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Rates and Trends of Coastal Change in California and the Regional Behavior of the Beach and Cliff System

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ABSTRACT

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The U.S. Geological Survey (USGS) recently completed an analysis of shoreline change and cliff retreat along the California coast. This is the first regional, systematic measurement of coastal change conducted for the West Coast. Long-term (~120 y) and short-term (~25 y) shoreline change rates were calculated for more than 750 km of coastline, and 70 year cliff-retreat rates were generated for 350 km of coast.

Results show that 40% of California's beaches were eroding in the long term. This number increased to 66% in the short term, indicating that many beaches have shifted toward a state of chronic erosion. The statewide average net shoreline change rates for the long and short term were 0.2 m/y and −0.2 m/y, respectively. The long-term accretional signal is likely related to large coastal engineering projects in some parts of the state and to large fluxes of sediment from rivers in other areas. The cliff-retreat assessment yielded a statewide average of −0.3 m/y. It was found that Northern California has the highest overall retreat rates, which are influenced by erosion hot spots associated with large coastal landslides and slumps.

The databases established as part of the shoreline change and cliff-retreat analyses were further investigated to examine the dynamics of the beach/cliff system. A correlation analysis identified a strong relationship between the geomorphology of the coast and the behavior of the beach/cliff system. Areas of high-relief coast show negative correlations, indicating that higher rates of cliff retreat correlate with lower rates of shoreline erosion. In contrast, low- to moderate-relief coasts show strong positive correlations, wherein areas of high shoreline change correspond to areas of high cliff retreat.

ADDITIONAL INDEX WORDS: *Shoreline change, cliff retreat, coastal erosion, coastal geomorphology, California.*

INTRODUCTION

Natural and human-induced changes along coastlines worldwide have become a major societal issue during the course of the past half-century, and problems associated with coastal erosion will likely increase as global sea levels continue to rise. In California, unlike most areas of the East and Gulf of Mexico coasts, erosion hazards are associated with not only sandy beaches but also coastal cliff erosion.

The coast of California comprises approximately 800 km of sandy shorelines, and 1300 km of coast are either rocky (with no fronting beach) or have a beach that is backed by cliffs and bluffs (California Department of Boating and Waterways and State Coastal Conservancy, 2002). Erosion of beaches and retreat of coastal cliffs are chronic hazards along the California coast, frequently resulting in property damage and land loss.

Previous studies of regional shoreline change in California include analyses by U.S. Army Corps of Engineers (1971), Griggs and Savoy (1985), Griggs, Patsch, and Savoy (2005), and Hapke *et al.* (2006), although most of these are compilations of existing data produced by different groups or agencies using a variety of techniques. The report by Hapke *et al.* (2006) is the first to systematically calculate and present rates for the entire state. Previous regional cliff-retreat analyses of two counties in California were presented by Moore, Benumof, and Griggs (1999). The most comprehensive study to date is Hapke and Reid (2007), where cliff-retreat rates were calculated for more than 350 km of the California coast.

Few studies have examined the spatial relationship between shoreline change rates and cliff-retreat rates. Sallenger *et al.* (2005) documented this relationship during the 1997–98 El Niño along a single beach in Central California. Their analysis indicated that hot spots of cliff erosion correlated to areas of decreased beach width and beach elevation over time scales of individual storms or storm seasons. If this holds true over longer temporal scales, it might be expected that areas undergoing high rates of sandy shoreline erosion in the long term would correspond to areas with high rates of cliff recession. Exceptions would include areas with wide beaches and cliffs that are undergoing only subaerial erosion (*i.e.,* waves no longer reach the cliff base) and/or areas where the cliff is armored.

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This article explores the relationship between coastal cliff retreat and shoreline change on a regional scale to assess whether both coastal systems are behaving similarly (*i.e.,* eroding at similar rates over the same temporal scale) and examines how the geomorphology of the California coast dictates the correlation, or lack thereof, between coastal cliffs and fringing beaches. In addition, this article provides a synthesis of the recent reports published by Hapke *et al.* (2006) and Hapke and Reid (2007), highlighting the key scientific findings and discussing the predominant regional trends.

Geology and Geomorphology of the California Coast

The diverse morphology of the California coast is primarily a result of the local geology, where lithology, geologic structure, and vertical tectonic movement play a prominent role in the configuration of the coast. Tertiary and Mesozoic rocks are the dominant coastal-rock type and, for the most part, represent sediment deposition, lithification, and uplift along the active Pacific–American plate boundary. The Tertiary rocks tend to be sandstone, shale, and conglomerate from marine environments. Mesozoic rocks, which include the Franciscan Complex, are typically sandstone and shale from oceanic crust and deeper marine settings, and oceanic basalts. Crystalline rocks are also present along the coast and are most common in Central California. In the process of deformation and uplift, rocks of varying strength and resistance to erosion, which respond differentially to coastal processes, are juxtaposed against one another. The result is a highly crenulated and variably oriented morphology that characterizes large segments of the California coast.

The strength of the rocks exposed along the coast is a critical parameter in determining the erodibility of the coast (Benumoff *et al.,* 2000; Hapke, 2005). Stronger rocks form prominent headlands that resist erosion and often form natural boundaries to littoral and Aeolian transport. Weaker rocks erode more quickly and form embayments, where coastal sediment may accumulate. Coastal cliffs tend to be formed in either high, steeply dipping, coastal mountains that plunge directly into the sea or in broad, near-planar, marine terraces.

Marine terraces are prominent features for much of the California coast and are best preserved where uplifted, marine, sedimentary rocks form the bedrock. Terrace preservation varies from moderate to poor in the other rock types that form coastal slopes, including metamorphic, granitic, and ophiolitic terranes. Marine terraces form when a coastal cliff retreats, generating wave-cut platforms, most notably during sea-level highstands, and are preserved as a slightly seaward-sloping, planar surface during tectonic uplift (Anderson, Densmore, and Ellis, 1999). Local uplift rates, duration of marine planation, and terrace composition determine the width and elevation of the terraces, which are typically 10s to 100s of meters high and 100s to 1000s of meters wide. The terrace surface often contains beach, dune, or alluvial deposits, and when combined with terrace erosional material, they can provide an important component of sediment contribution to the coast. Weaker rock types with an abundant sand component may contribute a significant amount of sediment to the beach system (up to ~10%–30%; Hearon and Willis, 2002; Inman and Masters, 1991; Runyan and Griggs, 2002). Cliff retreat rates vary dramatically from very low in granitic terranes to several meters *per* year in cliffs formed in poorly consolidated sediments, including coastal dunes. In addition to supplying sediment to the coast, marine terraces are important features, providing attractive coastal development sites (Griggs, Patsch, and Savoy, 2005).

Beaches in California are not as long and continuous as those along passive margins (*e.g.,* the U.S. South Atlantic and Gulf coasts) in part because of the geologically young nature of the coast that has not yet undergone weathering and sediment transport to allow for extensive sandy coastal plains to develop. Beach types found in California include pocket beaches, long expanses of linear to gently curved beaches, barrier spit beaches at stream mouths, and cuspate headlands. Pocket beaches are bound by headlands and occur in both small stream valley and cliffed-coast settings.

Coastal cliffs, as defined here, are steeply sloping geomorphic features, generally the seaward face of an elevated land surface, formed at the coast. Throughout the literature, *cliff* frequently refers to a slope formed in stronger, more-resistant rock units, whereas *bluffs* are slopes eroded in softer, unlithified material, such as glacial till or ancient dunes. For the purposes of this article, the term *cliff* is used to describe both cliffs and bluffs, without differentiating between the resistance of the geologic material to erosion.

The behavior of the coastal system is driven in large part by its geomorphology, and as such, the California coast has been divided into three sections for this study: Northern, Central, and Southern (see Figure 1). The coast of Northern California can be characterized as a rugged landscape with high rainfall and low population. Steep coastal cliffs dissected by numerous streams result in high sediment loads delivered to the coast. Franciscan Complex rocks are common, and the more resistant units often result in an irregular coast with steep cliffs, small offshore islands, and sea stacks. Barrier spits and beaches are common features at stream valleys and embayments. The largest barrier in the region extends across Humboldt Bay (Figures 2 and 3a). Marine terraces and wave-cut bluffs are common between the areas dominated by the steep mountain cliffs. The terraces south of Cape Mendocino are Holocene features that are undergoing rapid uplift. According to Savoy *et al.* (2005), as much as 1 m of uplift occurred during a single earthquake in 1992 along the Cascadia subduction zone.

Central California is the state's most diverse coastal region, having characteristics of both the north and south regions plus a few unique features of its own. This section represents the transition zone between the relatively wet and high wave-energy north and the drier and lower wave-energy southern section. Marine terraces and coastal bluffs are well developed along the coast south of Point Reyes, in the Monterey Bay region, and along parts of the southern Big Sur coast (Figures 2 and 3b). High-relief coastal slopes occur immediately north and south of San Francisco, and along most of the Big Sur coast (Figure 3c). Both linear and pocket beaches occur throughout Central California. In general, pocket beaches are more common along stretches of high-re-

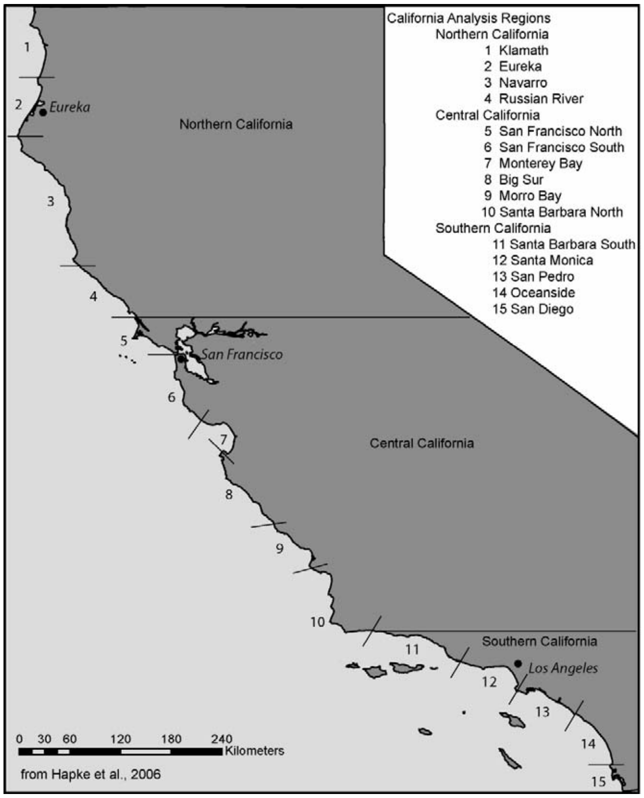

Figure 1. Location map of California showing the broad divisions of Northern, Central, and Southern California, as well as the 15 analysis regions, within which, rates and trends of shoreline change and cliff retreat are assessed.

Figure 2. Map showing place names discussed in text as well as major geographic features along the California coast.

lief coast, forming between small headlands where coastal creeks provide a sediment source. Linear beaches occur within larger embayments (*e.g.,* Monterey Bay) or as narrow features fronting marine terrace cliffs.

The coast of Southern California, extending from Point Conception to the Mexican border (Figure 2), is markedly different from the rest of the state. Point Conception marks a dramatic change in coastal orientation because of tectonic movement along the Transverse Ranges that has resulted in an east–west trending coast. Further south, the coast gradually returns to the northwest–southeast trend. Coastal cliffs and marine terraces are widespread and are typically fronted by narrow beaches. This section is the most urbanized stretch of coast in California (Figure 3d).

Climate and Waves

The climate of California is strongly influenced by a persistent zone of high pressure in the North Pacific, a southerly flowing cold-water ocean current, and the Sierra Nevada mountains, which block the continental air from affecting the coastal climate. During the summer months, the northward migration of the semipermanent North Pacific High diverts most storm tracks to the north, and as a result, California seldom receives rain from Pacific storms during the summer. During the winter, the North Pacific High migrates southward directing storms toward California. Occasionally, storms will arrive from the southwest and are accompanied by relatively warm temperatures and heavy rains. Average annual precipitation varies dramatically from north to south with 200 cm and above in the north and only about 25 cm falling in the San Diego area.

Seasonal weather patterns are modified during El Niño and La Niña years. During El Niños, California's climate experiences above-average rainfall, warmer sea-surface temperatures, and large waves, often resulting in increased coastal erosion. The 1997–98 El Niño–Southern Oscillation (ENSO) was a significant climatic event, responsible for widespread coastal flooding, beach loss, and coastal cliff retreat (USGS/UCSC/NASA/NOAA Collaborative Research Group, 1998). According to Storlazzi and Griggs (2000), the most damaging coastal storms have historically occurred in association with El Niños. In contrast, La Niñas are generally accompanied by colder ocean temperatures, drier conditions, and less-severe storms.

Waves and currents are the primary forces that move sediment in the littoral zone, and annual wave-height variations are responsible for seasonal beach erosion and accretion patterns along the California coast. Wave characteristics depend on weather patterns and are modified by factors such as offshore islands, storm climatology, coastline orientation, and local bathymetry. The predominant direction of nearshore

Figure 3. Photographs representing the variable geomorphology of the California coast: (a) a spit across Humboldt Bay, (b) a moderate-relief marine terrace in Santa Cruz, (c) a high-relief coastal slope along the Big Sur coast, and (d) an example of an urbanized coast in the Santa Barbara area of Southern California.

sediment transport along the California coast is from north to south (Hearon and Willis, 2002), with some exceptions because of variations in the local wave climate. Along the Northern California coast, the average wave height is greatest from November to February and averages about 3 m (Storlazzi and Wingfield, 2005). During El Niño winters, mean annual wave heights are 0.3 m–1.2 m greater than normal winter months. El Niño–driven storms typically approach from the west or southwest and may cause local littoral drift to the north—counter to the predominant southerly drift. Central California is a transition zone between the higher-energy wave climate experienced in Northern California and the milder conditions of Southern California. The largest swells generally occur between October and April, with typical heights between 1 and 4 m and periods ranging from 3 to 10 seconds. In Southern California, peak wave heights are greatest from November to February and average about 2.4 m during this time. In general, the southern region of the West Coast experiences more storms and higher wave energy during ENSO events (Seymour, 1998). Wave conditions along the Southern California coast are extremely variable because of coastal configuration, bathymetry, orientation of coastline, and the presence of large offshore islands. Wave height measurements can be substantially different over distances of a few miles (Newberger, 1982).

Littoral cells are segments of the coast with distinct sediment sources, defined longshore transport pathways, and sinks, where the sediment is removed from the littoral system. Conceptually, the cell boundaries delineate an area where the sediment budget can be balanced for quantitative analysis. Southern California littoral cells were first defined by Inman and Chamberlain (1960), and statewide littoral cells were delineated by Habel and Armstrong (1978). In California, the cells are typically bound either by prominent rocky headlands that block littoral transport around them or by submarine canyons that cross the continental shelf to a depth shallow enough to intercept alongshore-moving sediment.

METHODS AND DATA

The U.S. Geological Survey has, in recent years, focused effort on an assessment of coastal change along open-ocean coasts of the United States. To date, shoreline-change analyses have been completed for the Gulf of Mexico (Morton, Miller, and Moore, 2004), the southeast United States (Morton and Miller, 2005), and the California coast (Hapke *et al.,* 2006). In addition, an analysis of coastal cliff retreat was recently completed for the California coast (Hapke and Reid, 2007), using a subset of the data sources used in the shoreline assessment. For California, the primary data sources for the shorelines and cliff edges used in these studies are National Ocean Service (NOS) T sheets from the 1800s, 1930s, and 1950s–70s for the historical shorelines and lidar data (1998 or 2002) for the modern shoreline and cliff edge.

Historical shorelines from the NOS T sheets represent high-water lines (HWLs) or visual estimates of HWLs on the beach. The most recent shoreline is derived from lidar data and represents a mean high-water (MHW) shoreline that is based on a local tidal datum. For this analysis, a proxy-datum adjustment was applied to the lidar shoreline (Hapke *et al.,* 2006; Moore, Ruggiero, and List, 2006) to account for the bias in the data that occurs from using two different shoreline proxies.

The cliff edge was digitized directly from the 1930s T sheets after several pilot areas of known low-cliff retreat (*e.g.,* granitic headlands) were evaluated to verify that the cliff and cliff edge as rendered on the T sheets were valid features. The modern cliff edge was derived from the same lidar data used for the shoreline analysis. The data were gridded using a natural-neighbors algorithm, at a 1 m cell size. A hillshade, which is a shaded surface based on the reflectance values and shading effects of surrounding surface features, was created from each grid. Hillshading is a useful tool for enhancing the visualization of a surface, and the resulting three-dimensional rendering was used to interpret and hand-digitize the cliff edge using the visual break in slope. This visual-rendering approach has advantages over slope or second-derivative methods of edge enhancement in that objects such as buildings or vegetation that are near the cliff edge are easier to identify and omit from the data set. Oblique aerial photographs as well as historical maps were used during the digitization process to resolve ambiguities in the identification of the cliff edge.

The Digital Shoreline Analysis System (DSAS; Thieler *et al.,* 2005) was used to calculate change along coast-perpendicular transects, spaced at 50 m for the shoreline change analysis and at 20 m for the cliffs analysis. The spacing intervals varied for the different analyses so the shoreline analysis would conform to existing USGS products (Morton and Miller, 2005; Morton, Miller, and Moore, 2004) and the coastal cliff analysis would accommodate the highly crenulated nature of the rocky portions of the coastline. For all analyses, the coast was sectioned into 15 analysis regions (Figure 1). For the sandy shoreline change, both long-term ($\sim$120 y, four shorelines) linear regression and short-term ($\sim$25 y, two most-recent shorelines) endpoint rates were calculated. The dates of the T sheets are variable; dates for all linear-regression analyses are from the 1800s, the 1920s–30s, and the 1950s–70s. Modern lidar data were collected in either 1998 or 2001. For both the cliff recession analysis and the rates generated for the correlation analyses, the rates were assessed over 70 years using endpoints rates. The data for these analyses are from 1920–30 T sheets and modern lidar.

Errors were assessed separately for the linear regression and the endpoint rate calculations. For the linear regression shoreline change, the 90% confidence intervals of the regression coefficient were calculated and used as the uncertainty on the rates. For endpoint rates (both shoreline and cliff), the error of the original data sources was estimated and the error on the rate was derived by summing the individual errors in quadrature. Details on the methods used to calculate errors and uncertainties are given in Hapke *et al.* (2006) and Hapke and Reid (2007).

Although transects were generated along the entire coast, there are large gaps for all data sets because of (1) the lack of a sandy shoreline or a cliff, depending on the local geomorphology; (2) the lack of, or unusable, historical maps; and (3) gaps in the lidar data both along-coast and at the inland extent. In total, it was possible to calculate shoreline erosion rates for 729 km of the coast (long term) and 808 km of the coast (short term) (Table 1). In addition, the cliff-retreat rates and the correlation analyses covered a total of 355 km and 152 km of the coast, respectively. Although data are distributed along the entire length of the coast, the number of transects *per* region varies dramatically (Table 1) as a function of both the geomorphology within each region and the data gaps described above.

RESULTS AND DISCUSSION

Figures 4 and 5 show the regional results of the shoreline change and cliff-retreat analyses, respectively. Shoreline change varies widely throughout the state, and ranges are higher in the short-term *vs.* the long-term rates. Overall, rates of shoreline accretion are higher in Northern and Southern California as compared with Central California. The high accretion rates are likely related to large-scale engineering projects in Southern California and influxes of sediment from large coastal river systems in Northern California. Trends of long-term erosion tend to increase from north to south, peaking in the Monterey Bay region, and gradually, but not uniformly, decreasing again south of the Monterey Bay region. Some of the highest shoreline erosion rates occur in southern Monterey Bay and have been well documented previously by Thornton *et al.* (2006).

In Figure 5, there is a distinct trend of decreasing coastal cliff-retreat rates from north to south, with relatively uniform cliff retreat in the southern part of the state. Regional trends in the rates appear to be directly related to the geomorphology of the coast, with the highest rates, in general, occurring in areas with high-relief, steep coastal slopes and lower rates occurring in low- to moderate-relief areas dominated by marine terraces.

In the following section, we describe in more detail the results of the shoreline change and cliff-retreat analyses for Northern, Central, and Southern California. For specific details and interpretations of each region, we refer the reader to Hapke *et al.* (2006) and Hapke and Reid (2007). The shoreline and cliff edge data, as well as the results of the change analyses, are available to the public for download from the

Table 1. *Length of the coast and number of transects along which change was measured for shoreline change, cliff retreat, and correlation analysis.*

		Shoreline Long Term		Shoreline Short Term		Cliff		Correlation	
Section	Region	No. Transects	Coast Length (km)	No. Transects	Coast Length (km)	No. Transects	Coast Length (km)	No. Transects	Coast Length (km)
Northern California	Klamath	1430	72	1573	79	319	6	210	0.2
	Eureka	493	25	652	33	135	3	10	0.01
	Navarro	608	30	656	33	1441	29	350	0.4
	Russian River	435	22	483	24	433	9	36	0.1
Central California	San Francisco North	902	45	1039	52	1092	22	431	0.4
	San Francisco South	1125	56	1150	58	1551	31	564	0.6
	Monterey Bay	1013	51	1031	52	1098	22	547	0.5
	Big Sur	512	26	533	27	1929	39	264	0.3
	Morro Bay	447	22	458	23	738	15	105	0.1
	Santa Barbara North	1983	99	2267	113	3982	80	2273	2.3
Southern California	Santa Barbara South	1692	85	1760	88	828	17	15	0.02
	Santa Monica	1319	66	1504	75	1118	22	829	0.8
	San Pedro	605	30	925	46	498	10	219	0.2
	Oceanside	1561	78	1587	79	1993	40	1712	1.7
	San Diego	437	22	524	26	501	10	53	0.1
Total		14,562	729	16,142	808	17,656	355	7618	152

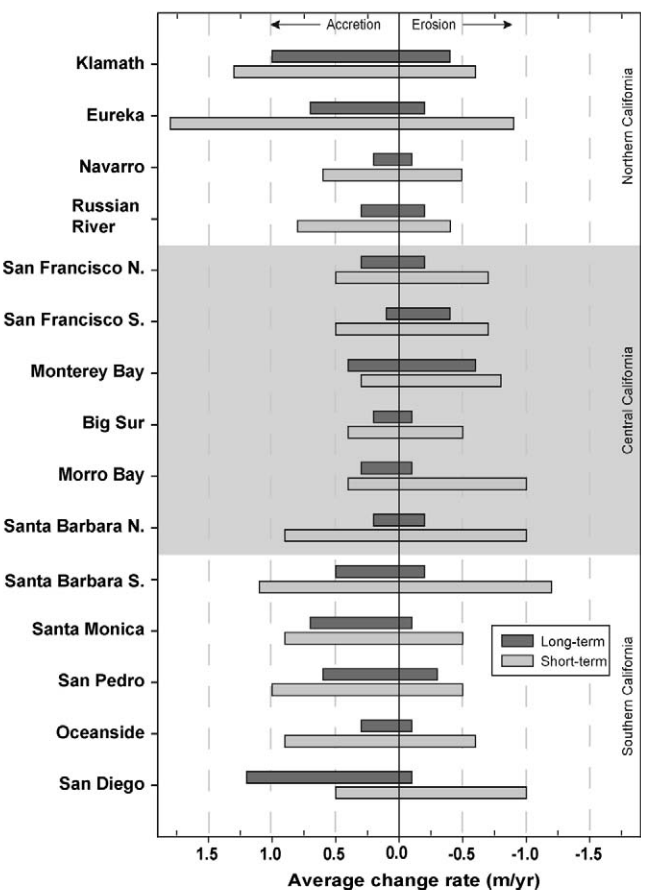

Figure 4. Range of average rates of shoreline change (averages of erosional and accretional transects). The ranges of the rates are much larger in the 25-y short-term (lighter-colored bars) than the 120-y long-term (darker bars).

Internet and can be accessed through the references cited above.

Northern California

The Northern California analysis extends from the Oregon border to Tomales Bay, a distance of approximately 550 km (Figure 2). For the presentation of the shoreline change and cliff-retreat analyses, Northern California is divided into four regions: Klamath, Eureka, Navarro, and Russian River (Figure 1). Much of Northern California is a highly crenulated, rocky coastline with small sections of pocket beaches, except near major river mouths (Figure 3a), and a few areas where steep coastal cliffs are fronted by narrow beaches. As a result of this geomorphology, there are many gaps in both the shoreline and cliff-retreat data. Long-term shoreline change was measured along only 148 km of the shoreline and short-term shoreline change over 168 km. Both long-term (0.5 m/y) and short-term (0.3 m/y) net shoreline change rates were accretional when averaged over all of the Northern California transects (Table 2). Of the 2966 transects along which the long-term shoreline change was measured, 23% have an erosional trend, with an average erosion rate of −0.3 m/y. For the short-term shoreline change analysis, the percentage of beach eroding more than doubled, increasing to 47%, and the average short-term shoreline erosion rate was −0.6 m/y.

The maximum long-term shoreline erosion rate, −1.2 m/y, was associated with a dynamic sand spit at the mouth of a large river (the Klamath) in the Klamath region (Table 2). Although shoreline rates tend to be lower in Northern California than other regions of California, the variable sediment influx can result in high erosion rates at site-specific locations. The maximum short-term shoreline erosion rate, −2.7 m/y, was measured in the Eureka region just north of the Humboldt Bay jetty.

For the cliff-retreat analysis in the Northern California section, rates were measured along 158 km on 2325 transects (Table 1). The average amount of coastal cliff recession measured over 70 years in Northern California was 28.8 m, at an average rate of −0.5 m/y (Table 2). Many of the highest rates in Northern California were measured on headlands that lie interspersed with small embayments along the coast. The embayments occur either where there are small creeks draining the coastal slope or, in many cases, where there are deep-seated landslide complexes with wavelengths (distance from the center of one embayment to the next) on the order of 1 km. The highest amount of retreat, 222.7 m (Table 3), was in the Navarro region, near Cape Vizcaino (Figure 2). Overall, the cliff-retreat rates in Northern California were higher than the rest of the state.

Central California

The Central California coast has a more mixed geomorphology than Northern California, in that there are areas of high-relief coast (Figure 3c); long stretches of developed, elevated marine terraces (Figure 3b); and coastal lowlands that are typically associated with river mouths. The Central California section begins approximately 5 km south of Tomales Bay and extends 740 km south to a stretch of coast just north of Santa Barbara (Figure 2). This section is divided into six regions: San Francisco North, San Francisco South, Monterey Bay, Big Sur, Morro Bay, and Santa Barbara North. The average net long-term shoreline change rate (the average of all rates, including those measured on both erosional and accretional transects) for Central California was found to be undetectable at the significance of this analysis and is reported as 0.0 m/y (Table 2). In the short term, however, the average net shoreline change rate is strongly erosional (−0.5 m/y).

There are many gaps in our analysis along this coast because much of the shoreline is rocky with isolated pocket beaches, which were not included in the analysis; there are a few continuous linear beaches, such as in the Monterey Bay region. Coastal engineering structures and nourishment projects are limited to small harbor construction and some harbor bypassing. Numerous seawalls and revetments exist along the coast and likely influence the reported rates of coastal change.

Overall, the highest long-term shoreline erosion rates were found in the Monterey Bay region, where the average rate of eroding transects was −0.6 m/y. Although the short-term erosion rate for the Monterey Bay region was also high (−0.8 m/y), short-term rates for both the Morro Bay and Santa Barbara North regions were even greater (−1.0 m/y). The maximum long-term erosion rate for Central California was measured immediately north of Point Año Nuevo in the San Francisco South region (Table 3). The −1.8 m/y rate was measured in an area of rapid erosion adjacent to a former sand spit that connected Año Nuevo Island to the mainland (Griggs, Patsch, and Savoy, 2005). The spit was breached sometime in the late 1800s, providing a path for the rapid transport of sand to the south. The maximum short-term erosion was in the Santa Barbara North region just south of the Santa Maria River mouth and is likely related to flood control projects on the Santa Maria River.

Cliff retreat for Central California was measured on 208 km of coastline on 10,400 transects. The average retreat rate

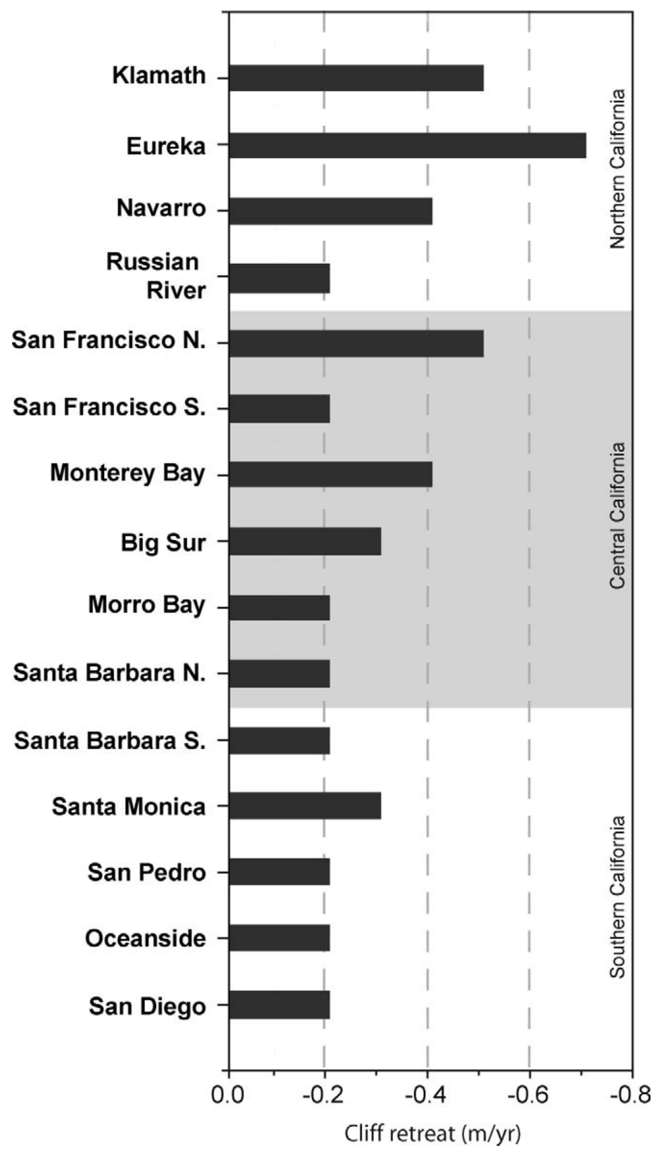

Figure 5. Average rates of coastal cliff retreat showing overall higher rates in Northern California and decreasing consistently to the south.

was −0.3 m/y, and the average amount of retreat was 17.3 m over the 70 year period of this study (Table 2). Numerous seawalls and revetments exist along this stretch of coast, especially in more heavily developed areas. These structures, built in response to cliff erosion threatening private homes and/or community infrastructure, act to reduce the rate of cliff retreat, although they may have negative impacts. The highest retreat rate in Central California was in the San Francisco South region, where a large landslide in the steep coastal slope just north of Pillar Point resulted in a 70 year rate of −3.1 m/y (210.5 m of retreat).

Southern California

The Southern California section extends from just north of Santa Barbara to the Mexico border (Figure 2), along ap-

Table 2. *Mean shoreline change and cliff-retreat rate data used in both the individual change analyses and the correlation analysis.*

Section	Region	Long-Term Shoreline (m/y ± 0.1)	Short-Term Shoreline (m/y ± 0.4)	Cliff (m/y ± 0.2)	Correlation Analysis: Shoreline (m/y ± 0.2)	Correlation Analysis: Cliff (m/y ± 0.2)
Northern California	Klamath	0.7	0.4	−0.5	−0.3	−0.4
	Eureka	0.7	0.4	−0.7	<0.1	−0.5
	Navarro	0.1	0.0	−0.4	0.1	−0.4
	Russian River	0.2	0.4	−0.2	0.1	−0.1
Central California	San Francisco North	0.1	−0.5	−0.5	−0.4	−0.5
	San Francisco South	−0.2	−0.5	−0.2	−0.3	−0.3
	Monterey Bay	−0.2	−0.6	−0.4	−0.4	−0.6
	Big Sur	0.0	−0.2	−0.3	−0.1	−0.2
	Morro Bay	0.1	−0.7	−0.2	−0.3	−0.3
	Santa Barbara North	0.0	−0.6	−0.2	−0.2	−0.2
Southern California	Santa Barbara South	0.1	−0.5	−0.2	−0.1	−0.2
	Santa Monica	0.4	−0.1	−0.3	<0.1	−0.2
	San Pedro	0.5	0.5	−0.2	−0.1	−0.1
	Oceanside	0.2	−0.1	−0.2	0.1	−0.2
	San Diego	0.9	−0.8	−0.2	<0.1	−0.6

proximately 420 km of coastline. The shoreline change and cliff-retreat data for this section of the California coast are divided into five regions: Santa Barbara South, Santa Monica, San Pedro, Oceanside, and San Diego (Figure 1).

Southern California has the longest stretches of continuous, linear beaches in the state, although there are many areas where the beaches are narrow and are backed by coastal cliffs. This is also the most engineered coastline in the state, consisting of numerous harbors, ports, breakwaters, jetties, and groins. There are only a few small data gaps in the shoreline change assessment for Southern California because of the lack of complete coastline coverage in the 1800s-era T sheets. The cliff-retreat data is fairly discontinuous because of the predominance of coastal lowlands, which in many cases, are not backed by cliffs, as compared with Northern and Central California.

Approximately 281 km of coastline was included in the long-term Southern California analysis, whereas the short-term analysis covered 315 km of coast (Table 1). The net long-term shoreline change rate for the section was accretional, with an average rate of 0.3 m/y, and the net average short-term rate was −0.1 m/y (Table 2). The San Diego region exhibited the largest change in net rate from the long term to the short term, shifting from a strong accretional signal (0.9 m/y) to the highest short-term net change rate in the state (−0.8 m/y).

Most of the erosion hot spots are associated with large coastal facilities that disrupt the alongshore flow of sediment. The highest long-term erosion rate, −2.4 m/y, was measured just south of the harbor at Newport Bay (Table 3), and the highest short-term erosion rate (−5.5 m/y) was located less than 2 km south of Port Hueneme (Figure 2). Southern California is defined geomorphically by long, linear stretches of sandy beach that, in some areas, are backed by low- to moderate-relief cliffs; there are a few areas of large, deep-seated landslides, and these are usually the locations of the highest cliff-retreat rates for each region. The highest rate of retreat (−1.8 m/y; Table 3) is along the Malibu coast and is associated with a large coastal landslide. Many of the portions of the coast that are backed by cliffs have coastal protection structures, which have likely affected the rates of cliff retreat

Table 3. *Maximum shoreline and cliff edge erosion rates for California.*

Section	Long Term (m/y)	Region: Location	Short Term (m/y)	Region: Location
Shorelines				
Northern California	−1.2	Klamath: Klamath River mouth, south side	−2.7	Eureka: North Spit Beach, 0.8 km north of Humboldt Bay jetty
Central California	−1.8	San Francisco South: north side Pt. Ano Nuevo	−6.7	Santa Barbara North: Guadalupe Dunes
Southern California	−2.4	San Pedro: 1.5 km south of Newport Bay Harbor	−5.5	Santa Barbara South: Ormond Beach, 1.7 km south of Port Hueneme Harbor
Cliff Edges				
Northern California	−3.1	Navarro: Rockport Beach, near Cape Vizcaino		
Central California	−3.1	San Francisco South: 2.3 km north of the Pillar Point Harbor breakwater		
Southern California	−1.8	Santa Monica: Big Rock Beach, Big Rock Mesa landslide		

and thus contribute to Southern California having the lowest average retreat rates in the state (−0.2 m/y).

Correlation Analysis

To statistically evaluate the relationship between cliff retreat and shoreline change, it was necessary to reevaluate the rates using a new data set of transects that were coincidental to both features and to generate rates over the same time period. This required a reduction in the total alongshore coverage, and the endpoint rate change was generated using only the 1930s and 1998/2001 data sources (T sheets and lidar).

For the 152 km of coastline along which coincident shoreline change and cliff retreat was calculated, the average shoreline change rate (−0.1 ± 0.1 m/y) is lower than the average cliff-retreat rate (−0.3 ± 0.2 m/y) (Table 2). In certain areas, the shoreline is prograding, and as such, the net shoreline change contains averages of positive and negative values. The average shoreline erosion rate (the average of those transects with an erosional trend, 72% of the transects) is −0.3 ± 0.2 m/y, the same as the cliff-retreat rate. This implies that, based on a regional average, the beaches and cliffs along the California coast are retreating at an equivalent rate.

The average change rates presented here will not be the same as those reported above and in Hapke *et al.* (2006) and Hapke and Reid (2007). This is because different transects were generated for this analysis to increase the density of the data and to ensure the transects intersected with both the 1930s and 1998/2002 shorelines and cliff edges. Also, less data are available for the shoreline change and cliff-retreat calculations because of the requirement that, for the correlation analyses, there be both cliffs and shorelines present in each transect.

Figure 6 shows the average 70 year rates of shoreline change and cliff retreat based on the correlation data set for each of the 15 analysis regions. In general, the cliff-retreat rates are highest in Central and Northern California, with the exception of the San Diego region in Southern California. Rates of shoreline change are highest in Central California. Besides some overlap in these broad regional trends (*i.e.,* high rates of both erosional shoreline change and high cliff-retreat rates), there is not consistent evidence of a strong relationship between shoreline change rates and cliff-retreat rates when values are averaged along the ~100 km analysis regions. In some regions where the average cliff-retreat rates are high (>0.4 m/y), such as the Eureka, Navarro, and San Diego regions, the average shoreline change is <0.1 m/y. Central California exhibits the most consistent relationship between shoreline change and cliff retreat. The lack of similar behavior between the beach and cliff in Southern California is attributed to the impact of human manipulation to the system (seawalls, groins, nourishments projects, *etc.*). In Northern California, the coastal system is dominated by high-relief, steep slopes, where large, deep-seated landslides are the dominant process of cliff retreat. Beaches tend to occur at river and stream mouths where valleys interrupt the coastal slope. Because the beach/cliff systems are rarely coincidental,

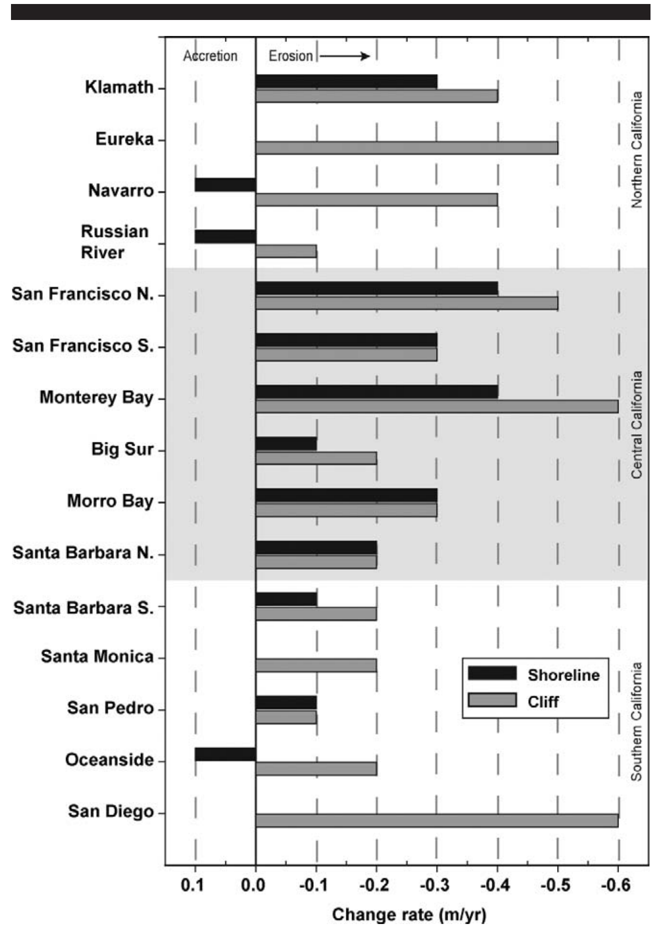

Figure 6. Comparison of shoreline change and cliff-retreat rates for the 15 regions analyzed in this study. There are data gaps in the shoreline change (black bars) for the Eureka, Santa Monica, and San Diego regions because the rates measured in those regions are not significant within the uncertainty range of the data.

it is not surprising that there is little apparent relation between the shoreline change and cliff-retreat rates.

The previous discussion focused on assessing the average trends of the shoreline change and cliff-retreat data on a large spatial scale (*i.e.,* the state of California). To explore the relationship of the beach/cliff system on a somewhat more localized scale, plots of cliff retreat *vs.* shoreline change were generated for each of the 15 analysis regions (Figures 7–9). The scatter plots show the relative distribution and correlation of the data, and these data were correlated to assess the relationship between cliff retreat and shoreline change within each individual region.

Northern California

Figure 7 shows the cliff retreat *vs.* shoreline change plots for the four regions in Northern California, and Table 4 provides the correlation and regression statistics. The data points correspond to the rates measured on individual transects. Two of these regions (Eureka and Navarro) show a strong negative correlation between the data sets, which in-

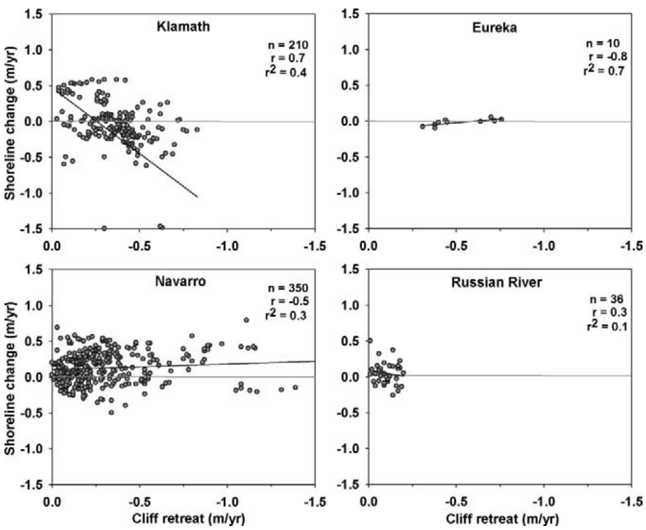

Figure 7. Shoreline change *vs.* cliff retreat for Northern California. The data points correspond to the rates measured on individual transects. The Eureka and Navarro regions show a reverse trend between the rates, indicating lower shoreline retreat rates in areas of higher cliff-retreat rates.

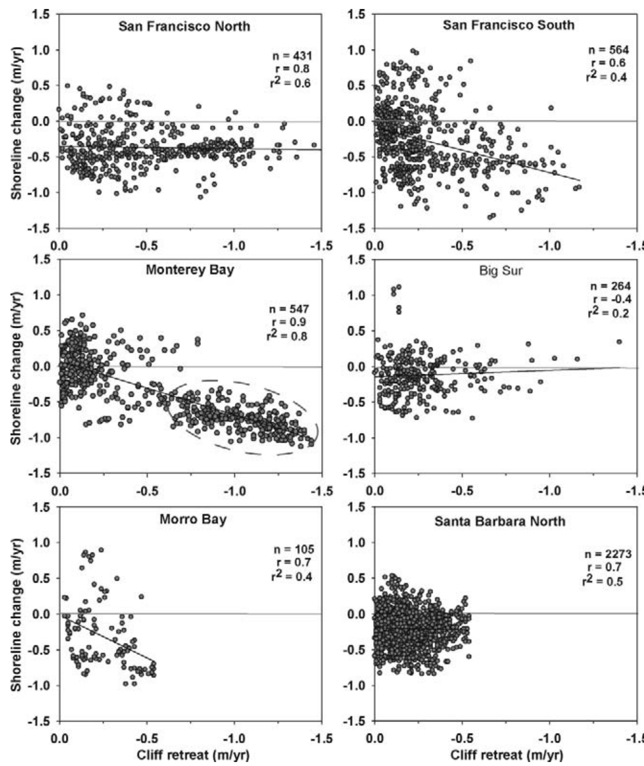

Figure 8. Shoreline change rates *vs.* cliff-retreat rates for Central California. The data points correspond to the rates measured on individual transects. The Monterey Bay region shows a strong correlation between high rates of shoreline and cliff erosion. The dashed oval indicates an area of Southern Monterey Bay where rates of cliff retreat and shoreline erosion are highly spatially correlated.

dicates that cliff retreat may be influencing rates of shoreline change. In areas of the coast where the characteristic geomorphology is steep, high-relief coastal slopes, large deep-seated landslides are the dominant process of cliff retreat. These landslides can contribute large volumes of material to the base of the slope, and this material may be stored on the subaerial beach, causing a seaward progradation of the shoreline.

Although the slopes of the regression lines in Figure 7, for the Eureka and Navarro regions, are not steep, there is evidence from the data that areas where cliff retreat is higher correlate to areas where the shoreline is prograding or retreating more slowly. The highest positive correlation and regression slope occur in the Klamath region (Table 4). Although Northern California, in general, is dominated by high-relief coastal slopes, the areas for which data in the Klamath region exist are primarily beaches backed by low cliffs or flat marine terraces. The processes resulting in cliff retreat in this type of geomorphic setting tend to be lower-volume, shallow failures of the cliff (Hapke and Richmond, 2002). Therefore, it is expected that the relationship between the beaches and cliffs will be different than in the large landslide-dominated regions.

Central California

All six of the analysis regions in Central California show some relationship between the beach and cliff system (Figure 8). In all regions, except Big Sur, the correlation is positive (Table 4), indicating larger cliff-retreat rates in areas with larger shoreline-retreat rates. As discussed above for the Klamath region, it appears that positive correlations occur in data sets from areas where the geomorphology is dominated by low- to moderate-relief cliffs that retreat *via* shallow failures of the cliff. This retreat mechanism results in a much lower contribution of material to the beach system relative to that delivered by large, deep-seated landslides. It appears that in these low- to moderate-relief, cliffed areas, the rates of shoreline retreat influence the retreat rates of the cliff. This observation is supported by the negative correlation in the Big Sur region, where the coastal geomorphology is dominated by large landslides, and the processes of coastal retreat are more similar to those observed in Northern California. The Monterey Bay region has the strongest correlation in the state. In Figure 8, the dashed oval in the Monterey Bay region delineates data that are primarily from the southern part of the bay, where high rates of shoreline retreat and cliff erosion are well documented (Thornton *et al.,* 2006). On the basis of our data, this area is the largest and most well-defined erosion hot spot in California, at least over the temporal scale of the 70 years of this analysis.

Southern California

The Southern California coastline, which was divided into five analysis regions for this study, is the most heavily affected by human development and engineering structures in the state. As a result, the correlations between the shoreline change and cliff-retreat data sets are poor (Figure 9). Most

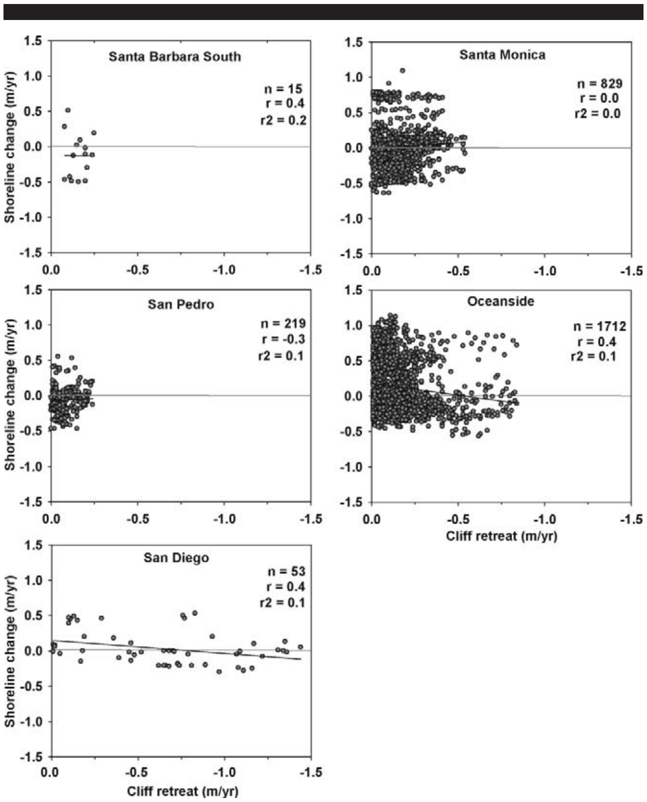

Figure 9. Shoreline change rates *vs.* cliff-retreat rates for Southern California. The data points correspond to the rates measured on individual transects. The regions all have low correlation values. The Santa Monica region is the only region in the state to have a zero correlation.

of the regions lack distinct trends in the data (*i.e.,* Santa Barbara South, Santa Monica, San Pedro). The Oceanside and San Diego regions appear to have a positive trend in the data visually, but the correlation coefficients are relatively low (Table 4). Santa Monica is the only region in the state to have a correlation coefficient of zero.

Table 4. *Correlation coefficients* (r) *and* r^2 *values of the best-fit line for assessing the relationship between shoreline change and cliff retreat.*

Section	Region	r	r^2
Northern California	Klamath	0.7	0.4
	Eureka	−0.8	0.7
	Navarro	−0.5	0.3
	Russian River	0.3	0.1
Central California	San Francisco North	0.8	0.6
	San Francisco South	0.6	0.4
	Monterey Bay	0.9	0.8
	Big Sur	−0.4	0.2
	Morro Bay	0.7	0.4
	Santa Barbara North	0.7	0.5
Southern California	Santa Barbara South	0.4	0.2
	Santa Monica	0.0	0.0
	San Pedro	−0.3	0.1
	Oceanside	0.4	0.1
	San Diego	0.4	0.1

CONCLUSIONS

In this analysis, we present the first regional (statewide) assessments of both shoreline change and coastal cliff retreat for California. Long-term shoreline change rates were calculated for 40%, and short-term rates calculated for 44%, of the total length of the California coast. The average long-term erosion rates for California were highest in the San Pedro region in Southern California (−0.3 m/y), the Monterey Bay region in Central California (−0.6 m/y), and the Klamath region in Northern California (−0.4 m/y). Overall the highest long-term accretion rates were associated with coastal engineering structures and beach nourishment sites (Southern and Central California) and with areas of high sediment supply from large rivers (Northern California). The percentage of eroding sandy shorelines increased from the long-term (40%) to the short-term (66%) throughout the state. This trend implies that erosion hazards have increased in California, especially from the 1950s–70s to the late 1990s. This may be related to the climatic shift that began in the mid-1970s when California's climate entered a period of more frequent and stronger storms, including two of the most intense and damaging El Niño winters of the past century.

The average 70 year cliff-retreat rate for California was −0.3 m/y, and the highest average rates were in the Santa Monica region in Southern California (−0.3 m/y), the San Francisco North region in Central California (−0.5 m/y), and the Eureka region in Northern California (−0.7 m/y). The maximum amount of retreat in the state was 223 m, at the site of a large, deep-seated coastal landslide in Northern California. The second highest amount of retreat, 210 m, was on the north-facing side of a large coastal headland south of San Francisco. Even in regions with relatively low average retreat rates, there are clearly specific areas of coastline with high erosion rates or hot spots.

Coastal cliff-retreat rates are directly related to the geomorphology and geologic processes driving overall retreat of the coast. As a result, the highest rates occurred along high-relief coastal slopes and were associated with large, deep-seated coastal landslide complexes. In lower-relief areas, the rates were highest where the cliffs are composed of weaker geologic materials. The geomorphic influences on the rates of cliff retreat are also evident in the relationship between promontories and headlands and high rates of retreat. In almost all of the analysis regions, the rates were consistently high in focused headland areas. This relationship was more frequently true in Northern and Central California, where the coastline is more crenulated and thus has a higher density of headlands and embayments. The focusing of wave energy at headlands is likely driving these high rates and underscores the importance of geology, wave energy, and water level on processes of coastal cliff retreat.

A correlation analysis between rates of shoreline change and cliff retreat also supports that geomorphology and geology are strong controls on the relationship between the coastal retreat rates. In areas characterized by high-relief coasts, where the dominant coastal retreat process is movement on large, deep-seated landslides, the correlation between shoreline change and cliff retreat is negative. In these areas, locations with higher cliff-retreat rates correlate to areas of lower shoreline erosion or shoreline progradation. The mechanism of retreat, deep-seated landslides, results in the contribution of large volumes of material to the subaerial beach environment, thus slowing erosion or increasing accretion. In areas where the geomorphology is dominated by low- to moderate-relief cliffs, there tend to be a strong positive correlation between rates of shoreline change and cliff retreat, such that areas of higher shoreline erosion are also areas of higher cliff retreat. The processes of retreat of low- to moderate-relief cliffs (shallow landslides and slumps) do not appear to contribute high volumes of material to the subaerial beach system. Human-modified systems have the poorest correlation, as is demonstrated throughout Southern California, where lack of correlation suggests that the beaches and cliffs behave independently in terms of rates of retreat.

Many of the techniques developed, tested, and applied in this study are directly applicable to coastal change assessments in other areas of the world, including along rocky coasts. As interest and concern about impacts of global sea-level rise on the world's coastline continue to increase, a fundamental understanding of past behavior of coastal systems, including rates and mechanisms driving change, is critical to future planning and management.

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