the 1997–98 ENSO event. This armoring substantially reduced susceptibility to the higher than normal sea surface elevations and wave heights that occurred during the 1997–98 winter. Not only were large amounts of armoring emplaced along the coast, but the 1982–83 ENSO event destroyed most of the old and poorly designed structures. As a result, most areas that experienced significant damage over the 1982–83 winter rebuilt their protective structures according to new design criteria: the maximum wave heights and sea levels experienced in the 1982–83 winter. The significant improvement in coastal armoring design is evident in the back beach communities of southern Santa Cruz County. The timber bulkhead at Seacliff State Beach, rebuilt after the 1983 storms with a sacrificial bumper, survived the 1997–98 winter intact. Figure 11a shows the southernmost home along Via Gaviota in Aptos-Seascape in January 1983. Designed in 1968, the revetment was constructed to a height of 4 m above mean sea level. Over the last days of January 1983, waves were breaking over the top of the revetment, which appears to have experienced at least a meter of settling, and caused over $3 million in damages. The new protective structure consists of a curved concrete seawall anchored into the underlying bedrock with a rip-rap toe constructed to an elevation of 5.5 m above mean sea level (Figure 11b). The higher elevation of the new seawall and the lower sea level conditions prevented the damaging wave over-topping experienced in 1982–83.

CONCLUSIONS

The results of this study imply that the most important factor in affecting the severity of storm damage is the timing of large wave impacts on the coast. Not only did the 1982–83 winter storm waves arrive at the coast during high astronomical tides, but also there were a larger number of storms over the winter season. On average, the storms lingered along the coast over several tidal cycles, and the storms coincided with southerly winds that increased wave set-up and induced offshore flow of beach sediment. Federal and state agencies, including the National Oceanic and Atmospheric Agency (NOAA), FEMA, and the California Office of Emergency Services (OES), have touted successful mitigation stories, claiming a savings of hundreds of millions of dollars in comparison to the two previous winters in California through advanced forecasting. While this may be the case for some inland fluvial environments where flood damages may have been minimized, this is certainly not true for the coastal zone. In reality, at least along the high energy west coast, there is relatively little that can be done over the short term to reduce the impacts of an ENSO event along California's heavily urbanized coastline.

The 1997–98 winter storm waves arrived during low tides, the wave heights decreased before the next tidal cycle, and the storms coincided with westerly winds that directed sediment-laden bottom currents onshore, all of which effectively limited the landward penetration and energy of the waves. Although increases in shoreline armoring structures and improvements in armoring design, particularly in Santa Cruz County and along Monterey Bay, were a secondary factor in minimizing damages, the benefits to the private homeowners are not without significant impacts to public resources.

Looking to the future, studies that attempt to explain the coastline's response to large episodic events by examining both the natural physical processes and the anthropogenic factors will be necessary to improve the resiliency of our coastal communities. VAN DER VINK et al. (1998) showed that even disregarding climate trends of increased storm activity and rising sea levels, the US coastal zone is experiencing an exponential growth in natural disaster liabilities due to increases in wealth and the significant investments of that wealth in high risk coastal property and infrastructure. Recognizing the primary importance of ENSO events along the central California coast, our results show that while well-designed engineering structures can minimize marine driven damages from ENSO winter storms, the most effective method to reduce damages is to avoid the encroachment of any new structures in the highest risk areas—back-beach environments, coastal dunes, and unstable, eroding seacliffs.

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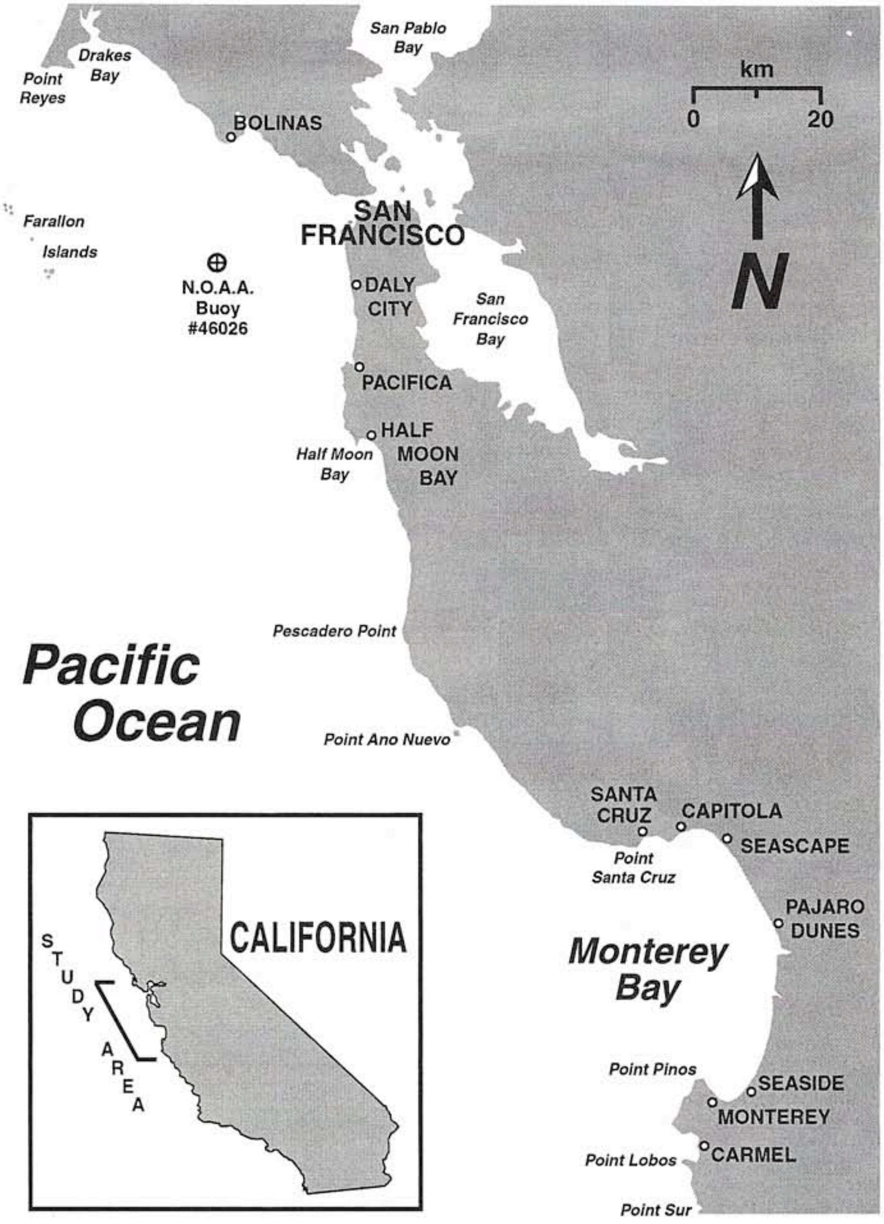

Figure 1. Map of the study area showing the major coastal population centers and prominent features of the central California coast.

ifornia amounted only to $6 million. While significant wave heights during the 1997–98 storms met or even exceeded those in 1982–83, the 1997–98 winter storms struck the coast during significantly lower tidal conditions and coincided with more northerly waves and winds that reduced set-up along the coast. Moreover, the communities constructed along the back-beach in northern Monterey Bay severely damaged in 1982–83 invested heavily in coastal protection structures, engineered according to new design criteria provided by the 1982–83 storms. The coupling of waves, winds, and spring tides, along with the increase in armoring and the redesign and/or reconstruction of much existing armoring decreased the overall damage to coastal structures during the 1997–98 winter. These factors are likely largely responsible for reducing the economic impacts of the 1997–98 winter storms by more than 50% of the damage costs incurred during the 1982–83 winter.

STUDY AREA

This study focuses on the coastline of central California from San Francisco in the north to the Carmel River in Monterey County in the south (Figure 1). This 147 km section of shoreline is characterized by population centers in San Francisco, Pacifica, Half Moon Bay, Santa Cruz, and along Monterey Bay, but with approximately 103 km (71%) of undeveloped shoreline interspersed between these cities. The primary sources of coarse-grained sediment to the littoral environment are sand discharged through the Golden Gate and the numerous small, steep perennial streams and less frequent rivers that drain the coastal mountains (BEST and GRIGGS, 1991). The mouths of many of these streams were inundated during the Holocene transgression, forming low-gradient floodplains, coastal lagoons, and marshes in their lower reaches, many of which are backed by dune fields (GRIGGS and SAVOY, 1985; DINGLER *et al.,* 1985).

Steep, up to 100 m high, actively eroding coastal bluffs bound the central coast; these are often incised into uplifted marine terraces and, in northern Santa Cruz County, are commonly fronted by low, wave-cut shore platforms. The seacliffs are interrupted at irregular intervals by pocket beaches that form at the mouths of coastal streams or in joint-bounded coves and by infrequent continuous beaches in sheltered bays. Seacliff erosion, with long-term rates ranging from essentially zero to greater than 30 cm/year, 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 8m (NATIONAL MARINE CONSULTANTS, 1970). The southern hemisphere swell is generated by storms off of 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 sec). The local seas 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).

THE 1982–83 ENSO WINTER

The role that the 1982–83 ENSO event played on the west coast's shoreline and the central coast of California has been well documented. During the months of January, February, and March, eight major storms struck the coast (SEYMOUR, 1983). These storms were associated with offshore maximum significant wave heights between 5 m and 7 m, with the largest waves recorded in northern Monterey Bay (SEYMOUR, 1983). The elevated sea levels and large waves damaged breakwaters, piers, park facilities, seawalls, coastal infrastructure and private and public structures. The January 1983 storms alone destroyed 27 homes and 12 businesses along the state's coastline.

On the central coast, wave impact, flooding, seacliff erosion, and undermining of coastal structures occurred from Pacifica to Monterey Bay. Over 20 m of bluff recession in Pacifica forced the removal of an entire row of mobile homes in a large oceanfront mobile home park. Significant damage to cliff top roads occurred in Santa Cruz, destroying one home. The interior of Monterey Bay provided the best example of the problems associated with building permanent structures on the beach. The common wave approach along the central coast of California is from the northwest and thus the beaches in the northeast corner of Monterey Bay tend to be protected because of the high degree of energy loss incurred by waves refracting around Point Santa Cruz. A wide sandy beach, which is typically in quasi-equilibrium with the predominant northwesterly waves, normally protects this stretch of coast. During January and February of 1983, however, the central coast was struck by a series of storms that approached from the west and southwest. This more southerly approach caused the large waves to strike southerly and southwesterly-facing sections of the coast relatively unimpeded by refraction, resulting little to no energy loss.

For a distance of 4.5 km from Pot Belly Beach to Aptos Seascape, private homes, a state recreational vehicle campground, a county road, restrooms, and a major sewer line have been built on or buried beneath the beach. Damage during early 1983 was extensive and a look at the historic records reveals that past damage has been frequent in this area, particularly during past El Niño events (1925–27, 1929–32, 1939–41, 1977–78, 1982–83). Damage to a timber bulkhead and other facilities at Seacliff State Beach, which had just been rebuilt for the eighth time several months earlier at a cost of \$2.75 million, received \$1.2 million in damage (GRIGGS and FULTON-BENNETT, 1987). Just downcoast, along Beach Drive, waves and large logs damaged or destroyed virtually every protective structure which had been built to protect homes and a parking lot. Pilings were exposed as sand was scoured from behind the damaged seawalls. Two houses collapsed onto the beach as their pilings were undermined, and other houses lost decks, windows, doors, and stairways (Figure 2). Damage along the adjacent beach front development at Aptos-Seascape was similar, as waves overtopped a revetment and broke through the windows, sliding glass doors, and walls. Further south, waves caused up to 12 m of bluff recession at the Pajaro Dunes development in central Monterey Bay, threatening a number of expensive homes before emergency rip-rap was emplaced (Figure 3). The wharf and restaurants in downtown Capitola were heavily damaged as the waves broke through seaward facing doors and windows.

Due to the severe damages experienced along the majority of the California coast, a systematic inventory of damages and cost estimates was undertaken by the state's coastal zone management agency, the California Coastal Commission (SWISHER, 1983). Our cost estimates were primarily taken from this report and were augmented by other damage inventories published shortly after the 1983 winter storms (GRIGGS and JOHNSON, 1983). To make the cost of damages directly comparable to the 1997–98 damages, we adjusted the 1982–83 cost estimates for inflation using the consumer price index. Table 1 shows the distribution of the approximately \$14 million in damages along the central coast in 1982–83.

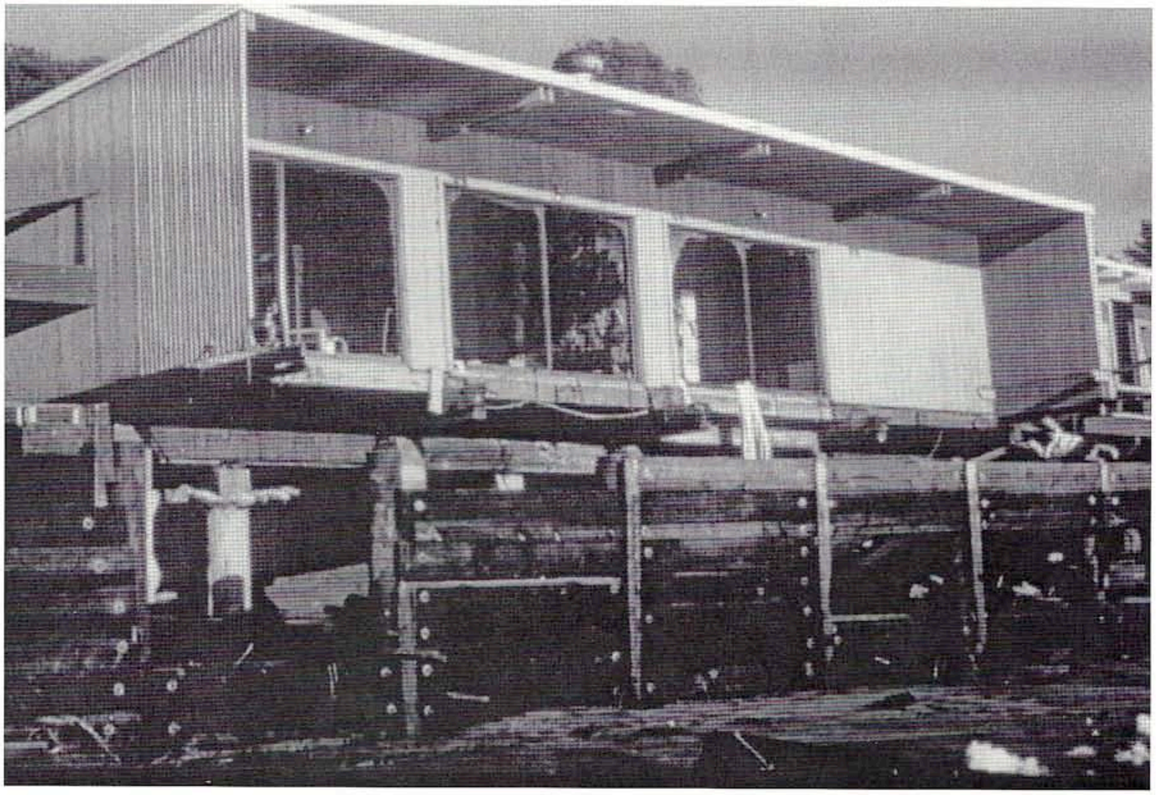

Figure 2. Damage to a house and timber seawall along Beach Drive in northern Monterey Bay resulting from the storms of early 1983. The seawall was battered and breached by waves and debris, allowing over 2 m of fill behind the wall to be scoured, undercutting the structure and threatening the structural support system.

THE 1997–98 ENSO WINTER

The development of a large positive sea surface temperature anomaly in the equatorial Pacific was observed at least as early as June of 1997. The decline of the easterly trade winds in conjunction with the development of persistent westerly onshore winds caused higher than normal sea surface temperatures along the central coast of California during most of the summer and fall. The effect of the decline in offshore wind strength, in conjunction with the propagation of the warm water bulge across the Pacific and up the west coast of the Americas, was first observed in June as the mean monthly sea surface elevation exceeded the maximum monthly elevation recorded in San Francisco during the previous eleven years. By November, strong positive sea level anomalies along the central coast were identified by NASA satellites while the sea surface temperature anomalies had reached +1°C to +2°C along California and greater than +4°C in the eastern equatorial Pacific, surpassing the 28°C threshold necessary for deep tropical convection and precipitation.

The latter half of December, 1997 and the first week of January, 1998 was marked by a rather mild wave climate, with nearshore significant wave heights in northern Monterey Bay never exceeding 1.5 m. In northern Monterey Bay, the first nearshore significant wave heights in excess of 2 m arrived in the second week of January that again coincided with higher than normal sea levels and onshore winds. The waves continued to come out of a more westerly to southwesterly direction than normal and steadily increased in height until the end of the month which was marked by a wave event with nearshore significant wave heights exceeding 2.5 m for the first time since the winter of 1995–96 (Storlazzi and Griggs, 1998). This storm was felt all across the Pacific, generating greater than 10 m waves off Baja California, Mexico, the Hawai'ian Islands, and in Half Moon Bay, California.

The first two weeks of February were marked by the largest waves of the winter in northern Monterey Bay, with nearshore significant wave heights exceeding 4.2 m, higher than any waves in the previous 10 years (Storlazzi and Griggs, 1998). These storms also came out of the southwest and coincided with higher than normal wind velocities and sea level elevations while sea level barometric pressures dropped below 985 mBar, a level not observed in offshore buoy records since the storms of early 1983. The end of February was less energetic than the first half of the month, with one storm producing waves with nearshore significant heights greater than 2.5 m and a second storm with significant wave heights just over 2 m. March was marked by the passing of only three storms that generated abnormally high waves or wind veloc-

Figure 3. Beach and dune erosion at the Pajaro Dunes development in early 1983. Over 15 m of the dunes were eroded during the storms of early 1983, undermining the foundations of many structures. The rip-rap was emplaced at the height of the storms to stop further erosion and the possible collapse of structures.

ities. While all three storms produced significant wave heights greater than 1.5 m, only one of these storms came out of the southwest. Overall, the oceanographic conditions were relatively benign compared to those encountered between mid-January and mid-February.

The coastal areas of central California fared much better during the 1997–98 winter storms, experiencing roughly $6 million in property damages. The most visibly damaged area along the central coast was in Pacifica, where a segment of poorly cemented bluffs retreated over 10 m. In immediate danger of falling over the bluff edge, ten homes were condemned and eventually removed (Figure 4). The Federal Emergency Management Agency (FEMA) bought out the homeowners for approximately $2 million and provided the local government with $1.5 million to reconstruct a large rip-rap revetment along the toe of the bluff, even though a re-

Table 1. *Central California coastal damages from 1982–83 and 1997–98 winter storms.*

Winter	Location	Description of Damage	Cost Estimate ($)*
1982–1983	Pacifica: Pacific Skies Trailer Park	13–26 m of bluff retreat	93,150
	Pacifica: Beach Boulevard	2–4 m of bluff retreat	291,600
	Santa Cruz County	Road and utility damages	3,137,940
	Capitola: Esplanade & Wharf	Wave impact and innundation	2,106,000
	Seacliff State Park	Damage to bulkhead and facilities	1,198,800
	Aptos: Las Olas Drive	Damage to beachfront homes	648,000
	Rio Del Mar: Beach Drive	Damage to beachfront homes	3,240,000
	Seascape: Via Gaviota	Damage to beachfront homes	3,240,000
	Pajaro Dunes	6–13 m of dune retreat	270,000
			Total: 13,955,490
1997–1998	Pacifica: Esplanade Drive	10 m of bluff retreat	2,000,000
	Santa Cruz: East and West Cliff Drive	Road and bikepath damage	3,300,000
	Santa Cruz: municipal wharf	Structural damage to pilings	500,000
	Capitola: wharf	Structural damage to pilings	35,000
			Total: 5,835,000

*All 1982–1983 coast estimates have been adjusted for inflation using the Consumer Price Index.

Figure 4. Erosion of the seacliff and undercutting of houses along the Esplanade at Pacifica in March of 1998. Rip-rap on the beach marks the location of the cliff toe before the winter storms. The scatter of these several-ton boulders testifies to the wave energies encountered along this section of the central coast during the 1997–98 ENSO storms. Photograph courtesy of Monty Hampton, U.S. Geological Survey.

vetment failed to protect the bluff during the 1997–98 winter. The second area to receive major damage was the city of Santa Cruz, 86 km to the south. Wave damages to the municipal pier and public roads totaled \$3.8 million. The back-beach communities in northern Monterey Bay, which were heavily damaged in 1982–83, survived the winter unharmed. While most coastal structures were spared, large amounts of precipitation triggered landslides and flash floods throughout the central coast, damaging crops, washing out roads and bridges, and flooding homes (Figure 5). If all damages are considered, not just coastal damages, the total property damages in the central coast region reach levels comparable to 1982–83, nearly \$15 million. Similarly, this pattern of precipitation induced damages—flooding, landslides, and debris flows—dominated over marine driven impacts throughout the state, with overall damages for California reaching \$550 million for the 1997–98 winter.

CAUSES FOR DIFFERENTIAL RESPONSE BETWEEN WINTERS

Winds

During the 1982–83 winter, the two largest storms struck the coastline of central California on January 25th and February 27th. Both of these storms were associated with strong, sustained southerly winds (Figure 6a). These winds caused net onshore movement of surface water due to enhanced set-up along many sections of the coast that face the southwest, increasing sea level at the shoreline. This flux of surface water induced downwelling along the coast and near-bed offshore flow, likely increasing beach profile deflation and the susceptibility of structures to wave damage. As shown in Figure 7a, sea surface temperature remained high and fluctuated very little along central California, demonstrating that most strong wind events tended to coincide with more southerly directions by the lack of any significant wind-induced upwelling episodes.

In contrast, the two dominant storms during the 1997–98 winter, which reached the central coast on January 31st and February 15th, were associated with lower sustained wind velocities and more westerly directions (Figure 6b). This caused relatively less wind-induced set-up along the coastline, suppressing nearshore downwelling and near-bed offshore flow. Figure 7b displays the response of the thermocline to these strong northwesterly wind events as sea surface temperatures typically dropped significantly. These differences most likely resulted in less subaqueous beach profile deflation and thus reduced the susceptibility of the coastline to large, damaging waves during the 1997–98 winter.

Sea Surface Elevations

The monthly mean sea surface elevations recorded in San Francisco during the 1997–98 winter were, on average, slightly greater than those observed during the 1982–83 ENSO event. Between June and December, the 1997–98 event was marked by monthly mean sea surface elevations that were on average 4 cm higher than those observed over the same time span in 1982–83. Both winters, however, exceeded the 1984–1995 mean sea surface elevation by more

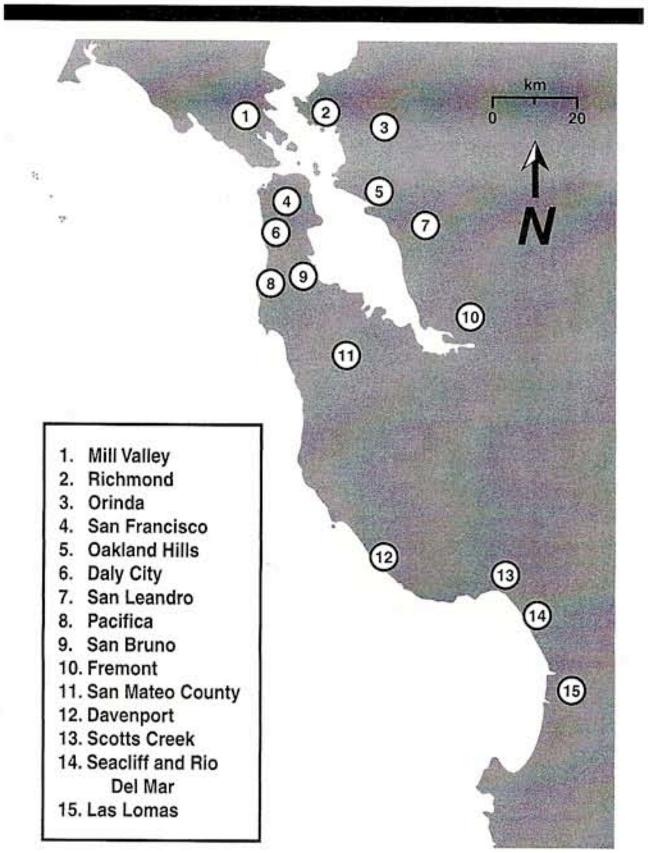

Figure 5. Location of major landslides along the central coast during the 1997–98 ENSO winter. All of the landslides were a result of the high precipitation during the 1997–98 winter; wave erosion played a part in the failure of the coastal bluffs only in Pacifica. Data from the California Department of Conservation's Division of Mines and Geology (http://www.consrv.ca.gov/dmg/).

than 25 cm on average during the more energetic months between November and February (STORLAZZI and GRIGGS, 1998). As discussed by FLICK (1998), the peak astronomical tides were lower and occurred earlier in the 1997–98 winter than in 1982–83 due to the different phases of cycles of the 4.4 year lunar perigee and 18.6 year lunar nodal cycles. Most importantly, however, was simultaneous occurrence of higher than normal sea levels with the impact of large waves as discussed in the next section.

Waves

Although the 1997–98 winter did have nearshore waves approximately 20% higher than any observed in northern Monterey Bay during the 1982–83 winter, the latter was marked by larger waves over a longer span of time. As of May 1998 significant wave heights greater than 2.5 m only occurred during two months while northern Monterey Bay endured five months that were marked by significant wave heights greater than 2.5 m during the 1982–83 winter (STORLAZZI and GRIGGS, 1998).

As shown in Figure 8, while comparable wave heights were observed during the 1982–83 and 1997–98 ENSO winters, the major storms struck the central coast during distinctly different periods of the monthly tidal cycle. During the 1982–83 winter, the two largest storms struck the central coast during spring tides. The high tides elevated the level of wave attack relative to the protective beach, decreased wave energy loss to bottom friction, and increased beach pore fluid pressures, all of which increased beach erosion and the susceptibility of structures to wave-induced damage. During the 1997–98 ENSO winter, the largest storms hit during lower periods of the monthly tidal cycle, significantly reducing the impact of waves upon the shoreline. Since wave impact upon coastal structures is strongly dependent upon tidal elevation along meso-tidal coastlines, we defined a relative wave power (P_r) to describe the influence of this interaction:

$$P_r = P\frac{d}{\min(d)}$$

where: $P = ECn$ and d is the instantaneous water depth or tidal elevation. Thus, the relative wave power increases fourfold for waves with similar heights and celerities but which strike the coast during a +2 m high tide than during a +0.5 m low tide assuming the minimum tidal elevation is +0.5 m. As demonstrated in Figure 9, the relative wave power was shown to have been substantially higher during the 1982–83 winter than in 1997–98, most likely contributing to the much higher wave damage that occurred in 1982–83. These differences in relative wave power are supported by the storm surge data presented by FLICK (1998).

Duration of Exposure to Anomalous Conditions

Another contributing factor to the disparity in winter damages between 1982–83 and 1997–98 was the difference in the length of time that the central coast was impacted by severe weather (Table 2). Although the 1997–98 winter experienced a slightly longer duration of larger than normal deep-water waves, the 1982–83 ENSO event was marked by a longer duration of higher wind velocities and lower sea level barometric pressures and thus wind-induced set-up, most likely increasing the damage to coastal structures. However, when the tidal elevation is included into the wave height data as defined by relative wave power, the 1982–83 ENSO event caused the central coast to be exposed to large waves at higher tidal elevations over a much longer period of time than during the 1997–98 winter.

As discussed earlier, the dominant direction of wave approach for the central coast is from the northwest and therefore northern Monterey Bay, where much of the damage occurred in 1982–83, is largely sheltered from large waves. Thus, nearshore wave heights in northern Monterey Bay are a proxy for the combination of deep-water waves and westerly to southwesterly directions of wave approach with which the central coast is typically not in equilibrium. During the 1982–83 winter, northern Monterey Bay was struck by abnormally large (>2.5 m) waves in the nearshore as early as November which, except for March, persisted every month through April. During the 1997–98 winter, however, the northern Monterey Bay was struck by waves higher than 2.5 m only during January and February (STORLAZZI and GRIGGS,

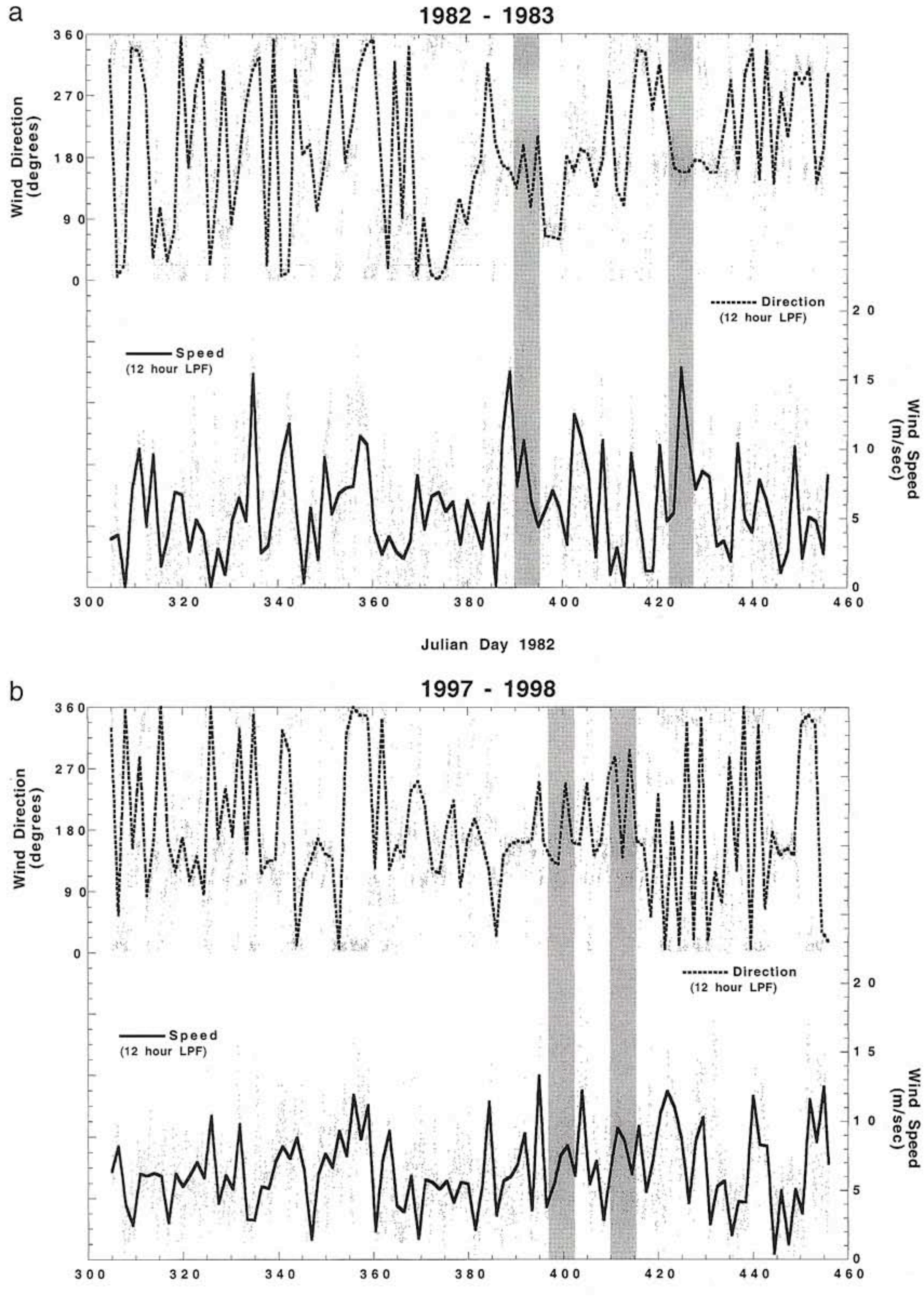

Figure 6. Fluctuations in wind direction and velocity from N.O.A.A. buoy #46026 during the (a) 1982–83 ENSO event, and (b) the 1997–98 ENSO event. The grey bands denote the periods when the most intense storms struck the central coast. Note the correlation between the higher wind velocities and the more southwesterly directions during the major 1982–83 storms as compared to the 1997–98 storms.

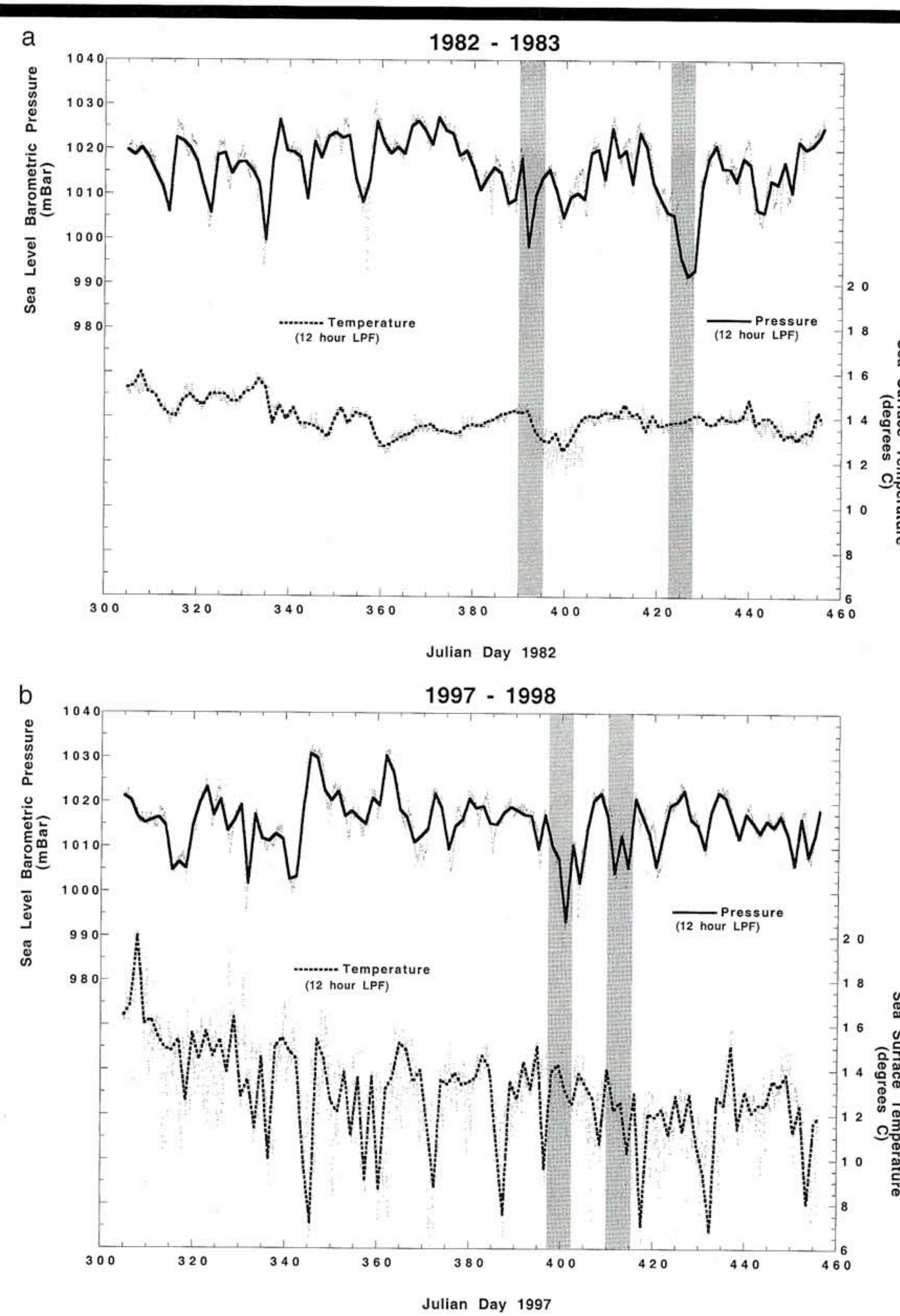

Figure 7. Fluctuations in sea level barometric pressure and sea surface temperature from NOAA buoy #46026 during the (a) 1982–83 ENSO event, and (b) the 1997–98 ENSO event. The dark lines represent 12-hour low-pass-filtered signals while the dots represent hourly data values. The grey bands denote the periods when the most intense storms struck the central coast. The sharp drops in sea surface temperature during the 1997–98 winter typically follow storms incident from the northwest with high sustained wind velocities.

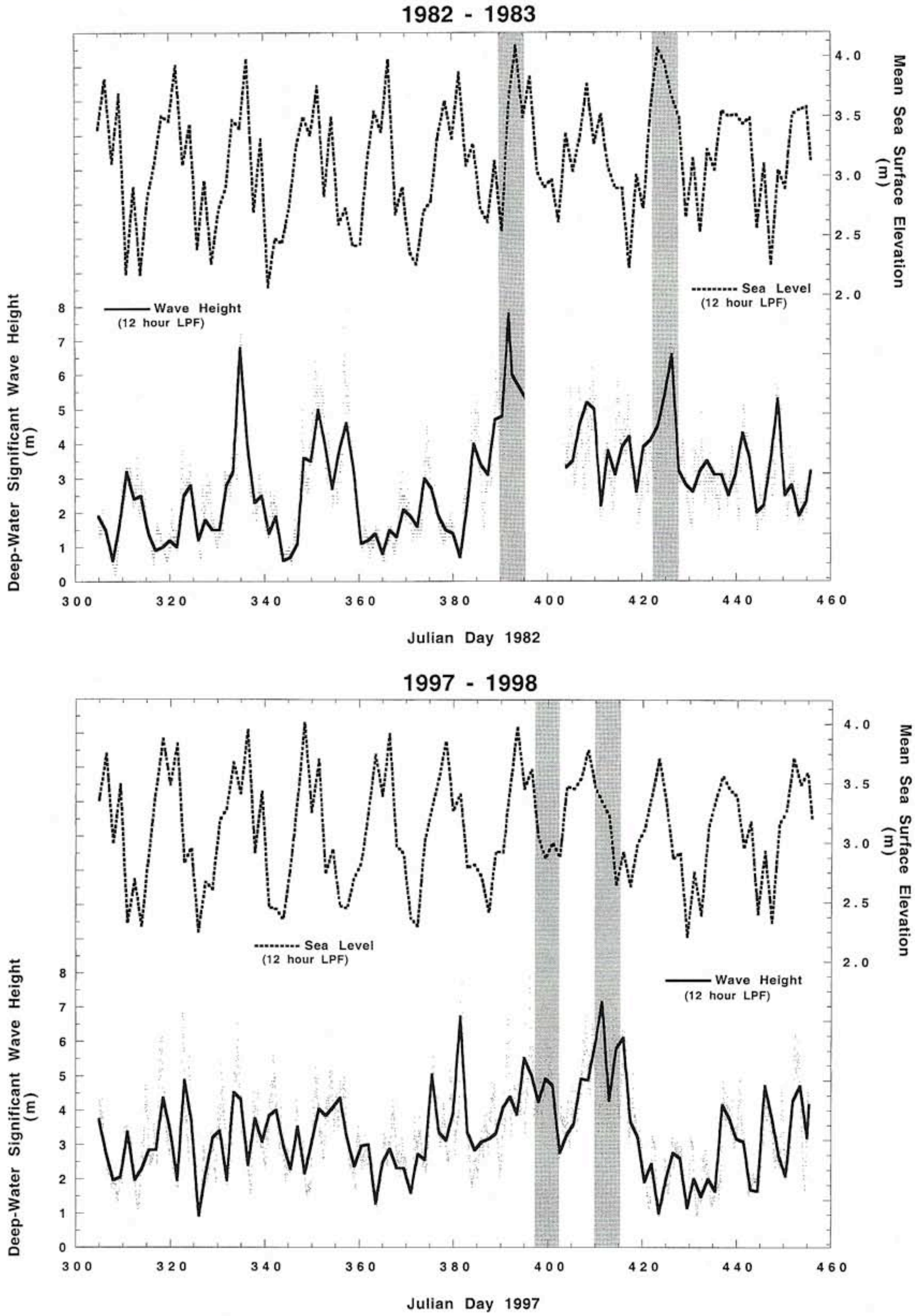

Figure 8. Fluctuations in the sea surface elevation at Monterey Harbor and wave height from N.O.A.A. buoy #46026 during the (a) 1982–83 ENSO event, and (b) the 1997–98 ENSO event. The dark lines represent 12-hour low-pass-filtered signals while the dots represent hourly data values. The grey bands denote the periods when the most intense storms struck the central coast. Note the coincidence of large waves and spring tides in 1982–83, while the largest waves in 1997–98 struck the central coast during neap tides.

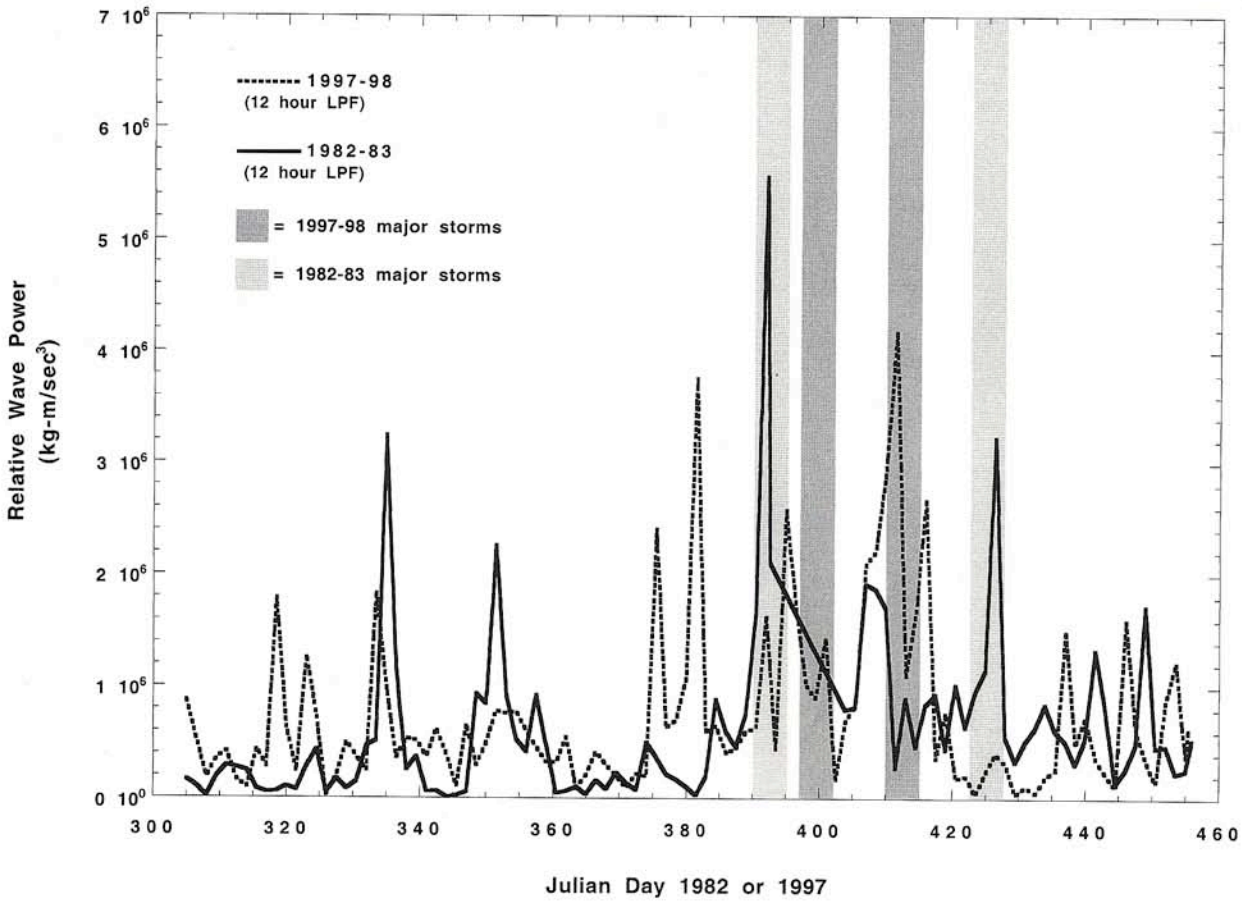

Figure 9. Fluctuations in the relative wave power data for the 1982–83 and 1997–98 ENSO events. The dark lines represent 12-hour low-pass-filtered signals while the dots represent hourly data values. The grey bands denote the periods when the most intense storms struck the central coast.

Table 2. *Duration of exposure to anomalous conditions during 1982–83 and 1997–98 ENSO events as recorded by N.O.A.A. buoy #46026.*

Parameter	Level Exceeded	1982–1983 Hours Exceeded		1997–1998 Hours Exceeded	
Deep-Water Significant Wave Height (m)					
	>7	11		13	
	>6	66		93	
	>5	269		352	
Wind Speed (m/sec)					
	>17	9		6	
	>15	48		30	
	>10	525		422	
Sea Level Barometric Pressure (mBar)					
	<990	0		9	
	<995	77		27	
	<1000	116		57	
Relative Wave Power (kg-m/sec³)					
	$>6 \times 10^6$	1		0	
	$>5 \times 10^6$	7	2,5*	0	
	$>4 \times 10^6$	12	3,9*	8	1,2,2,3*
	$>3 \times 10^6$	37		52	

* Number of consecutive hours the relative wave power was exceeded.

1998). The longer duration of higher than normal wave heights during the 1982–83 winter caused beaches sheltered from the dominant northwesterly wave approach to be eroded earlier in the winter which hampered their recovery through the winter by the sustained high energies. Beach erosion therefore allowed the large winter waves to attack coastal bluffs, structures and infrastructure relatively unimpeded, causing considerable erosion and damage. During the 1997–98 winter, however, the central coast experienced a narrower window with abnormally high nearshore waves, and thus the amount of time that coastal cliffs and human structures were unprotected by fronting beaches and directly exposed to wave energy was substantially less, reducing the amount of erosion and damage.

Antecedent Conditions

Another factor that may have caused the greater damage that occurred during the 1982–83 ENSO event was that it followed a distinctly more energetic winter than the 1996–97 winter. The 1981–82 winter was marked by two storms that caused coastal erosion and damage to the central coast of California while no damaging or erosive storms were record-

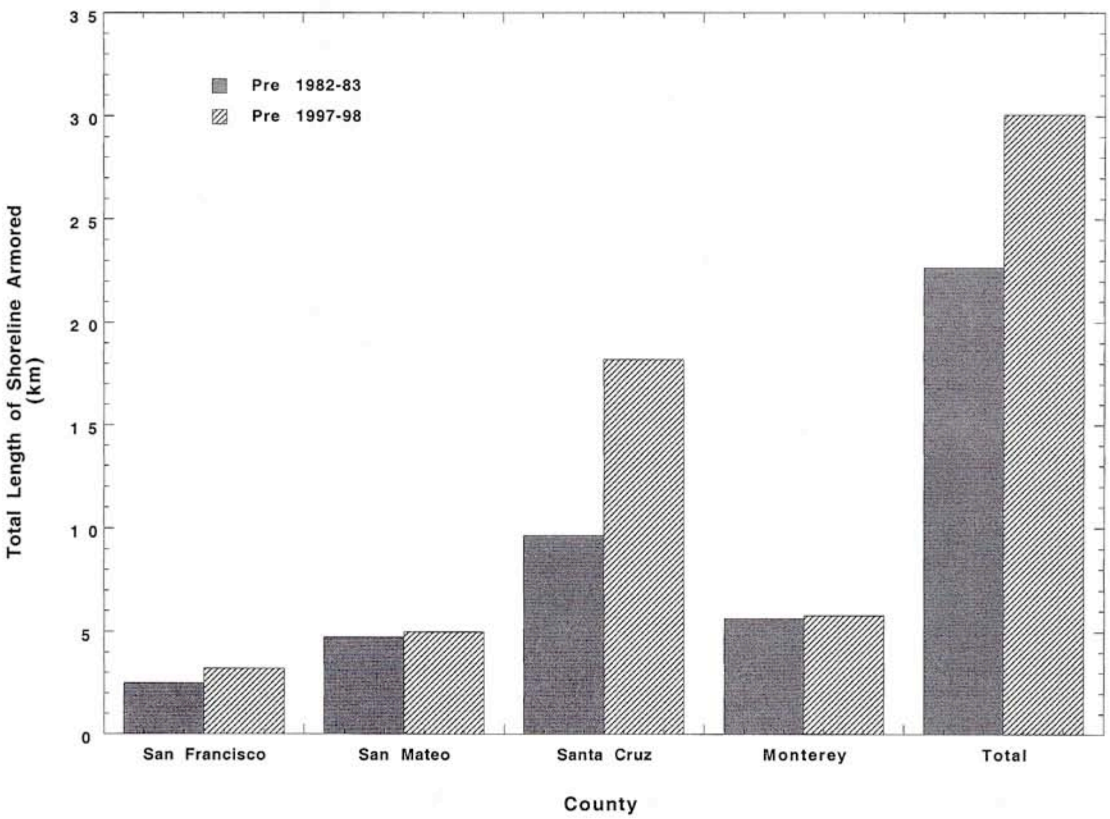

Figure 10. Distribution of coastline protection structures along central California and the increase in the number of structures between the 1982–83 and 1997–98 ENSO winters. Overall, there was a 30% increase in armoring along the central coast following the 1982–83 ENSO event.

ed during the relatively benign 1996–97 winter. The storms and erosion that occurred during 1981–82 may have caused the beaches to erode to a degree that they were not able to completely recover before the following winter. This would have made the shoreline more vulnerable to the high-energy conditions encountered during the 1982–83 winter. While there are no beach erosion data for the 1982–83 winter to substantiate this hypothesis, it does remain a distinct possibility.

Precipitation

The 1997–98 ENSO winter was marked by much higher levels of precipitation than those observed in 1982–83. Between November and March, the 1997–98 winter's mean monthly accumulated precipitation exceeded the 1982–83 event by 9 cm on average, and during February of 1998, the mean accumulated precipitation recorded was roughly three times the precipitation observed during February of 1983 (Storlazzi and Griggs, 1998). The significantly higher levels of precipitation during the 1997–98 ENSO event caused large volumes of sediment to be supplied to the coastline during the energetic winter months, helping to buffer wave impact. This buffering was a result of the deposition of sediment across the beaches' subaqueous profiles downcoast of streams and rivers, resupplying sediment to the bed that had been lost to offshore-directed flow resulting from increased wave heights and infragravity motions. Numerous bars formed offshore many of the river and stream mouths, causing waves to break further offshore, dissipating much of their energy before reaching the shoreline (USGS/UCSC/NASA/NOAA Collaborative Research Group, 1998). The high sediment concentrations in the nearshore also dampened turbulence by increasing stratification of the water column, reducing sediment suspension from the bed and thus bed erosion, reducing subaqueous beach profile deflation. The higher level of precipitation during the 1997–98 ENSO event was the primary cause for the larger number of both coastal (Figure 4) and inland (Figure 5) bluff and slope failures than during the 1982–83 winter.

Armoring

A final factor that contributed to the higher amount of coastal damage caused by the 1982–83 winter was the higher degree of shoreline armoring at the time of the 1997–98 winter compared to 1982–83. Between the 1982–83 and the 1997–98 ENSO events, roughly 7 km of coastal protective structures were built along the central coast (Figure 10). In Santa Cruz County, for example, the proportion of coastline protected by seawalls, revetments, bulkheads, or other types of structures prior to 1982–83 was approximately 17%. By

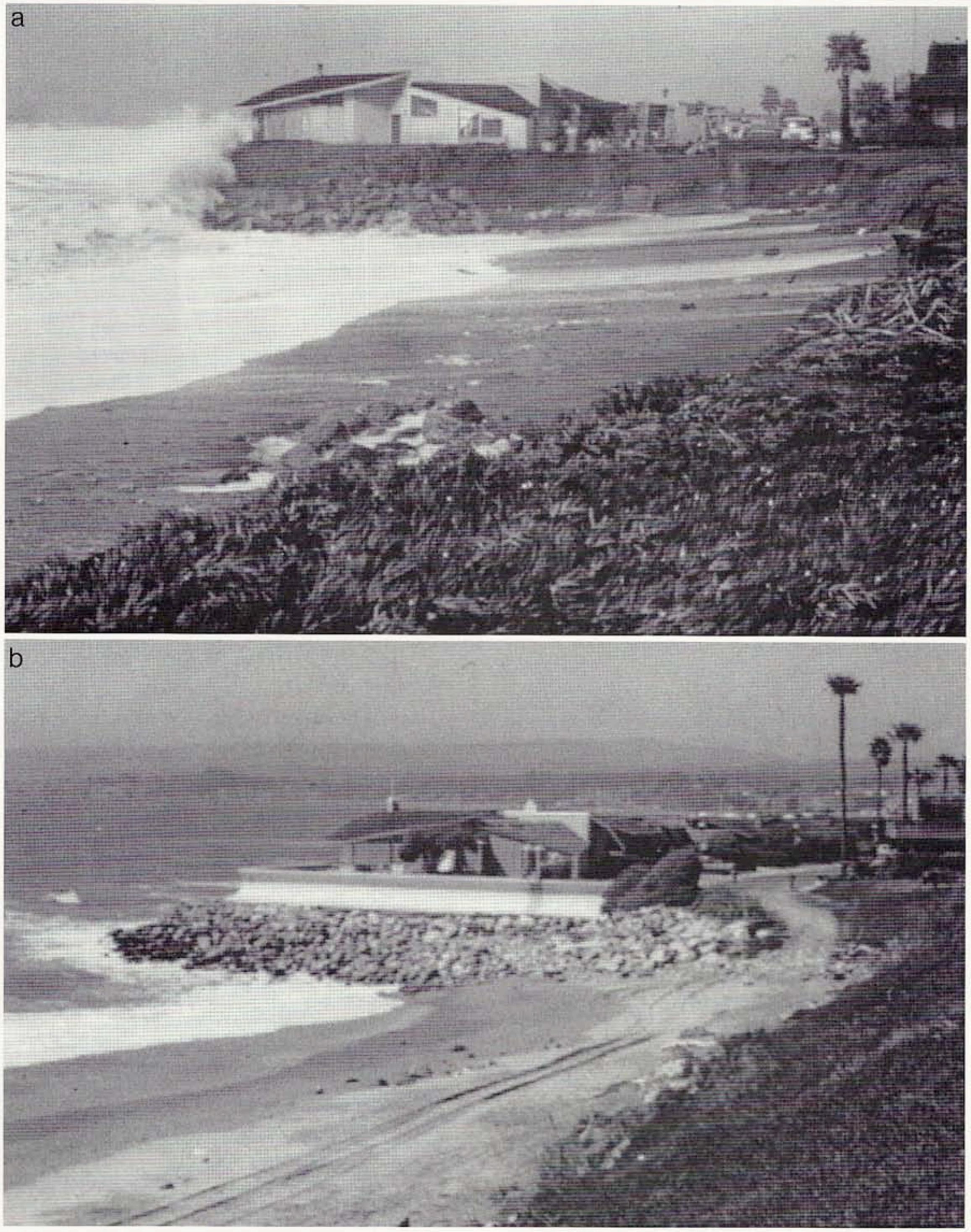

Figure 11. Changes in the construction and the effectiveness of coastal protection structures along Via Gaviota in Aptos-Seascape during early (a) 1983, and (b) 1998. Following the storms of early 1983, the rip-rap revetment was removed, a new curved-face concrete seawall was placed upon steel piles driven to refusal, and the rip-rap was then placed back at the toe of the seawall to provide additional protection. None of the houses along Via Gaviota reported wave-induced damage during the 1997–98 winter.

the latter half of the 1990s, the percentage of shoreline armored rose to more than 65%, nearly a threefold increase. The majority of this increase in armoring can be attributed directly to the 1982–83 storms: 50% of all armoring approved by the California Coastal Commission between 1978 and 1994 occurred in the months following the 1982–83 winter (CALIFORNIA COASTAL COMMISSION, 1995). Of the unprotected regions along northern Monterey Bay that were hard hit during the 1982–83 winter, almost all of them were armored or rearmored before the 1997–98 ENSO event. This armoring substantially reduced susceptibility to the higher than normal sea surface elevations and wave heights that occurred during the 1997–98 winter. Not only were large amounts of armoring emplaced along the coast, but the 1982–83 ENSO event destroyed most of the old and poorly designed structures. As a result, most areas that experienced significant damage over the 1982–83 winter rebuilt their protective structures according to new design criteria: the maximum wave heights and sea levels experienced in the 1982–83 winter. The significant improvement in coastal armoring design is evident in the back beach communities of southern Santa Cruz County. The timber bulkhead at Seacliff State Beach, rebuilt after the 1983 storms with a sacrificial bumper, survived the 1997–98 winter intact. Figure 11a shows the southernmost home along Via Gaviota in Aptos-Seascape in January 1983. Designed in 1968, the revetment was constructed to a height of 4 m above mean sea level. Over the last days of January 1983, waves were breaking over the top of the revetment, which appears to have experienced at least a meter of settling, and caused over $3 million in damages. The new protective structure consists of a curved concrete seawall anchored into the underlying bedrock with a rip-rap toe constructed to an elevation of 5.5 m above mean sea level (Figure 11b). The higher elevation of the new seawall and the lower sea level conditions prevented the damaging wave over-topping experienced in 1982–83.

CONCLUSIONS

The results of this study imply that the most important factor in affecting the severity of storm damage is the timing of large wave impacts on the coast. Not only did the 1982–83 winter storm waves arrive at the coast during high astronomical tides, but also there were a larger number of storms over the winter season. On average, the storms lingered along the coast over several tidal cycles, and the storms coincided with southerly winds that increased wave set-up and induced offshore flow of beach sediment. Federal and state agencies, including the National Oceanic and Atmospheric Agency (NOAA), FEMA, and the California Office of Emergency Services (OES), have touted successful mitigation stories, claiming a savings of hundreds of millions of dollars in comparison to the two previous winters in California through advanced forecasting. While this may be the case for some inland fluvial environments where flood damages may have been minimized, this is certainly not true for the coastal zone. In reality, at least along the high energy west coast, there is relatively little that can be done over the short term to reduce the impacts of an ENSO event along California's heavily urbanized coastline.

The 1997–98 winter storm waves arrived during low tides, the wave heights decreased before the next tidal cycle, and the storms coincided with westerly winds that directed sediment-laden bottom currents onshore, all of which effectively limited the landward penetration and energy of the waves. Although increases in shoreline armoring structures and improvements in armoring design, particularly in Santa Cruz County and along Monterey Bay, were a secondary factor in minimizing damages, the benefits to the private homeowners are not without significant impacts to public resources.

Looking to the future, studies that attempt to explain the coastline's response to large episodic events by examining both the natural physical processes and the anthropogenic factors will be necessary to improve the resiliency of our coastal communities. VAN DER VINK et al. (1998) showed that even disregarding climate trends of increased storm activity and rising sea levels, the US coastal zone is experiencing an exponential growth in natural disaster liabilities due to increases in wealth and the significant investments of that wealth in high risk coastal property and infrastructure. Recognizing the primary importance of ENSO events along the central California coast, our results show that while well-designed engineering structures can minimize marine driven damages from ENSO winter storms, the most effective method to reduce damages is to avoid the encroachment of any new structures in the highest risk areas—back-beach environments, coastal dunes, and unstable, eroding seacliffs.

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