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Shoreline Change and Pacific Climatic Oscillations in Kihei, Maui, Hawaii

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ABSTRACT

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Increasing demands on coastal areas require enhanced understanding of coastal erosion hazards. Here we analyze a 5-km segment of the Kihei coastline (Maui, Hawaii) centered on an area of chronic coastal erosion. A high-resolution database of variations in shoreline sediment volume over the past century reveals a complex and dramatic pattern of changes between 1900 and 1997. Comparisons of historical sediment erosion and accretion at barriers to longshore transport are used to estimate longshore sediment fluxes over this period. In the absence of detailed long-term oceanographic and meteorological data for the site, fluctuations in the magnitude and direction of net longshore sediment transport (NLST) are a potentially valuable resource for investigating why documented changes have occurred. Available data suggest that observed patterns of NLST reflect multidecadal variations in Kona storm (strong, rain-bearing winds from the southwest) activity. These storms appear to be modulated by the Pacific Decadal Oscillation (PDO), which has a tendency to alter atmospheric circulation such that Kona storm activity in the vicinity of the Hawaiian Islands is reduced during its positive phase. Correlations among the PDO cycle, Kona storm activity, and NLST in Kihei, and the apparent inability of other possible forces to produce the observed patterns of NLST, suggest a cause-and-effect relationship. Consideration of the PDO may improve our understanding of coastal sediment dynamics in many areas, enhancing existing efforts to forecast erosion hazard areas and effectively manage sandy shorelines.

ADDITIONAL INDEX WORDS: *Shoreline change, beach erosion, Kona storm, Pacific Decadal Oscillation.*

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INTRODUCTION

Sandy beaches are common along many of the world's coastlines, yet our understanding of the behavior of beach and nearshore sediment systems on scales of years to decades remains limited. Movement of sediment by waves and currents is both complex and difficult to measure (*e.g.,* WEIGEL, 1992; NRC, 1995; KOMAR, 1998). The many variables, operating over a range of time scales, and the general inability to predict erosion-causing forces confound our ability to accurately predict beach and shoreline dynamics (*e.g.,* NRC, 1990; KOMAR *et al.,* 1991; LIBBEY *et al.,* 1998; THIELER, *et al.,* 2000). As recommended by the National Research Council (NRC, 1990), the use of high-quality, computer-based historical shoreline change analysis, improved by correlation with data on oceanographic forces, is the only presently viable means of decadal shoreline prediction. The research reported in this paper is part of an ongoing effort to implement the NRC recommendation in the Hawaiian Islands.

In addition to the quantification of historical changes and projections of future erosion hazards, coastal managers expressed strong interest in finding out why the site investigated here is such a "hotspot" of coastal erosion. As with many other areas experiencing similar problems, understanding the causes of erosion can be difficult, especially when there are inadequate data available to conclusively address the question. Here we develop a high-spatial-resolution decadal to century scale database of historical shoreline fluctuations to assist in resolving this problem. These are analyzed in conjunction with records of climatic parameters to gain insight into the forces responsible for erosion problems at the study site. Although interpretations reported here cannot be considered definitive, disparate data and results all suggest a consistent scenario that is likely to have relevance to many Pacific shorelines. Serious coastal erosion problems are prevalent in many areas that also lack extensive long-term oceanographic and coastal monitoring programs. These problems, and the socioeconomic and ecological importance of beach resources, dictate the need for further research and the development of innovative methods for defining causes of shoreline change.

STUDY SITE

The study area (Figure 1) encompasses 5 km of coastline fronted by a fringing reef along the southwestern, or Kihei, coast of Maui, Hawaii. Coastal erosion at a county park and along private, developed shoreline to the north led to the

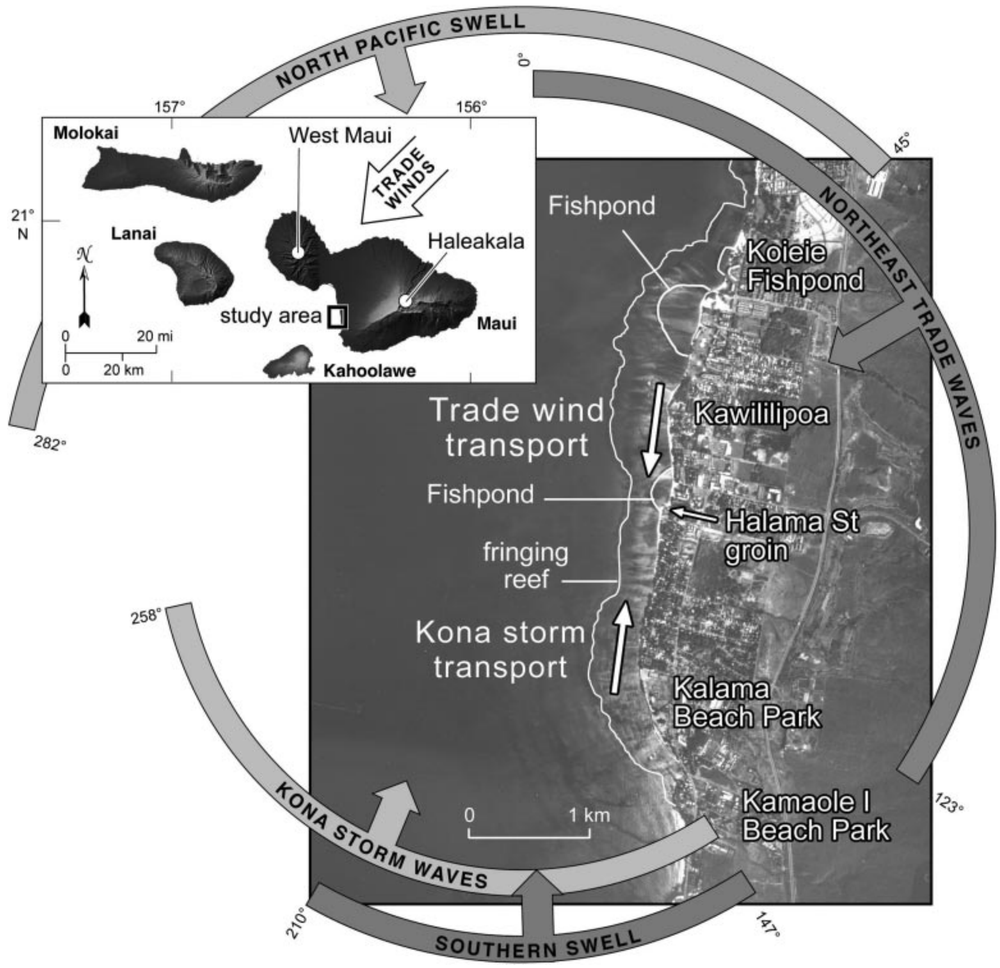

Figure 1. Location and characteristics of Kihei, Maui, Hawaii study site.

widespread construction of seawalls and revetments. As a result of chronic shoreline retreat, in time this resulted in the almost complete loss of sandy shoreline in front of the coastal armoring. Concerns over the severe and continuing loss of the beach resource prompted the present study.

The site terminates to the north at the rock walls of the ancient Hawaiian Koieie Fishpond, and the southern terminus is marked by a small rocky headland. These features define the north and south (respectively) endpoints of a large, open littoral cell. The reef flat fronting the site is 300 m to 400 m wide and 1 m to 2 m deep with a thin veneer of sand. Occasional large (approximately 5–10 m diameter) sand pockets are located across the reef surface. Seasonal change on the fringing reef-fronted beach is characterized by localized updrift accretion and downdrift erosion resulting from variations in longshore sediment transport rather than beach-wide erosion or accretion resulting from cross-shore transport (NORCROSS *et al.,* 2003).

The site contains anthropogenic features that have influenced littoral sediment dynamics, including several ancient rock-wall fishponds. More recently, a shore-normal drainage outfall, protected by a rock revetment, and referred to here as the “Halama groin,” was constructed across the beach in the center of the site between 1949 and 1960. Beginning in the late 1960s and early 1970s, the series of revetments and seawalls mentioned above were built as a defense against coastal erosion. Today they stretch, unbroken except for a few beach access paths, along the southern 1.8 km of the site, replacing formerly sandy shoreline.

Trade Winds and Swells

In the lee of West Maui and the islands of Molokai, Lanai, and Oahu, the study site is protected from large North Pacific swells that impact Hawaii every winter and from waves generated by the brisk northeasterly trade winds. The limited fetch between the site and the head of Maalaea Bay (approximately 4 km) precludes the generation of large waves from north or easterly winds within the bay itself. Trade winds occur about 70% of the year, with typical maximum sustained speeds of 8 to 13 m/s, particularly in the summer months of May through September (HARAGUCHI, 1979). On Maui, the

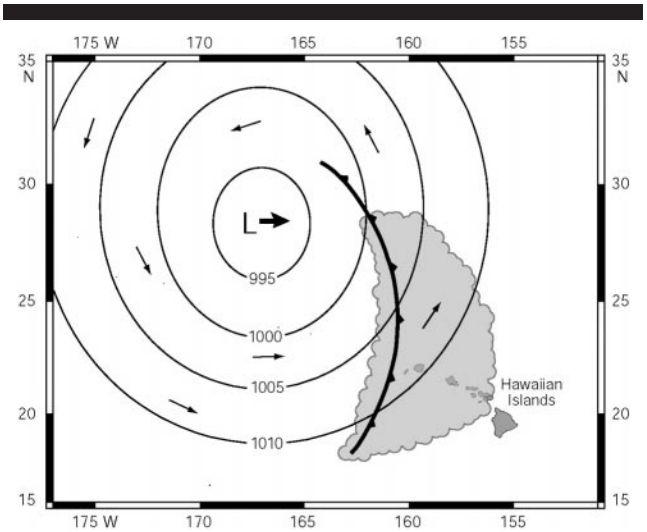

Figure 2. Characteristics of a typical major Kona storm. Shaded area is characterized by thunderstorms, rain clouds, and southwesterly winds. Isobars depict surface pressure in millibars, thin arrows show wind direction, and the heavy arrow indicates the direction of movement for the entire low (adapted from HARAGUCHI, 1979).

trade winds accelerate through the central valley separating the volcanic peaks of West Maui and Haleakala. On leaving the valley the air stream diverges south along the Kihei coast and rises up the sun-heated western slope of Haleakala, forming an ascending spiral of air know as the "Maui vortex" (SCHROEDER, 1993). Thus, the Kihei coastline does experience strong trade winds, but they are usually northwesterly rather than from the northeast. The trade winds tend to accelerate in the late morning and reach their maximum speed in midafternoon. During times when these winds are active, sand can be observed moving southward by saltation along the dry beach and in the swash zone.

South swell, generated in the Southern Hemisphere, usually impacts the Hawaiian Islands in the summer and early autumn. These events typically have deep-water wave heights of approximately 0.3–1.2 m and periods of 14–22 seconds (ARMSTRONG, 1983). The Kihei area is somewhat protected from south swells by the island of Kahoolawe but does receive wave energy from between Kahoolawe and the southwest corner of Maui. These, however, tend to dissipate, giving waves from the south less of an impact along the coastline that those from the southwest (U.S. ARMY CORPS OF ENGINEERS, 1967).

Kona Storms

Although somewhat protected by the islands of Lanai and Kahoolawe, the study site is susceptible to damage from Kona storms approaching from the southwest (Figure 2). Kona storms are "low-pressure areas (cyclones) of subtropical origin that usually develop northwest of Hawaii in winter and move slowly eastward, accompanied by southerly winds, from whose direction the storm derives its name, and by the clouds and rain that have made these storms synonymous with bad weather in Hawaii" (GIAMBELLUCA and SCHROEDER, 1998). Kona storms occur during winter months, generally between October and April. Forming west of Hawaii, they tend to bring wind, rain, and large surf to normally leeward sides of the islands, typically generating waves with heights of 3–5 m and periods of 8–11 seconds. Occasional strong Kona storms have caused extensive damage to south- and west-facing shorelines, including the study site. Less severe damage has also been recorded as a result of the passage of unusually strong fronts on a few occasions (U.S. ARMY CORPS OF ENGINEERS, 1967; MOBERLY, 1968; MAKAI OCEAN ENGINEERING AND SEA ENGINEERING, 1991; ROONEY and FLETCHER, 2000). We use the term "Kona storms" to refer to both true Kona storms and the rare frontal passages that have significantly impacted the Kihei coastline. Geomorphic evidence and anecdotal reports show that Kona storms have transported high volumes of sediment northward along the Kihei coast in addition to causing extensive erosion (ROONEY and FLETCHER, 2000).

METHODS

Historical Shoreline Positions

Historical shoreline positions are used to determine sediment transport at the study site. Historical shoreline positions are acquired from both aerial photographs and NOAA topographic surveys, or T-sheets. Only 1:12,000 scale or larger series of vertical, survey-quality aerial photographs are used. Series of photographs meeting these criteria date from 1949, 1960, 1963, 1975, 1987, 1988, and 1997. Scanned images of the photographs from each series are corrected for distortion errors (THIELER and DANFORTH, 1994) and mosaicked together using software from PCI Geomatics, Inc., following the methodology of COYNE *et al.* (1999). We define the seaward and landward boundaries of the beach as the position of mean lower low water (MLLW) and the vegetation line, respectively (BAUER and ALLEN, 1995). The horizontal distance between them is defined as the beach width. Both features are digitized on each photomosaic, and the position of MLLW is used as the shoreline change reference feature (SCRF). T-sheet shorelines, available from 1900 and 1912 and covering the northern and southern halves of the study site, respectively, show the position of the mean high water line (MHWL). MHWLs are shifted seaward a distance equal to the median distance between the MHWL and the MLLW position, as measured from 5 years of seasonal beach profiles taken within the study site (GIBBS *et al.,* 2001). Movement of these features is measured along shore-normal transects nominally spaced every 20 m along the shoreline. Further details are available from ROONEY (2002) and FLETCHER *et al.* (in press).

Volumetric Shoreline Change

Five years of seasonal beach profile surveys within the site (GIBBS *et al.,* 2001) are used to develop a model, modified from BODGE (1998), that estimates volumetric changes along the coast as a result of historical shoreline movement (Figure 3). The model has terms to account for changes in the sandy

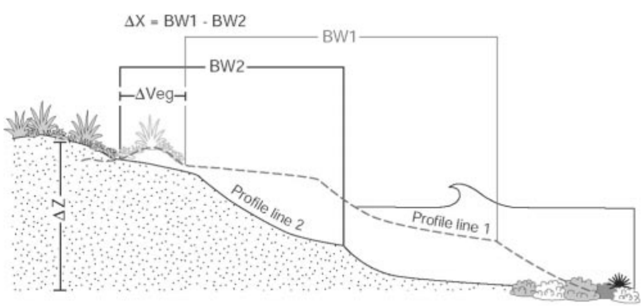

Figure 3. Model to convert horizontal movement of beach boundaries to volumetric units.

shoreface portion of the profile as well as the vegetated coastal plain. Together these give the total change in volume, ΔVol, under a 1-m-wide shore-normal strip. That result is multiplied by 20 m, the width of beach represented by each measurement of historical shoreline movement or transect. This procedure can be written as:

$$\Delta Vol = [(G_p * \Delta X) + (Veg * \Delta Z)] * 20 \quad (1)$$

in which ΔVol is the total volume change for a 20-m-wide strip of beach, G_p is the ratio of changes in shoreface volume to beach width characteristic of this site, ΔX is the change in beach width, ΔVeg is the horizontal movement of the vegetation line, and ΔZ is the elevation difference between the coastal plain and depth of closure. From Equation 1, volumetric changes are calculated for each time increment of our shoreline history at 20-m alongshore spacing. Volumetric uncertainty for a single transect results from uncertainty caused by position error of MLLW and vegetation line positions, error in the ΔZ term (± 1.0 m), and error in the G_p term (± 40%). These are assumed to be independent for each transect, so the total volumetric uncertainty of each is defined as the root sum of squares of these terms, multiplied by the 20-m longshore distance each transect represents. Individual terms used to calculate volumetric uncertainty are assumed to be dependent alongshore, so transect volumetric uncertainties are therefore summed over the shoreline segment of interest (see FLETCHER *et al.* (in press).

Another component of the sediment budget that should be considered is the contribution of coralline algae, coral, foraminifera, and other carbonate sediment-producing organisms found at the site. HARNEY and FLETCHER (1999) measured sand production and assign gross calcium carbonate production rates of 1.4 and 7.0 kg m^2/yr, respectively, to Hawaiian reef flat and slope environments. From surface area measurements for each environment and other terms from their sediment production model, total *in situ* sediment production within the site is estimated for the period between 1900 and 1997. Further details on calculating sediment volumes are available from ROONEY and FLETCHER (2000).

Net Longshore Sediment Transport

KOMAR (1998) defines net longshore sediment transport as "the summation of the movement [of sediment] under all wave trains arriving from countless wave generation areas, accounting for the different transport directions." KOMAR (1998) and the Coastal Engineering Manual (U.S. ARMY CORPS OF ENGINEERS, 1998) state that structures blocking longshore sediment transport (LST) can provide the best evidence of the magnitude and direction of NLST, particularly over longer time scales. A structure that interferes with LST will trap a portion of the sediment moving along the shoreline on its updrift side, resulting in accretion, and induce erosion on its downdrift side. To gain insight to why the shoreline has changed through time, a single time series of NLST is developed for the entire study site. The NLST record is based on the volumetric difference in sediment impoundment around rocky headlands and anthropogenic structures on the shoreline, as indicated by historical shoreline positions. Despite structures at both ends of the site that partially isolate it from neighboring shorelines, differences in the total volume of coastal sediments over time show that the site does exchange sediment with other areas. Although the best method for quantifying long-term rates of longshore transport, shoreline structures will often not trap 100% of the sediment moving along the coast, so this method will usually underestimate rates of NLST. Northward transport values are assigned positive values here, whereas southerly transport is indicated by negative values. One structure, the Halama groin (see Figure 1), was not constructed until after the 1949 photographs were obtained. Additionally, armoring on the southern portion led to beach loss and the lack of significant sand resources for LST by 1988. These two major physical changes at the site necessitate the use of multiple sediment-trapping features to develop a complete times series. Further details are available in ROONEY (2002).

Kona Storm Activity

A record of Kona storms that may have impacted this coast was compiled from several published sources, and augmented in a few cases by anecdotal reports (NATIONAL WEATHER SERVICE, 1959–1998; U.S. ARMY CORPS OF ENGINEERS, 1967; SHAW, 1981; U.S. DEPARTMENT OF AGRICULTURE, 1905–1948). Oceanographic and meteorological data to quantitatively compare Kona storms are not available. However, given the reported significance of Kona events in this area, it is important to attempt to evaluate their impact on coastal erosion, which we accomplish using the published descriptions. Kona events are cataloged and assigned a magnitude from 0 to 4 based on the expected duration of changes they induced on the sandy portion of the Kihei coastline, as shown in Table 1. Durations are based on observations of the persistence of major changes to the shoreline induced by specific Kona events. Based on considerations of increased wave height, storm surge, and duration typical for each magnitude, we assume that each increase in event magnitude will result in a 10-fold greater impact to the shoreline. In other words, an M3 event will induce northward transport of an order of magnitude more sediment than an M2 event.

The record has shortcomings: (1) details are frequently sparse, leading to speculation about a storm's impact, (2) reporting of events was not always consistent, and (3) histori-

Table 1. *Magnitudes assigned to individual Kona storms and passing fronts.*

Magnitude*	Duration of Effects
0	No effect
1	A single season
2	1 year
3	5 years
4	20 years

* Magnitude assigned to individual events based on the estimated duration of their effects on the sandy shoreline in Kihei, Maui, Hawaii.

cally, erosion of beaches was of relatively little concern and rarely mentioned. We assume that major Kona events are reported more consistently than minor ones, so only events of magnitude 2 or greater are included in our analysis.

In addition to seasonal changes, other fluctuations in global atmospheric circulation, such as El Niño/Southern Oscillation (ENSO), can impact Kona genesis. During El Niño events, warmer sea surface temperatures in the equatorial Pacific cause the subtropical ridge to shift closer to the islands, forcing trade winds to subside and suppressing Kona storms and fronts near Hawaii (SCHROEDER, 1993; GIAMBELLUCA and SCHROEDER, 1998). As a result, leeward areas in Hawaii that depend on winter season rain from Konas for a significant portion of their annual rainfall tend to experience drought. Conversely, during neutral periods and La Niñas, this high-pressure center is absent, enabling Konas and fronts to form or migrate into their vicinity (DIAZ and KILADIS, 1992; SCHROEDER, 1993). A comparison of mean values of the Multivariate ENSO Index (MEI) (WOLTER and TIMLIN, 1993) for months with major Konas, to all winter months in the index, corroborates this finding. Negative (positive) values of the MEI indicate El Niño-like (La Niña-like) conditions. Months with major Konas have a mean value of −449.4, versus 4.7 for all winter months, which are statistically different at the 90% confidence level.

Because of the shortcomings of the Kona storm record, it is desirable to have a less subjective indicator of Kona activity in the Hawaiian Islands. We use total winter season precipitation from Waianae, Oahu (NATIONAL CLIMATIC DATA CENTER, 2000) as a proxy and compare it with other climatic records. Note that data are not available for this station for the years between 1982 and 1992. Of the hundreds of locations within the state of Hawaii for which precipitation data are available, we judge the record from Waianae to be the best one to use in examining effects of Kona storms because it is isolated from orographic rainfall by two mountain ranges. Hence, periods of high precipitation in the Waianae record reflect greater than average Kona storm and frontal passage activity in the main Hawaiian Islands.

To identify decadal scale periods of higher and lower than average Kona storm and frontal passage activity, we subtract the mean winter season rainfall from each winter's total precipitation to determine each years "rainfall residual." For each year of the precipitation record, we plot the cumulative sum of all of the winter rainfall residuals from the start of the record up to that year. Essentially a low-pass filter, this "cumulative residuals" technique (HURST, 1951, 1957) helps identify changes in trends of inherently noisy and scattered data. Periods of higher (lower) than average precipitation reflect high (low) Kona storm activity and will plot with a positive (negative) slope.

RESULTS

Volumetric Changes

This coast has been quite dynamic over the past century, receding or prograding almost 100 m in some areas, which is several times the width of the average Hawaiian beach. Because of variations in coastal morphology, shoreline change is more comparable for different areas when expressed in units of sediment volume, rather than as horizontal movement. Detailed information on the timing, magnitude, and location of sediment volume changes help to characterize the behavior of this coast and yield clues as to why the changes occurred. Figure 4 gives a complete history of volume changes, based on measured movement of the vegetation line and the shoreline as applied to Equation 1. The smoothed surface illustrated in the figure is generated by fitting continuous curvature splines (SMITH and WESSEL, 1990) to all volume change data for the 1900 to 1997 period and reflects the net result of all sediment transport processes for the entire study site. Estimates of volume change associated with a variety of specific shoreline processes are shown in Table 2.

Between 1912 and 1997, the reef-fronted southern portion of the study area lost $1.7 \times 10^5 \pm 4.2 \times 10^4$ m^3 of sediment. The greatest losses occurred at the southern end of Kalama Beach Park between 1912 and 1949, with the shoreline receding as much as 90 m. Net erosion during this period gradually decreased to the north and was replaced by accretion from the middle of Halama Street to the south side of Koieie Fishpond. By 1949 the southern end of Kalama Park had stabilized and changed little until a revetment was constructed along the length of the park in the early 1970s. Between 1949 and 1997 erosion continued, but the area of greatest erosion shifted gradually north from the middle of Kalama Park to several hundred meters south of the Halama groin. The northern half of the site prograded significantly between 1900 and 1997, accreting about $4.16 \times 10^5 \pm 4.5 \times 10^4$ m^3, or about three times more sediment than was lost in the south.

Superimposed on the above major patterns of shoreline change are several smaller features that are discernable in Figure 4. A series of major storms in the early 1960s caused widespread erosion, and accretion in a few localized areas, while poststorm recovery induced an opposite pattern between 1963 and 1975. The Halama groin had an obvious impact on the coastline, causing about 4.2×10^4 m^3 to accrete along its southern side while the downdrift or northern side experienced erosion. Localized accretion of approximately 2.3×10^4 m^3 of sediment in the Kawililipoa area is also evident in Figure 4.

In estimating sediment production, the area of the reef characterized as "reef slope," covering 0.46 km^2, is assigned a gross $CaCO_3$ production rate of 7.0 kg m^{-2} yr^{-1}. The "reef flat" area encompasses 1.28 km^2 and is assigned a production rate of 1.4 kg m^{-2} yr^{-1}. Annually the entire reef is estimated

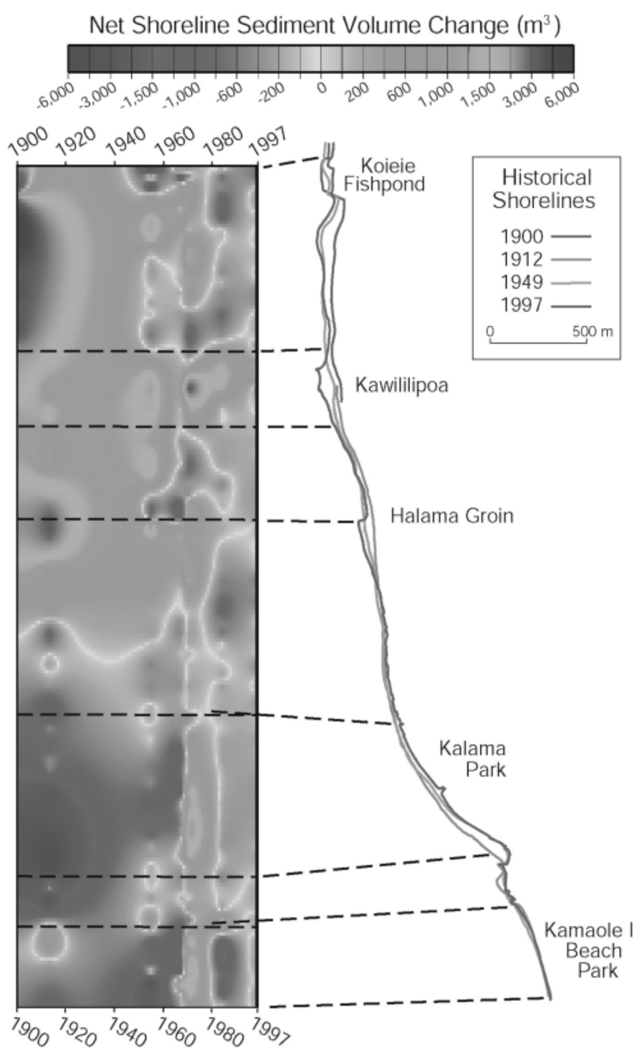

Figure 4. Volumetric change within the study site through time, and superposition of 1900, 1912, 1949, and 1997 shorelines. Negative values indicate erosion while positive values show accretion. Note that values shown here have been smoothed for illustration purposes only and are not used for calculations.

to produce approximately 530 m^3 of sediment that is potentially available to the beach system. That yields a total production of approximately 5.2×10^4 2.5×10^4 m^3 over the 97-year period covered by this study.

Longshore Sediment Transport

Calculations of NLST and total coastal sediment volume change within the site (dVt), based on movement of historical shorelines for different periods, reveal large fluctuations in both magnitude and direction (Figure 5). Between 1900 and 1912 we estimate that the rate of NLST was quite high and to the north, at 12.2×10^3 m^3 y^{-1}. Northward NLST dropped significantly between 1912 and 1949 and then jumped up again between 1949 and 1963. Since 1963 an increasingly southward trend in NLST has been observed, with southward

Table 2. *Shoreline sediment volume change* (in m^3) *caused by specific processes at the study site.*

Specific Process	Volume Change* 1900/12–1949	Volume Change* 1949–1997
Accretion in northern half of study site	284,000	132,000
Erosion from southern half of site	−119,000	−28,000
Sediment production on reef available to littoral system	26,000	25,500
Accretion south of groin	NA	−42,000
Accretion from reef rubble features at Kawililipoa	NA	−23,000
Accretion in dunes near groin	???	−1,400

* Negative values indicate processes that remove sediment from the system or trap it such that it is no longer acted on by LST-inducing forces.

rates as high as -1.1×10^3 m^3 y^{-1}. Changes in dVt follow the same general pattern as those of NLST but are usually of a somewhat smaller magnitude.

Kona Storm Activity

A total of 32 major Kona storms are found in the historical record. These are plotted against their estimated impact, as dots in Figure 6 along with a proxy record of Kona storm activity, rainfall in Waianae, Oahu. The cumulative sum of the residuals (differences between each data point and the mean of the entire dataset, summed from the start of the record through the given data point) of winter season rainfall, is plotted as a black line. Periods of higher than average rainfall show a positive slope, whereas periods with lower than average rainfall show a negative slope.

DISCUSSION

Causes of Shoreline Change: Geomorphic Evidence

Clues to why the shoreline has changed are available from geomorphic evidence. Fishponds within the site, at least one of which is at least 500 years old (RYAN, 2000), are still located at the water's edge, suggesting a long-term balance in sediment dynamics. This is despite a relative sea-level rise of 2.1 mm y^{-1}, according to NOAA tide gauge records from Ka-

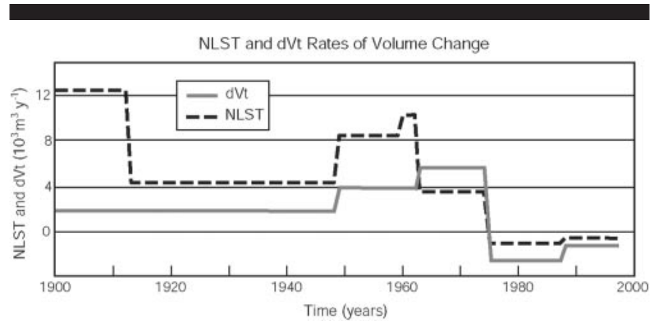

Figure 5. Time series of mean rates of NLST and dVt (changes in volume for the entire site) over each period between historical shorelines. Note that because of lack of data, the dVt record shows a single estimated mean rate of change for the 1900/1912 to 1949 period, and the NLST record shows different rates for 1900 to 1912 and 1912 to 1949.

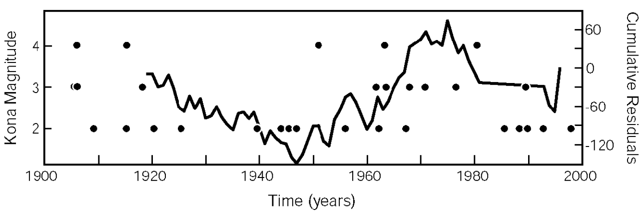

Figure 6. Dates and relative magnitudes of major Kona storms and frontal passages on the Kihei coast in the historical record are plotted as black dots. The cumulative sum of the residuals of winter season precipitation in Waianae, Oahu is shown as a solid line. The latter, a proxy for Kona storm and front activity in Hawaii, plots periods of higher (lower) than average precipitation with a positive (negative) slope. Data are not available for the period between 1982 and 1992.

halui, Maui. Despite its net balance, the system has experienced dramatic changes over the last century. The shoreline around Koieie Fishpond in 1900 (Figure 4) was about 30 m further seaward on its north side and 60 m further landward on the southern side relative to the 1997 shoreline. Such a configuration is indicative of southward NLST prior to 1900. The head of Maalaea Bay is only 4 km to the north, so there is limited fetch within the bay for wave development at the site. The area is also well sheltered from waves arriving from the northwest, north, east, and southeast. Hence, there does not seem to be a mechanism to move high volumes of sediment to the south. This suggests that the 1900 shoreline reflects a significant period of dominantly southward, presumably trade wind-driven, LST. Between 1900 and 1949, however, the north side of the fishpond accreted about 20 m while the south side accreted about 40 m. Between 1949 to 1960, and 1960 to 1963 the north side eroded 36 m and 12 m, respectively, while the south side experienced jumps in accretion of 7 m and 15 m, respectively. There were a number of major Kona storms in the first half of the 1900–1949 period as well as between 1949 and 1960 and especially during the 1960–1963 period. This can been seen in Figure 6, which depicts major Kona storms and their estimated relative impact on the Kihei coast. Movement of the shoreline around Koieie Fishpond is indicative of northward NLST during these periods, and is interpreted to be a result of intensive Kona storm activity.

Between 1963 and 1997 there was particularly heavy localized accretion in the Kawililipoa area. The sequence of aerial photographs for this area documents gradual shoreward movement of accumulations of reef rubble conglomerate. Similar features, described as "coral-conglomerate tongues," have been identified along South Pacific island shorelines and interpreted as reworked storm deposits (RICHMOND, 1997). We hypothesize that the rubble material at this site may have been broken off the reef during major Kona storms in the early 1960s and gradually pushed towards shore. Whatever their origin, these features have been interrupting LST along the coast here, resulting in the localized accretion of 2.3×10^4 m^3 of sediment since 1975.

Annual *in situ* sediment production, 530 m^3, is relatively small compared to the total volume of sediment transported along the coast. Over the 97-year period covered by the study for example, *in situ* production accounts for only ~20% of the net sediment accumulation. On time scales of years to decades, sediment transport processes are predominant shapers of the coastline. On the other hand, as the timescale of interest becomes longer, *in situ* sediment production and storage become increasingly important components of the sediment budget. Long-term storage of biogenic sediment was demonstrated by HARNEY *et al.* (2000), who found that fossiliferous sand up to 5000 years old dominates the surficial sand reservoir at Kailua Beach on the island of Oahu, Hawaii. On scales of thousands of years, sediment production and storage are responsible for creating the beach and become important geologic processes.

Causes of Shoreline Change: Anthropogenic Activity

Another set of features or processes affecting littoral sediment dynamics within the site are predominantly anthropogenic. The first of these was the construction of several fishponds by the native Hawaiian community. The only one with significant portions of its basalt boulder walls still above sea level is Koieie Fishpond, built more than 500 years ago (RYAN, 2000). Although the full impact of this structure on the shoreline is not known, alternating accretion and erosion of sediment along its side walls demonstrate that at the least it interferes with LST.

The Halama groin was reportedly built to trap northward moving sand (MAKAI OCEAN ENGINEERING AND SEA ENGINEERING, 1991). Between 1912 and 1949, before the groin was built, the shoreline had accreted seaward about 40 m in this general area. When it first appeared in the 1960 photographs, the groin had already caused about 20 m of localized accretion on its south side and 20 m of erosion to the north. This trend continued during the 1960–1963 period, indicating continued net northward LST, as expected given the high levels of Kona storm activity at this time. About 4.2×10^4 m^3 of sediment had accumulated in a several hundred meters-long wedge on the south side of the groin by 1997. An additional 1.4×10^3 m^3 is trapped in sand dunes inland of the groin, although it appears from the 1949 photographs that at least part of the dune complex was already there before the groin was built (see Table 2).

Over the past century and particularly in the last few decades, much of the coastline within the study site has been developed. In response to periods of erosion along the shoreline, seawalls and revetments were constructed between the beach and the abutting property. By 1975 a line of seawalls, unbroken except for a few beach access paths, extended over 1400 m from the south end of Kalama Park to the north. Before this armoring of the coastline, sediment was eroding from the backshore along this portion of the coast at a mean rate of 3,300 m^3 y^{-1}. After the segment was armored, that value changed to 1,000 m^3 y^{-1}, more than a threefold decrease in net sediment transport. This may reflect a decrease in Kona storm activity as well as impacts of armoring. However, in January 1980, probably the largest Kona storm on record hit the islands. Despite this, the 1975 to 1988 period shows the strongest southerly NLST of any period. The relatively minor erosion at the site from this event is likely because of the presence of coastal armoring. The impact of armoring is also apparent in the statistics on beach widths. Between 1949 and 1997, mean beach width for the entire study site decreased by 44%, primarily reflecting a drop in front of the armored shoreline, from 16.9 m to less than 1 m. This serious loss of the beach resource is particularly significant given its vital role in the visitor industry, which is the predominant source of jobs and income in Maui County. Kona events and episodes of south swell since the late 1980s would have, in the absence of armoring, eroded the vegetation line landward, exposing sand from the coastal plain in the southern half of the site to the active littoral system and helping to maintain a healthy beach.

Net Longshore Sediment Transport

Movements of the historical shoreline positions documented in the present study are much too large to be simply reflecting seasonal variations at the site, which average less than 4 m (FLETCHER et al., in press). As seen in Figure 4, in areas within the study site showing major change, episodes of accretion and erosion are manifested as incrementally greater displacements of the shoreline from one year of coverage to the next. If cycles of shoreline erosion and accretion of a comparable magnitude were occurring between intervals of photographic coverage, there would be aliasing issues with the historical shoreline positions. However, such large-amplitude movements would be evident in the photographs, in the form of much wider beaches reflecting insufficient time for vegetation to become reestablished, infrastructure that had been destroyed and not rebuilt, etc. Evidence of such fluctuations are not seen in the photographs or reported in the literature or anecdotally. This observation and the persistence of many of the major changes to the shoreline (*e.g.,* accretion on the south side of the Halama groin) indicate that the historical shorelines are effectively documenting long-term trends in shoreline behavior.

Rates of NLST, shown in Figure 5, are the integrated result of all transport processes that occurred during the period between historical shorelines. Features used to estimate NLST experience some leakage of trapped sediment, and there is significant sediment exchange between the study site and shoreline areas to either side. The method used here will tend to underestimate NLST in situations in which there is a significant component of cross-shore transport. The accuracy of the curve is impacted by the limited number of historical shorelines available, which results in periods lacking data. In addition, unless a shoreline position happens to capture the configuration of the coast just as there is a change in LST, our rates will integrate both the earlier and later magnitudes and directions of sediment transport. Hardening of the shoreline, construction of the Halama groin, and development of the reef rubble structures at Kawililipoa have all acted to reduce the ability of sediment to move along the coast.

The record of total volumetric changes along the shoreline is well constrained relative to that of NLST. It is useful, therefore, to compare the two, to ensure that values of NLST are reasonable. The cumulative volume change between 1900 and 1997 from the NLST record is 4.4×10^5 m^3, versus 2.4×10^5 m^3 from dVt. Because the site has experienced significant net accretion, and most of the erosion from the southern portion cooccurred with greater rates of accretion to the north, the total volume lost from the south, 1.7×10^5 m^3, is assumed here to have been redeposited in the north. This redeposited volume, if subtracted from the total volume from the NLST record, yields a remainder of 2.7×10^5 m^3, which is not significantly different from the total volume from the dVt record.

Although overall volumes of the two records are in reasonable agreement, differences in their rates of volume change are apparent from an inspection of Figure 5. Note that the dVt record shows a single value between 1900 and 1949, whereas the NLST record is broken into two different values (see ROONEY, 2002, for further details), with a markedly higher rate for the 1900 to 1912 period. NLST rates from 1900 through 1963 are significantly higher than those from the dVt record, reflecting the redistribution of sediment from the southern to the northern side of the site.

The largest jump in dVt occurs between 1963 and 1975, immediately after a major peak in the NLST record. However, the 1963 photographs were taken 7 months after two major storm events and still show obvious signs of their impact. Kamaole I Beach, for example, has sand along only half its length. Because these photographs extend only slightly seaward of the shoreline, it is impossible to tell if there are significant volumes of sand in storage on the reef flat that have not yet been transported to shore. Therefore, the overall gain in volume between 1963 and 1975 may be secondary to sediment transport into the site during earlier periods.

After 1975, absolute values of dVt are consistently larger than those of NLST. This is probably because of the use of the Halama Street groin to estimate NLST and reflects leakage of sediment sequestered there. In addition, after 1975, the records show southward NLST, extensive hardening or other stabilization of the shoreline, and loss of sediment from the site, precluding the continued use of larger areas within the site to estimate NLST. However, the reasonably close agreement between dVt and NLST data add further evidence that the historical shorelines are adequately characterizing NLST in this area.

The NLST history shows that there have been significant changes in both the magnitude and direction of transport in this area over the past century and provides evidence of the forces responsible. One possible mechanism forcing NLST is hurricanes. The greatest damage in Kihei from any hurricane on record was from Hurricane Iniki, which, in September 1992, passed about 400 km south of the island of Hawaii before turning north to pass directly over Kauai. This unusual track subjected the Kihei coast to a particularly long and direct period of exposure to hurricane-induced wave energy. Iniki is the only hurricane for which beach erosion in Kihei is specifically identified, although reports from multiple Kona storms indicate more severe damage to beaches there. Additionally, CHU and CLARK (1999) show that almost all hurricane tracks in the central Pacific between 1966 and 1997 that reached Maui pass to the southwest of the island. Wave energy they generated would induce northward NLST in Kihei.

CHU and CLARK (1999) further report a significant rise in tropical cyclone activity (tropical depressions, storms, and hurricanes) between the 1966–1981 and 1982–1997 periods. The pattern of NLST, however, shows an increasing southward component during this time, further reinforcing the hypothesis that hurricanes have not been the dominant force inducing shoreline change.

Although tsunamis have had a major impact on portions of the Hawaiian coastline, the Kihei area seems to be well protected, particularly from tsunamis originating in the Northern Hemisphere. Although there have been 4 tsunamis with measurable runup within Maalaea Bay over the past century, only the tsunami of May 22, 1960, originating in south central Chile, appears to have had a significant impact in Kihei (LANDER and LOCKRIDGE, 1989; WALKER, 1994; FLETCHER *et al.,* 2002). This event flooded Kalama Park and caused light to moderate damage to 11 houses, but there are no reports of beach erosion (MAUI NEWS, 1960). We conclude that tsunamis have had only a minor impact on sediment dynamics in Kihei over the period covered by this study, while several of lines of evidence suggest that Kona storm processes are likely responsible for most of the changes to the shoreline within the study site.

Pacific Decadal Oscillation

ENSO events, typically occurring every 3 to 4 years (GODDARD and GRAHAM, 1997), exert a significant influence on Kona storm activity in Hawaii. They tend to last 6 to 18 months and may go from one extreme to the other, *e.g.,* from a strong El Niño to a strong La Niña event, in adjacent years (DIAZ and KILADIS, 1992). These characteristics make it difficult to discern multidecadal variations in the ENSO signal that might correlate with and explain the changes in NLST. The Pacific Decadal Oscillation (PDO), however, has been described as an ENSO-like climatic fluctuation, with warm and cool phases that generally last 20–30 years (MANTUA *et al.,* 1997; ZHANG *et al.,* 1997). The terms "warm" and "cool" are commonly used to describe phases of both the PDO and ENSO. They refer to SSTs of the tropical eastern Pacific Ocean and along the west coast of the Americas (HARE *et al.,* 1999).

The leading eigenvector of North Pacific monthly sea surface temperatures poleward of 20° N for the 1900–1993 period has been established as an index to compare the relative intensity of the PDO (MANTUA *et al.,* 1997; MANTUA, 2000). Anomalies in the mean SST, sea-level pressure (SLP), and wind stress fields associated with a positive phase of the PDO are illustrated in Figure 7. A positive phase is characterized by a wedge-shaped body of anomalously warm water in the eastern equatorial Pacific, surrounded by a horseshoe-shaped band of cooler than normal water, with a drop in sea level pressure centered over the Aleutian Islands. This pattern reverses during the negative phase. ENSO events exhibit patterns that are broadly similar to, but of greater intensity than, those of the PDO and more focused in the tropics, whereas the PDO is most pronounced at higher latitudes (MANTUA *et al.,* 1997; ZHANG *et al.,* 1997). There is strong evidence that the PDO modulates ENSO events such that

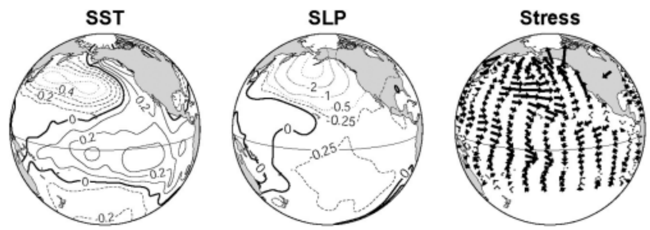

Figure 7. Warm phase PDO surface anomalies: (left panel) sea surface temperature anomaly pattern, dashed contours depict cooler than average temperatures, and solid contours reflect warmer than average temperatures, contour interval is 0.1 degree C; (center panel) atmospheric sea level pressure anomaly pattern, dashed contours depict lower than average sea level pressures, while solid contours reflect higher than average pressures; (right panel) wind stress anomaly vectors, the longest wind vectors represent a (psuedo) stress of 10 $m^2\ s^{-2}$. [From HARE *et al.* (1999). Reproduced with permission from the American Fisheries Society].

there is a greater tendency for strong El Niños (La Niñas) during positive (negative) phases of the PDO (GERSHUNOV and BARNETT, 1998; GERSHUNOV *et al.,* 1999; MCCABE and DETTINGER, 1999; MANTUA *et al.,* 1997). Winter season means of the PDO index and MEI are consistent with their findings, correlating at well above the 95% confidence level. Although each phase of the PDO lasts 20–30 years, it may contain intervals of several years in length in which the sign of the PDO index is reversed. These high-frequency shifts are difficult to distinguish from actual phase changes of the PDO, except in hindsight, and appear to have the same impact on ENSO (MANTUA *et al.,* 1997).

Independent researchers have evidence for two full cycles of the PDO over the past century, with cool phases from 1890–1924 and 1947–1976 and warm phases from 1925–1946 and 1977 to about 1998 (MANTUA *et al.,* 1997; MINOBE, 1997). Other researchers have found evidence of PDO-like climatic fluctuations extending further back in time, suggesting that the PDO may be a true internal oscillation. Using tree ring data and proxy records of SST from corals, MINOBE (1997) and LINSLEY *et al.* (2000), find evidence of PDO-like climatic fluctuations as far back as the 1700s. BAUMGARTNER *et al.* (1992) document similar variations extending back to AD 270 based on scales from anchovy and sardines preserved in Santa Barbara Basin sediments. Considerable debate exists, however, over all aspects of the PDO, with the observed climatic fluctuations attributed to causes ranging from simple manifestations of stochastic external forcing (HUNT and TSONIS, 2000) to oscillations of the ocean atmosphere system, with variety of trigger and feedback mechanisms invoked (*e.g.,* LATIF and BARNETT, 1996; GU and PHILANDER, 1997).

Although its signal is most pronounced at higher latitudes, the PDO has been shown to induce changes in climate near Hawaii. CHU and CLARK (1999) document an increase in the frequency and intensity of tropical cyclones in the central North Pacific between 1982 and 1997. They note that the changes appear to be modulated by decadal-scale changes in SST, with warmer conditions during this period, perhaps leading to stronger El Niño events as well as greater tropical

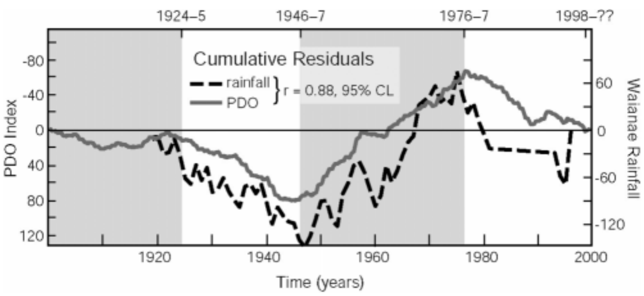

Figure 8. The cumulative sum of residuals of the PDO (gray line) and Waianae rainfall (black dotted line). Note that the Y-axis for PDO cumulative residuals has been reversed. Alternating gray and white backgrounds indicate negative and positive phases, respectively, of the PDO, with dates between phases labeled at the top of the figure. Their correlation (r = −0.88) is significant at the 95% confidence level (CL).

cyclone activity. As might be expected, positive (negative) PDO phases are found to correlate with periods of reduced (enhanced) precipitation in Hawaii (Mantua *et al.,* 1997; Wright, 1979).

Positive PDO phases are characterized by a general tendency for anomalously warm SSTs in the central and eastern equatorial Pacific, inducing a migration of the midlatitude storm belt and, as with El Niño events, enhancing the tendency for the ridge aloft to be found in the vicinity of Hawaii. Both mechanisms tend to suppress Kona storm activity in the islands (T. Schroeder, personal communication). It is expected, therefore, that there will be fewer Konas during positive PDO phases and more during negative ones.

We hypothesize that NLST along the Kihei coast during positive PDO phases is characterized by a relative lack of Kona storm-driven transport, and dominated therefore by trade wind-driven southward NLST. During negative phases, however, we expect a greater than average level of Kona storm activity and increased potential for northward NLST. To test these hypotheses, we compare our record of NLST in Kihei with local climate histories (the precipitation and Kona storm records from Hawaii) and the PDO index.

Leeward Rainfall and the PDO

As discussed earlier, a local proxy for Kona storm activity in the Hawaiian Islands is winter rainfall in Waianae on Oahu. The cumulative sum of residuals of total winter season rainfall and winter season means of the PDO index are shown in Figure 8. Areas on these curves with a positive (negative) slope represent periods of lower (higher) than average measurements. To more clearly illustrate its relationship to the precipitation time series, the Y-axis of the PDO plot has been reversed. The previously mentioned changes in PDO phase are shown in the figure as alternating gray and white backgrounds and appear at the same time as major changes in slope from the two curves.

The PDO and Waianae rainfall time series each describe or reflect multidecadal climatic shifts; hence, there is a tendency for successive measurements to have similar values. Reducing the degrees of freedom before testing for significance can accommodate this nonindependence of the data. We use both Chen's (1981) technique and another method commonly applied in analyzing climatological data (J. Loschnigg, personal communication) for reducing the degrees of freedom for the correlation. Both methods are based on autocorrelations of the data but vary as to which is more stringent when applied to a given time series. The second method, which we refer to as the "$1/e$" technique involves running an autocorrelation on, for example, annual values of the PDO index. Autocorrelations are run for lags from zero to $n - 1$, and the values of the correlation coefficient, r, are plotted against the number of lags. The number of data points, n, is divided by the value from the plotted curve at which $r = 1/e$, to yield the degrees of freedom. The confidence level reported here reflects results from the technique, which yields the most conservative, or least statistically significant, result. The correlation coefficient, r, for overlapping periods of the Waianae rainfall and PDO records has a value of 0.88, which is statistically significant at the 95% confidence level. The obvious similarity and high correlation of the PDO and precipitation time series offer strong evidence that the PDO exerts a strong and predictable influence on Kona storm (and frontal passage) activity in the Hawaiian Islands.

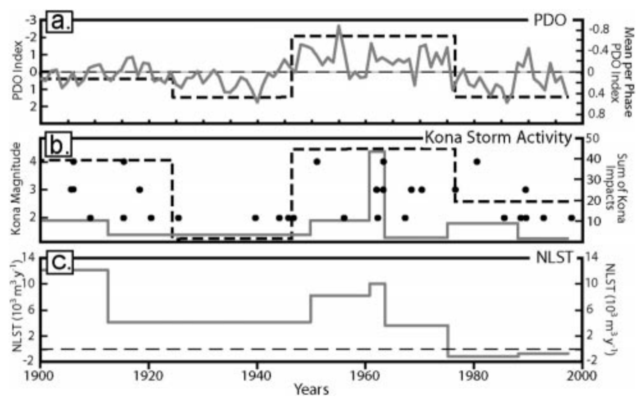

Figure 9. (a) Winter season mean values of the PDO index (gray line) and means per PDO phase (dashed black line). Note that the Y-axis is reversed so that positive values, indicating periods of the El Nino-like phase of the PDO, are toward the bottom. (b) Dates and magnitudes of major Kona events (dots) and the sum of their impacts per PDO phase (black dashed line) and per period between historical shorelines, normalized by the duration of periods between them (solid gray line). The "per PDO phase" values of the PDO index and Kona activity (dashed line) from Figures 9a and 9b correlate (r = −0.796) at the 85% confidence level. (c) Time series of net longshore sediment transport estimated from impoundment and erosion around features within the site. The correlation between NLST and the sum of Kona impacts over periods between historical shorelines (gray line) from Figures 9b and 9c (r = 0.532) is significant at the 80% confidence level.

The PDO, Konas, and NLST

To facilitate their comparison, time series of the PDO index, Kona storm activity, and NLST are plotted in Figure 9, with each subplot sharing a common X-axis of time in years. Figure 9a depicts winter season means of the PDO index and their average per phase of the PDO, shown as a black dashed line. The latter is compared to a time series of Kona impacts, which have been summed over each PDO phase and is also depicted as a dashed black line, in Figure 9b. It is apparent that both records behave similarly on a "per PDO phase" basis, and the correlation between them is significant at the 85% confidence level. As discussed earlier, the historical record of Kona storm impacts includes a number of assumptions. However, by comparing the cumulative impact of all Kona events over multiple years, the influence introduced by a single event that is incorrectly ranked is reduced. Also, the reliability of conclusions based on it are considerably strengthened by the fact that, over different phases of the PDO, the Kona storm record closely matches the general pattern of the robustly measured precipitation time series from Waianae.

Unfortunately, the temporal distribution of historical shorelines does not coincide very well with the beginning and end of PDO phases, making direct comparisons between them difficult. Accordingly, the sums of estimated impacts of major Konas for each period between historical shorelines, normalized by the duration of each period, are shown in Figure 9b as a gray solid line. That is compared to the record of NLST between historical shorelines within the site, shown in Figure 9c. Their correlation coefficient, r, is 0.53, which is significant at the 80% confidence level. Although one typically expects to see correlations being reported at the 95% confidence level, characteristics of what is being correlated must be considered. We are investigating a phenomenon that operates as a background set of multidecadal relatively low-magnitude climatic conditions. It has periods of up to several years within a phase in which the sign of the index reverses and includes only two complete cycles over the period for which we have data. Additionally, the generation of individual Kona storms is chaotic, and other factors influence NLST. Under the circumstances, we feel that the 80% confidence level is about as high a correlation as can be reasonably expected.

In an effort to cross check the above results, we appraise the ability of the historical Kona storms to move the volumes of sediment indicated by the NLST record (ROONEY, 2002). Deepwater wave characteristics from five Kona events (U.S. ARMY CORPS OF ENGINEERS, 1967) are used for three runs of the Simulating Waves Nearshore (SWAN) model (BOOIJ *et al.,* 1999). The breaking wave height and the angle of the crests to the shoreline, in conjunction with a number of assumptions, are applied to a longshore sediment transport equation adapted for Hawaiian beaches (SEA ENGINEERING INC., 1982). We calculate a total volume of 8.4×10^5 m^3 of sediment was transported northward by Kona storms, or about double that from the NLST record, but the associated uncertainty is estimated to be plus or minus an order of magnitude. This approach is much too simplistic and subject to error to consider the result to be confirmation of the dominance of Konas in shaping the history of NLST in the area. Rather, it suggests that Konas may be capable of causing the changes documented at the site.

The scenario suggested by Kona storms and NLST records at this site is consistent with other time series including the PDO and Multivariate ENSO indices and precipitation in Waianae. There are meteorological mechanisms linking the PDO and Kona storm activity, and Kona storms appear to have been able to induce the observed changes in NLST, while other possible forces do not appear to have caused them. Given these considerations, and the correlations and PDO-ENSO-Kona storm linkage discussed above, we conclude that there is strong evidence that the PDO does exert a significant influence on Kona storm activity in Hawaii. By suppressing (allowing) Kona storm activity in main Hawaiian Islands when it is in a positive (negative) phase, the PDO is found to reduce (enhance) northward NLST, over decadal time scales, within the Halama study site.

The PDO and Shoreline Change Prediction

The study site discussed here is uniquely situated, facing to the south and protected by West Maui and other islands, such that more of its decadal-scale sediment dynamics are driven by Kona storms than probably any other stretch of coast in at least the Hawaiian Islands. However, many other Pacific shorelines are impacted by forces that show some degree of response to the PDO. As discussed above, the PDO strongly influences hurricane activity near Hawaii and, although the affect may change for different areas, across the entire equatorial Pacific (CHU and CLARK, 1999). Positive PDO phases, which are associated with a deepening of the Aleutian low, appear to be linked to the occurrence of large winter season waves in the Hawaiian Islands. Particularly large North Pacific swell events are found to correlate at the 95% level with unusually high PDO index values, suggesting that these shoreline-modifying events are also modulated by the PDO (ROONEY et al., in press). We anticipate that as further research is conducted, sediment dynamics along many Pacific shorelines will be found to be strongly influenced by PDO-controlled forces.

An understanding of the physics driving the PDO is required before we will be able to predict PDO-induced impacts to the shoreline on decadal time scales. Given the PDO's long period and the relatively short duration of observational records, longer-term proxy records of climatic data must be developed to address the many questions regarding this phenomena (CANE and EVANS, 2000). Despite shortcomings in our understanding, the PDO's tendency to persist for decades gives it some use as a tool for enhancing ENSO-based climate and weather predictions (GERSHUNOV and BARNETT, 1998; GERSHUNOV *et al.,* 1999; MCCABE and DETTINGER, 1999). Answering some of the fundamental questions regarding the nature of the PDO will help to enhance our understanding of and ability to cope with climatic impacts on shoreline change at decadal time scales.

CONCLUSIONS

Over the period 1900 to 1997, net accretion of 4.2×10^5 m^3 of sediment occurred in the north part of the Kihei coastline while the southern part experienced a net loss of 1.5×10^5 m^3. This pattern suggests that there has been net northward longshore sediment transport. The timing of shoreline changes suggest that the bulk of sediment dynamics have been caused by natural, rather than anthropogenic, forces. However, sediment impoundment through hardening of the shoreline is primarily responsible for an observed 50%decrease in mean beachwidth and rates of NLST and is estimated to have resulted in a loss of 4.2×10^4 m^3 of sediment to the active beach system between 1975 and 1997. Production of calcium carbonate on the adjacent fringing reef is estimated to have added about 5.2×10^4 m^3 of sediment between 1900 and 1997, indicating that it is a markedly less important process than LST at these time scales.

We discuss results of a case study of the not uncommon situation of an area with a serious coastal erosion problem, but with very little oceanographic and other data available to facilitate a thorough evaluation. Given the importance of the beach resource and need for improved management indicated by severe loss of that resource, it is necessary to use what data are available to make the best possible analysis of what is causing these changes. Here, unique wave exposure characteristics at the study site enable the use of a history of NLST to gain insight into forces responsible. It has been suggested (*e.g.,* MANTUA *et al.,* 1997) that the PDO modulates aspects of atmospheric circulation in the Pacific, causing ENSO-like fluctuations in SST and SLP. We hypothesize that migration of the midlatitude storm belt and an enhanced tendency for the ridge aloft to be located in the vicinity of Hawaii are characteristic of positive PDO phases. These cause below-average Kona storm activity in the Islands and result in trade wind-driven southward NLST during positive PDO phase. During negative PDO phases, higher than average Kona storm activity occurs, resulting in northward NLST. Historical records and dissimilarities between patterns of NLST, hurricane activity, and tsunamis suggest that hurricanes and tsunamis have had a relatively minor impact over the last 150 years. We find statistically significant correlations among the PDO index, Kona-related precipitation, historical Kona storm activity, and NLST calculated from shoreline movement. Historical data appears therefore to support the hypothesis that the PDO exerts a primary control on decadal-scale fluctuations in shoreline behavior in Kihei. Given the PDO's influence on hurricanes and North Pacific swell in Hawaii, and other Pacific basin-wide changes, it probably exerts some control on sediment dynamics in many other areas as well. Consideration of PDO impacts is likely to improve management of beach resources on many Pacific shorelines.

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