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Are beach erosion rates and sea-level rise related in Hawaii?

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ABSTRACT

The islands of Oahu and Maui, Hawaii, with significantly different rates of localized sea-level rise (SLR, approximately 65% higher rate on Maui) over the past century due to lithospheric flexure and/or variations in upper ocean water masses, provide a unique setting to investigate possible relations between historical shoreline changes and SLR. Island-wide and regional historical shoreline trends are calculated for the islands using shoreline positions measured from aerial photographs and survey charts. Historical shoreline data are optimized to reduce anthropogenic influences on shoreline change measurements. Shoreline change trends are checked for consistency using two weighted regression methods and by systematic exclusion of coastal regions based on coastal aspect (wave exposure) and coastal geomorphology. Maui experienced the greatest extent of beach erosion over the past century with 78% percent of beaches eroding compared to 52% on Oahu. Maui also had a significantly higher island-wide average shoreline change rate at −0.13 ± 0.05 m/yr compared to Oahu at −0.03 ± 0.03 m/yr (at the 95% Confidence Interval). Differing rates of relative SLR around Oahu and Maui remain as the best explanation for the difference in overall shoreline trends after examining other influences on shoreline change including waves, sediment supply and littoral processes, and anthropogenic changes; though, these other influences certainly remain important to shoreline change in Hawaii. The results of this study show that SLR is an important factor in historical shoreline change in Hawaii and that historical rates of shoreline change are about two orders of magnitude greater than SLR.

1. Introduction

It has not been widely documented if historical rates of sea-level rise (SLR) are an important factor in shoreline changes observed on coasts around the world. Zhang et al. (2004) document that on the U.S. east coast rates of coastal erosion are about two orders of magnitude greater than the rate of SLR. However, this has not been confirmed elsewhere and the relative contribution of SLR to regional shoreline change patterns remains debatable. Improved understanding of the influence of SLR on historical shoreline trends will aid in forecasting beach changes with increasing SLR. Globally-averaged sea-level rose at about 2 mm/yr over the past century. Studies indicate that the rate of rise is now approximately 3 mm/yr (Church and White, 2006; Merrifield et al., 2009) and may accelerate over coming decades (Vermeer and Rahmstorf, 2009).

Few datasets embody detailed multi-decadal to century-scale historical shoreline positions on sandy beaches of wave-dominated coasts, with relations to SLR. List et al. (1997) examined beach profile response to accelerated SLR on barrier coastal islands of Louisiana since the 1880s, concluding that relative SLR is not the primary factor forcing the region's shoreline change. Leatherman et al. (2000) investigated the relationship between long-term (century-scale) shoreline change and varying rates of SLR along the U.S. east coast, finding a correlation between regionally-averaged shoreline change rates and localized rates of relative SLR. Brunel and Sabatier (2009) examined historical shoreline changes on the French Mediterranean coast in comparison to theoretical predictions of shoreline change due to SLR and found that sea-level rise is one of, but not the major, factor influencing shoreline retreat on wave-dominated coasts in that region. Webb and Kench (2010) described the response of central Pacific atoll islands to SLR using historical aerial photography over a 19 to 61 yr period and concluded that reef islands are dynamic landforms that undergo a range of physical adjustments to changing SLR and other boundary conditions.

Recently completed shoreline change studies for the islands of Kauai, Oahu, and Maui, Hawaii (Fletcher et al., 2012; Romine and Fletcher, 2013) indicate substantially higher erosion rates for the beaches of Maui compared to Oahu and Kauai. Tide gage data from the individual islands indicates higher rates of localized SLR around Maui compared to Oahu and Kauai (approximately 65% higher, http://tidesandcurrents.noaa.gov/). Coincidentally, the relative rate of SLR around Kauai and Oahu (1 to 2 mm/yr) is similar to the global-average rate of SLR over

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the past century, while the relative rate of SLR around Maui is similar to the present rate of global-average SLR (2 to 3 mm/yr). Oahu and Maui Islands provide a unique opportunity to investigate shoreline trends between two adjacent islands in similar physical settings and with similar geomorphologic history (including anthropogenic changes), but with significantly differing rates of relative SLR. SLR is only one of many factors driving shoreline change. Other drivers of shoreline change that must be considered carefully include sediment availability, anthropogenic changes, littoral processes, wave conditions, and coastal and nearshore geomorphology. Because of these multiple factors, establishing a direct causative link between historical shoreline change and SLR remains a challenge.

Using historical shoreline measurements from Fletcher et al. (2012), augmented with new data for the north and west coast of Maui, we provide further investigation of trends for the islands of Oahu and Maui to determine if there are significant differences between the islands and if SLR is an important factor in observed shoreline changes. We control for influences other than SLR to determine if SLR remains as the best explanation for observed changes. We also utilize a series of consistency checks to determine if results are significant and to eliminate other possible explanations.

2. Regional setting

The Hawaii archipelago, including the islands of Oahu and Maui (Figs. 1 and 2), is comprised of eight volcanic islands in the tropics of the central north Pacific. The islands are fringed by carbonate reef platforms built from a complicated patchwork of fossil Pleistocene reefs during interglacial sea-level high stands of the past 500 kyr or so (Fletcher et al., 2008).

Analysis of beach sediments in Hawaii shows they are typically comprised of biogenic calcareous debris eroded from nearshore reefs, with a minor fraction of volcanoclastic sediment eroded from adjacent watersheds (Moberly and Chamberlain, 1964; Harney and Fletcher, 2003). Grain size on beaches in Hawaii has been shown to be related to wave and current energy, which, in turn, is largely dependent on coastal aspect (wave exposure) (Moberly and Chamberlain, 1964). Beach sediments in Hawaii have been shown to typically be mid-Holocene in age (~500–2,000 yrs before present) likely due to changes in carbonate sediment production through the Holocene (Harney et al., 2000; Resig, 2004). Sediment storage on the inner reef platform in paleo-karst depressions and channels plays an important role in beach sediment supply (Bochicchio et al., 2009; Conger et al., 2009). Sediment may be lost from beaches by abrasion, longshore transport, transport offshore by wave-driven currents, landward transport by onshore winds, and human activities. Hawaii beaches, like most carbonate beaches, are, generally, narrower than siliciclastic beaches due to limited available sediment from the nearshore reef and coastal plain. We refer the reader to Fletcher et al. (2012) for a more thorough discussion of the coastal geology of Oahu and Maui on a regional basis.

While similar to global averages for SLR over the 20th century (~2 mm/yr; (Church and White, 2006)), localized rates of SLR vary along the Hawaii Island chain (http://tidesandcurrents.noaa.gov). SLR rates were similar for Kauai and Oahu (Kauai: 1.53 ± 0.59 mm/yr and 1.50 ± 0.25 mm/yr, resp.) and higher around Maui (2.32 ± 0.53 mm/yr) (Fig. 3). SLR rates for Kauai and Maui where not significantly different at the 95% Confidence Interval (95% CI) likely due to shorter time series for these tide stations compared to Oahu (~60 yrs for Kauai and Maui vs. ~100 yrs for Oahu). Fletcher et al. (2012) and Romine and Fletcher (2013) also found that island and regional shoreline trends for Kauai have high uncertainties likely due to high seasonal variability on some Kauai beaches, especially west Kauai. Kauai is excluded from this study where we are attempting to relate SLR and shoreline trends due to the lack of a significant difference between SLR trends for Kauai and Maui and high uncertainty with island-wide shoreline trends for Kauai. Historical shoreline data of comparable quality is not presently available for the other main Hawaiian Islands.

The variation in long-term SLR rates along the Hawaii archipelago may be related to variations in lithospheric flexure with distance from actively growing Hawaii Island (Moore, 1987) and/or decadal variations in upper ocean water masses (Caccamise et al., 2005). Acceleration of local SLR has not been detected in Hawaii tide gage records, likely related to climatological variability (e.g., tradewinds; (Merrifield and Maltrud, 2011)).

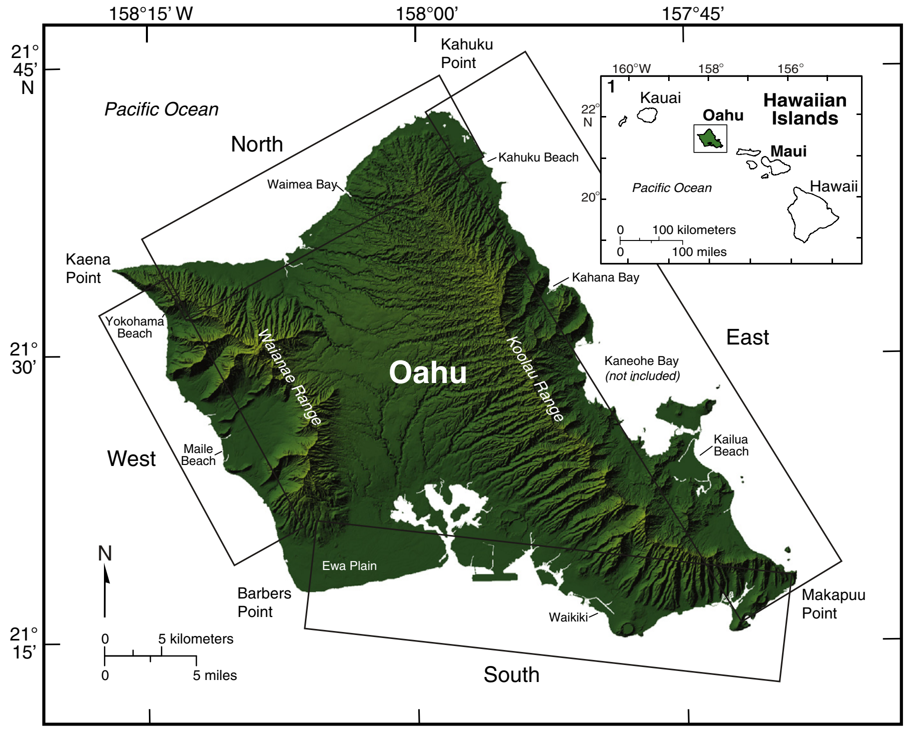

Fig. 1. Oahu island, Hawaii, showing four beach study regions: north, east, south, and west.

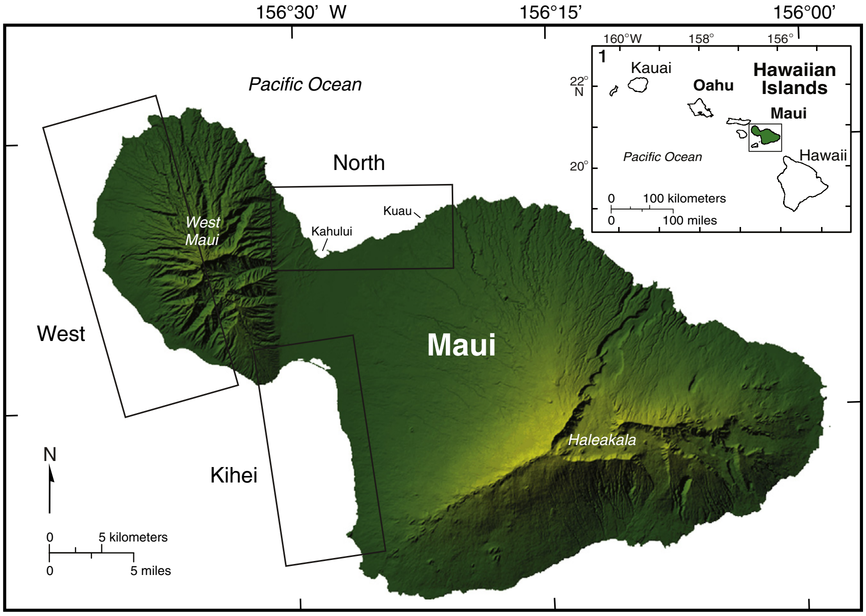

Fig. 2. Maui island, Hawaii, showing three beach study regions: north, Kihei, and west.

Hawaii has two dominant wave "seasons". In winter, large north Pacific swells affect north and west exposed shorelines while relatively calm conditions prevail along sheltered southern shores (Vitousek and Fletcher, 2008). In summer, southern hemisphere swells affect exposed southern and western shorelines and calm conditions are typical on north shores. At any time of year, extended periods of high trade wind waves from the east to northeast can cause short-term beach erosion and damage to coastal property on windward shores. Winter storm

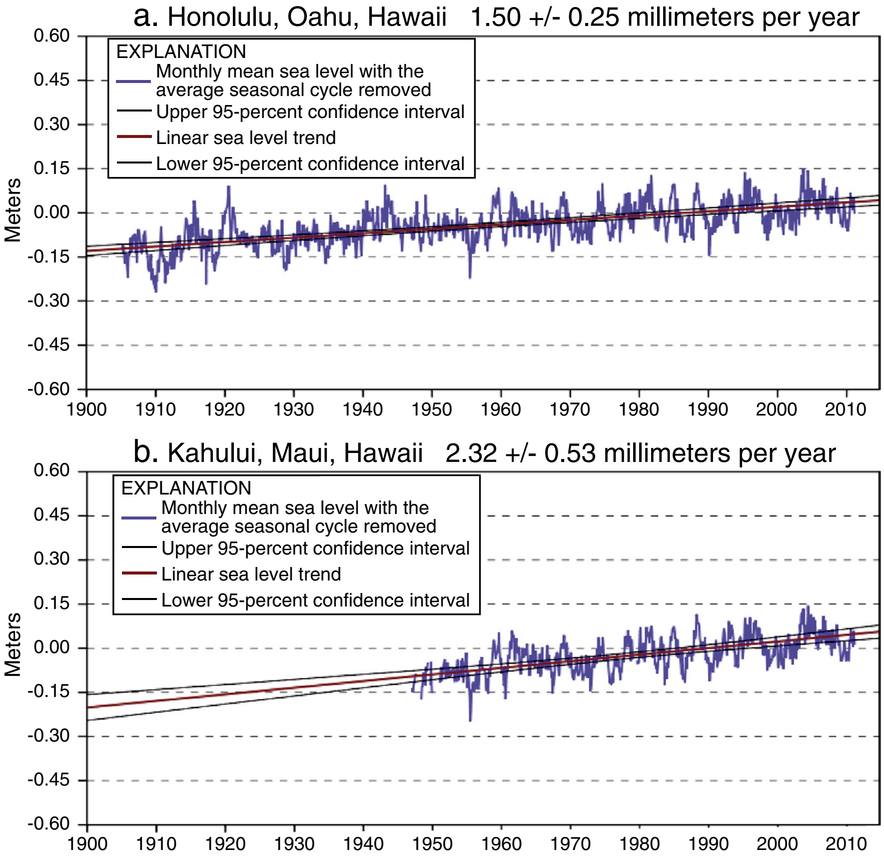

Fig. 3. Mean sea-level trends at a. Honolulu, Oahu 1905–2011; and b. Kahului, Maui 1947–2011 (http://tidesandcurrents.noaa.gov).

fronts and occasional hurricanes bring onshore “Kona” (westerly and southerly) winds and damaging waves to typically leeward shores.

3. Materials and methods

We utilize historical shoreline measurements for Oahu and Maui from Fletcher et al. (2012), augmented with new data for the west Maui and north Maui regions, to calculate historical shoreline trends. Below, we provide a summary of the methods for mapping historical shorelines and measuring shoreline change, and refer the reader to Fletcher et al. (2012) for more detail.

3.1. Mapping historical shorelines

Shoreline positions were manually digitized using photogrammetric and geographic information system (GIS) software from orthorectified aerial photo mosaics and topographic and hydrographic survey charts (T-sheets and H-sheets) provided by the National Ocean Service (NOS) (http://oceanservice.noaa.gov/). Following Fletcher et al. (2004) and Romine et al. (2009) the low water mark position (LWM) or “beach toe” was mapped as a shoreline proxy. Roughly one historical shoreline is available per decade over the past century. Only survey-quality high-resolution (≤0.5 m pixel) vertical aerial photographs with sufficient tonal quality and contrast to resolve shoreline features were used. T-sheets and H-sheets extend the time-span of historical shoreline data beyond available air photos (National Academy of Sciences, 1990). Survey charts are available as early as 1910 for Oahu and 1899 for Maui.

3.2. Positional uncertainties

Up to seven sources of positional uncertainty were combined to arrive at a total positional uncertainty for each historical shoreline (U_t, ± 3.2 m to 18.8 m, average 6.8 m). Positional uncertainty was calculated as the root mean square (RMS) of: image rectification (±0.0 to 13.5 m, average 1.9 m), digitization of shoreline position (±0.3 to 8.9 m, average 1.8 m), image pixel size (0.5 m for air photos, 1 to 3 m for charts), seasonal shoreline change (waves) (±1.3 to 14.6 m, average 4.3 m), and tidal fluctuations (±2.5 to 3.1 m, average 3.4 m). Two additional sources of uncertainty are included for T-sheet and H-sheet shorelines: original field survey and plotting of the High Water Mark (HWM) shoreline (±5.1 m) (Shalowitz, 1964) and conversion of the HWM shoreline to a LWM position (±1.2 m to 13.7 m, average 4.3 m). Shoreline positional uncertainties are applied as weights when calculating annual shoreline change rates with weighted least-squares regression (see: Section 3.3, below).

3.3. Calculating shoreline change

Shoreline movement through time was measured in a GIS at shore-perpendicular transects spaced approximately 20 m along the shore (Fig. 4). Annual rates of change are calculated from the time series of shoreline positions at each transect using two methods of weighted least-squares (WLS) regression as a consistency check on shoreline trends: single-transect (ST) and Eigen Beaches (EX) (Frazer et al., 2009; Genz et al., 2009).

Only wave-exposed beaches are analyzed in this study following Fletcher et al. (2012). The beaches at the back of the wide reef and lagoon system at Kaneohe Bay, Oahu are not included in the study (Fig. 1). In addition, the geologically-young northeast and southeast coasts of Maui, flanking Haleakala Volcano, were not included in the study due to the comparative lack of carbonate beaches.

For some beaches historical shoreline trends may have been influenced by human activities. Examples include removal of beach sand by mining operations along north Maui and Oahu beaches in the first half of the 20th century and beach nourishment projects at Waikiki, south Oahu. For this study, we calculate shoreline changes only for the period following major shoreline alterations in an effort to control for human impacts on shoreline changes and identify the natural components of beach change, to the extent possible. Where the beach has been completely lost to erosion (e.g., replaced by a seawall), we calculate shoreline change rates up to and including the first shoreline where the beach was lost.

The single-transect (ST) method is the most commonly utilized method for calculating shoreline change rates (e.g., USGS National Assessment of Shoreline Change Project). We utilize WLS, with a weight equal to the inverse of the shoreline positional uncertainty ($1/U_t$) (e.g., (Romine et al., 2009; Hapke et al., 2010)). Shorelines with high uncertainty (e.g., T-sheets) will thereby have less influence on the fit of the trend line.

We utilize the EX rate calculation method as a consistency check for rates calculated using ST. The EX method (Frazer et al., 2009; Genz et al., 2009) uses shoreline data from all transects on a beach to calculate a rate at each transect, recognizing that shoreline change among neighboring transects is related. A linear combination of eigenvectors — principle components calculated from the shoreline position data — are used as basis functions for modeling alongshore rate variation. Information criterion (Akaike Information Criterion, corrected for small samples with an unbiased estimator (Mcquarrie

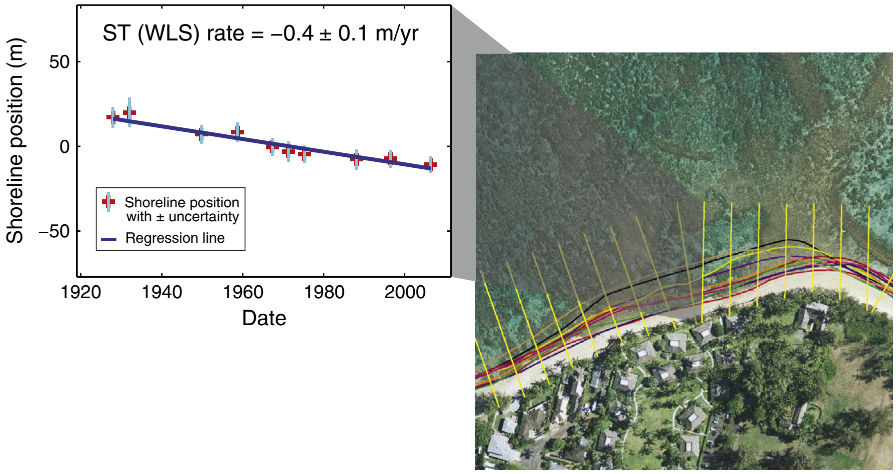

Fig. 4. Calculating shoreline change rate from historical shoreline positions with the single-transect (ST) method (using weighted least squares, WLS). Historical shoreline positions and transect locations are shown on a portion of a recent aerial photograph.

and Tsai, 1998)) serves to identify the optimal number of basis functions required to produce the most parsimonious (best fit, least parameters) model.

Uncertainties of the ST rates are the RMS error (misfit) of the WLS regression line. The EX method as utilized in Frazer et al. (2009) and Genz et al. (2009) may underestimate uncertainties with shoreline change rates. The Frazer et al. and Genz et al. studies effectively treat the Eigen vectors as independent of the shoreline data when estimating uncertainties when, in fact, the Eigen vectors are calculated from the shoreline data. For this study, uncertainties with EX rates are estimated using a non-parametric bootstrap method (Efron, 1981; Efron and Tibshirani, 1993) to re-sample the data with replacement 500 times, producing a probability distribution from which an uncertainty can be calculated. This method produces individual rate uncertainties similar in magnitude to those from the ST method. Rate uncertainties are reported at the 95% confidence interval (95% CI).

Shoreline change rates and uncertainties are reported from the ST method to remain consistent with other recent studies. The EX method is used only as a consistency check for the ST trends. A rate from ST (or EX) is considered statistically “significant” if the absolute value of the rate is greater than the uncertainty (95% CI); or, in other words, the ± rate uncertainty band does not overlap 0 m/yr.

Regionally-averaged rates are the average of rates from all (n) transects on beaches within a region. Uncertainty of a regionally-averaged rate may be estimated in a number of ways. Simply averaging the uncertainty values from all transects overestimates the uncertainty of a regionally-averaged rate because this method assumes there is no advantage in having multiple closely-spaced transects (Hapke et al., 2010). The root sum of squares of uncertainty values from all transects likely underestimates the uncertainty of a regionally-averaged rate (e.g., the method used in Fletcher et al., 2012) as the results are typically on the order of ±1 cm — often an order of magnitude smaller than an associated average rate.

Uncertainties of regionally-averaged shoreline change rates are estimated following Hapke et al. (2010) utilizing an adaptation of an autocorrelation method from Bayley and Hammersley (1946). Results from this method typically fall between the extremes of uncertainty estimates calculated using an average (likely an overestimate) and root sum of squares (likely an underestimate) of rate uncertainties. Hapke et al. (2010) use an effective number of independent observations (n^*) calculated from a spatially-lagged autocorrelation (ρ) of the individual rate uncertainties in the following equation from Bayley and Hammersley (1946) (Eq. (1)).

$$\frac{1}{n^*} = \frac{1}{n} + \frac{2}{n^2} \sum_{j=1}^{n-1} (n-j)\rho(j\tau). \tag{1}$$

The uncertainty of a regional average rate, U_{R^*}, is estimated following Hapke et al. (2010) with Eq. (2), where U_R is the mean of the individual uncertainties:

$$U_{R^*} = \frac{1}{\sqrt{n^*}} U_R. \tag{2}$$

A shoreline trend is identified as erosion or accretion at transects where the ST and EX method agree on the general direction (sign) of the shoreline trend (Table 1). A trend of erosion or accretion is considered “significant” at transects where the ST and EX methods agree on the direction of the shoreline trend and rates from both methods are statistically significant (95% CI). A trend is “undetermined” if the ST and EX models do not agree on the direction of shoreline change or if insufficient number (<2) of historical shorelines are available.

The total percent of erosional beach for a region is the sum of percent of transects where the ST and EX methods agree on a trend of erosion plus the percent of transects where the beach has been completely lost to erosion. The total percent of accretional beach for a region is the percent of transects where the ST and EX methods agree on a trend of accretion.

Table 1
Shoreline trend criteria.

Shoreline trend criteria	
Erosion	ST and EX methods indicate erosion or beach was lost to erosion.
Significant erosion	ST and EX methods indicate erosion and rates are statistically significant at 95% CI.
Accretion	ST and EX methods indicate accretion.
Significant accretion	ST and EX methods indicate accretion and rates are statistically significant at 95% CI.
Undetermined	ST and EX methods do not agree on direction (sign) of trend or insufficient data.
Beach lost	No dry beach is visible in the most recent aerial photograph(s).

4. Results

To examine a possible relationship between island shoreline trends and localized rates of SLR, this study provides a re-analysis of the Oahu and Maui shoreline trends from Fletcher et al. (2012) augmented with new data from north and west Maui, and with further consideration of anthropogenic changes to beaches, and using consistency checks of shoreline trends. Shoreline changes are analyzed along 107 km of beach (5332 transects) on Oahu island. Shoreline changes are analyzed along 67 km of beach (3329 transects) on Maui island.

Beaches on Oahu were slightly erosional to stable with an overall average shoreline change rate of −0.03 ± 0.03 m/yr (median rate = −0.03 m/yr), whereas Maui beaches were significantly more erosional with an average rate of −0.13 ± 0.05 m/yr (median rate = −0.12 m/yr) (Fig. 5, Table 2). Percentages of eroding and accreting beaches on the two islands, checked for consistency using the ST and EX rate methods, also indicate that Maui beaches are substantially more erosional. Fifty-two percent of beaches on Oahu were erosional over the past century (including 8% completely lost to erosion, Table 3), whereas 78% of beaches on Maui were erosional (including 12% completely lost to erosion). On Oahu, 39% of the beaches were accretional and 9% of beaches had an undetermined trend. On Maui, 17% of beaches were accretional and 5% of beaches had an undetermined trend on Maui.

Shoreline change is analyzed on a regional basis to explore possible relations between shoreline change and shoreline aspect (wave exposure). No particular side of the two islands (e.g., the north regions) stands-out as more erosional than the others (Table 4), thus eliminating unique wave exposure as a causative factor behind island-wide trends.

Looking at the four distinct coastal regions of Oahu (north, east, south, and west) and three distinct coastal regions of Maui (north, Kihei, and west), we find that all three coastal regions of Maui are substantially more erosional than the four coastal regions on Oahu (Table 4). In spite of different exposure to seasonal waves, north, Kihei, and west Maui had similar shoreline trends over the past century with regionally-averaged shoreline change rates between −0.12 (west Maui) and −0.15 m/yr (north Maui) (median rates between −0.11 and −0.13 m/yr). Between 73% (north Maui) and 82% (Kihei Maui) of beaches in the three coastal regions of Maui were erosional (including 10% to 14% of beach lost to erosion, Table 5). This is in contrast to the four Oahu coastal regions where regionally-averaged shoreline change rates varied from 0.04 m/yr (east) to −0.09 my/yr (north and west). Between 46% (east Oahu) and 63% (north Oahu) of beaches on Oahu were erosional including between 0% (west) and 13% of beaches completely lost to erosion.

Unlike Maui, one region of Oahu stands-out as substantially less erosional than the other island regions. The east region of Oahu is the least erosional of the four Oahu regions with a regionally-averaged

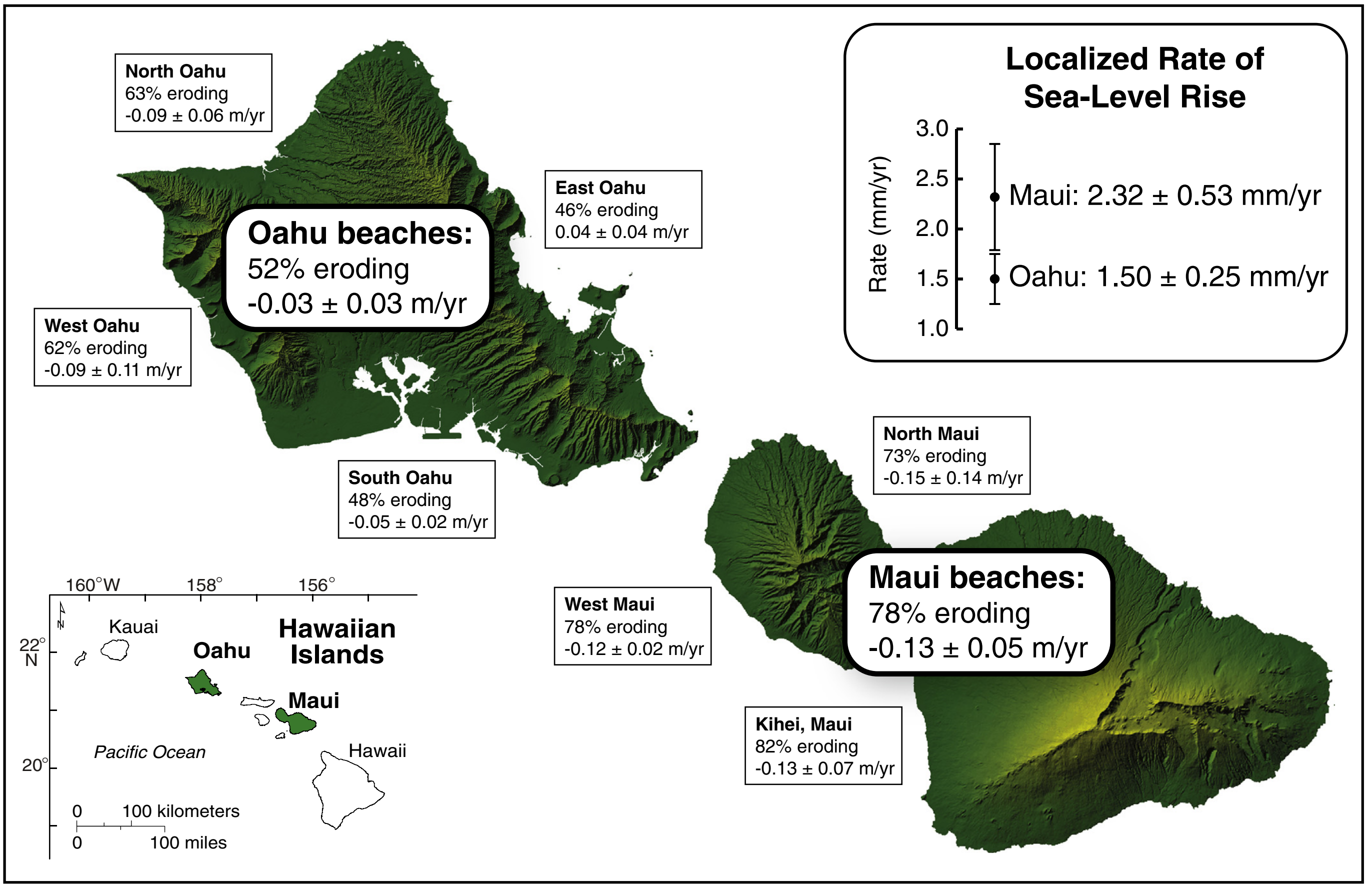

Fig. 5. Localized rates of sea-level rise and shoreline trends for beaches of Oahu and Maui after correcting shoreline data for human influences, and with shoreline trends checked for consistency using the ST and EX rate calculation methods.

shoreline change rate of 0.04 ± 0.04 m/yr (stable to accreting) (median rate = 0.01 m/yr) and roughly the same percentage of beach eroding as accreting (46% and 47%, respectively). No particular region of Maui stands-out as the most erosional.

5. Discussion

The islands of Maui and Oahu have similar physical settings and a history of anthropogenic coastal change. However, with significantly differing relative rates of SLR, they provide a unique opportunity to investigate if SLR may be an important driver of shoreline change in Hawaii and elsewhere. Historical shoreline data used in this study provides the only opportunity to observe shoreline changes over the modern period of sea-level rise.

Given the number of other factors driving beach processes, it remains a challenge to conclusively relate observed shoreline changes solely to SLR. Shoreline change is typically a result of multiple physical drivers including impacts to sediment availability, wave conditions, sediment supply, as well as coastal and nearshore geomorphology. To investigate the role of SLR on Oahu and Maui, we control for the influence of other physical drivers on historical trends.

Coastal structures; including seawalls, groins, breakwalls, and other features designed to protect coastal property and retain beach sand; are found in all coastal regions of Oahu and Maui. Coastal armoring in Hawaii has, historically, been a common response to preexisting beach erosion (Fletcher et al., 1997; Romine and Fletcher, 2012). In many locations, beaches have been completely lost to erosion fronting coastal armoring as the water line recedes toward a fixed position. To control for the influence of artificially-fixed shorelines (which would tend to indicate no shoreline change), we calculate trends up to and including the first shoreline after a beach has been lost.

Coastal armoring structures may have localized impacts on sediment availability. For example, groins typically lead to impoundment (accretion) of sand on the updrift sides and erosion on downdrift sides. Seawalls lead to “flanking” erosion of adjacent beaches in Hawaii (Romine and Fletcher, 2012). However, the localized effects

Table 2
Shoreline trends for the beaches of Oahu and Maui corrected for anthropogenic beach changes and with proportions of eroding, accreting, or undermined beach checked for consistency using the ST and EX rate calculation methods.

	Shoreline change rate[a] (m/yr)		Proportion of beach eroding, accreting, or undetermined (% of beach[b] (% significant[c]))		
Region	Mean	Median	Eroding	Accreting	Undetermined[d]
Oahu	−0.03 ± 0.03	−0.03	52% (23%)	39% (12%)	9%
Maui	−0.13 ± 0.05	−0.12	78% (31%)	17% (3%)	5%

[a] Mean and median of all shoreline rates in a region. Negative is erosion.
[b] Percent of beach where ST and EX rate calculation methods agree on trend plus percent of beach lost.
[c] Percent of beach where ST and EX rate calculation methods both find significant rates at 95% CI.
[d] Percent of beach where ST and EX rate calculation methods disagree on trend.

Table 3
Kilometers and percent of island beaches completely lost to erosion over the time period of analysis for Oahu and Maui islands.

Region	Beach lost km	% of beach
Oahu	8.6	8%
Maui	7.9	12%

of these structures, such as accretion and erosion on either side of a groin, should "average-out" when calculating island-wide and regional shoreline trends.

Beach sand mining and beach nourishment were common on some Oahu and Maui beaches over the past century. Sand mining is documented on Oahu at Waimea Bay, Kahuku, Maile, and Yokohama (Hwang, 1981; Fletcher et al., 2011). On Maui, sand mining was extensive along north shore beaches between Kahului and Paia (Makai Ocean Engineering and Sea Engineering, 1991; Fletcher et al., 2012). Visual inspection of historical shoreline positions shows rapid shoreline recession during the time period of sand mining in these regions with trends typically slowing (or in some cases reversing) following the termination of mining after it was made illegal in the late 1960s. To limit the influence of human-induced shoreline change due to sand mining, we calculate shoreline change rates for these areas using only the historical shorelines post-dating the end of sand mining. Beach nourishment projects were common over the past century along the highly engineered shoreline at Waikiki, south Oahu. Similar to areas of sand mining, we calculate shoreline trends in these areas using shorelines following the most recent beach fill to capture a better representation of natural shoreline trends at these beaches. Removing beaches from the data set for which we have documented evidence of sand mining or beach nourishment (14% of beaches on Oahu, 14% of beaches on Maui) we find little change in average rates (Oahu: −0.03 ± 0.03 m/yr, Maui: −0.12 ± 0.02 m/yr) and percent of eroding beach (Oahu: 54%, Maui: 80%).

Located in the central north Pacific, Hawaii beaches are exposed to large waves year-round from varying directions. Waves are the primary driver of sediment transport in Hawaii (Fletcher et al., 2012). In an island setting, overall shoreline trends are less likely to be influenced by variability in wave energy from one particular source region (wave direction). This is in comparison to mainland settings where beaches throughout a large region are typically exposed to only one or two predominant wave directions and, therefore, shoreline trends are more likely to be affected (biased) by changes in wave climate than in an island setting. Calculating overall shoreline trends for an island environment with exposure to waves from all directions provides an opportunity to control for the influence of variability in wave climate from any particular direction.

No particular region (coastal aspect, wave exposure) of Maui stands out as the most erosional. On Oahu the east region is noticeably less erosional than the other regions. None of the Maui study regions have a similar east-facing coastal aspect. The East Oahu region also stands out as having the most extensive fringing reef system of the island regions. Perhaps the unique coastal aspect or reef morphology of east Oahu is responsible, in part, for the differences in overall shoreline trends between Oahu and Maui? Removing the east Oahu region from the Oahu island data we find that Oahu remains less erosional than Maui with an average rate for Oahu beaches of −0.07 ± 0.04 m/yr (median rate −0.05 m/yr) and 57% of beaches eroding. This is in comparison to the island-wide results for Maui (including all coastal regions) with an average rate of −0.13 ± 0.05 m/yr (median rate −0.12 m/yr) and 78% of beaches eroding.

Sediment supply is undoubtedly an important driver of localized shoreline changes in Hawaii. However, we find no evidence that beach sediment processes are substantially different between Oahu and Maui on an overall island-wide scale. Beach sand in Hawaii is originally derived from erosion of carbonate sources from nearshore reefs (Calhoun et al., 2002; Harney and Fletcher, 2003). Nearshore sediment bodies are an important part of the active beach sand sharing system (Bochicchio et al., 2009). Beaches on Oahu and Maui are generally fronted by fringing reefs with similar geomorphologic history — constructed from a patchwork of carbonate units accreted and eroded over recent glacial cycles (Fletcher et al., 2008). Similar sand reservoirs have been identified on both islands, typically contained in submerged karst features and channels in reefs (Bochicchio et al., 2009; Conger et al., 2009; U.S. Army Corps of Engineers, Honolulu District and State of Hawaii Department of Land and Natural Resources, Office of Conservation and Coastal Lands, 2009, 2011). Beach strand plains and dunes are also are an important part of the active sand sharing system. Beaches in Hawaii often represent the leading edge of a sand-rich coastal plain with erosion of coastal plain and dune deposits providing an important contribution to littoral sediment budgets (Fletcher et al., 2012). We find no substantial differences in sediment processes on the coastal plains of the two islands on an island-wide basis. The beaches of both Oahu and Maui are generally backed by similar carbonate sand-rich coastal plains and low-lying coastal dune systems (Sherrod et al., 2007).

There are two notable differences between the coastal geomorphology of the shoreline study areas on Oahu and Maui. The older, more eroded volcanic edifice of Oahu (relative to Maui) features several deep bays created from submerged stream valleys, which are not found in the beach study regions on Maui. Two bays at Kahana and Kailua, east Oahu contain crescent-shaped beaches that are accreting at high annual rates of roughly half a meter per year (Fletcher et al., 2012). Shoreline trends are recalculated for Oahu after removing the shoreline data for the two deep bays to examine whether these unique accreting beaches have a substantial effect on the results for

Table 4
Shoreline trends for the distinct coastal regions of Oahu and Maui corrected for anthropogenic beach changes and with proportions of eroding, accreting, or undermined beach checked for consistency using the ST and EX rate calculation methods.

Region		Shoreline change rate[a] (m/yr) Mean	Median	Proportion of beach eroding, accreting, or undetermined (% of beach[b] (% significant[c])) Eroding	Accreting	Undetermined[d]
Oahu	North	−0.09 ± 0.06	−0.06	63% (23%)	25% (4%)	12%
	East	0.04 ± 0.04	0.01	46% (22%)	47% (19%)	7%
	South	−0.05 ± 0.02	−0.01	48% (24%)	45% (13%)	7%
	West	−0.09 ± 0.11	−0.11	62% (21%)	30% (5%)	9%
Maui	North	−0.15 ± 0.14	−0.13	73% (31%)	20% (2%)	7%
	Kihei	−0.13 ± 0.07	−0.13	82% (21%)	15% (5%)	2%
	West	−0.12 ± 0.02	−0.11	78% (36%)	17% (2%)	5%

[a] Mean and median of all shoreline rates in a region. Negative is erosion.
[b] Percent of beach where ST and EX rate calculation methods agree on trend plus percent of beach lost.
[c] Percent of beach where ST and EX rate calculation methods both find significant rates at 95% CI.
[d] Percent of beach where ST and EX rate calculation methods disagree on trend.

Table 5
Kilometers and percent of beaches completely lost to erosion over the time period of analysis for the coastal regions of Oahu and Maui.

Region		Beach lost	
		km	% of beach
Oahu	North	0.2	1%
	East	5.5	13%
	South	2.9	11%
	West	0.0	0%
Maui	North	1.6	10%
	Kihei	2.1	11%
	West	4.2	14%

Oahu. After removing Kahana and Kailua from the Oahu data, we find that Oahu remains less erosional than Maui with an average rate of −0.05 ± 0.03 m/yr (median rate −0.04 m/yr) and 54% of beaches eroding. Emerged fossil reefs and eolianite formations dating to the Eemian interglacial (Muhs and Szabo, 1994) are a common feature on Oahu coasts, forming many of the headlands and underlying much of the coastal plain. But, Eemian deposits have not been identified on Maui. Headlands on Maui are typically composed of basalt. The emerged limestone formations do not appear to be an important contributor of beach sands on Oahu, though they do support numerous pocket beaches. In general, areas on Oahu with the most extensive limestone outcrops, including Kahuku, the Ewa Plain, and much of west Oahu are not characterized by particularly large accreting beaches.

Zhang et al. (2004) document that on the U.S. east coast rates of coastal erosion are about two orders of magnitude greater than the rate of SLR. We find that island-wide rates of shoreline change in Hawaii (centimeters to tens of centimeters per year) are one to two orders of magnitude greater than rates of SLR (millimeters per year).

6. Conclusions

The islands of Oahu and Maui, with significantly different rates of relative SLR (roughly 65% higher on Maui) over the past century, provide a unique setting to investigate shoreline changes and possible relations to SLR. Results of island-wide historical trends, optimized to limit anthropogenic influences and checked for consistency using two methods of weighted least squares regression (ST and EX method), indicate that Maui beaches are significantly more erosional than beaches on Oahu. On Maui, 78% of beaches eroded over the past century with an overall (island-wide) average shoreline change rate of −0.13 ± 0.05 m/yr, while 52% of Oahu beaches eroded with an overall average shoreline change rate of −0.03 ± 0.03 m/yr.

All three coastal regions of Maui, distinguished by unique coastal aspect (wave exposure), are substantially more erosional than the four coastal regions of Oahu. No particular region of the two islands (e.g., the north regions) stands out as the most erosional. The east region of Oahu is the only region of the two islands that has an overall stable to accretional trend. Recalculation of Oahu trends with the east region omitted still indicates that Oahu beaches are less erosional than Maui beaches. Therefore, we conclude that overall island trends are not influenced by shoreline changes or unique wave exposure of one or more island regions.

Littoral processes and sediment supply (including human impacts) are undoubtedly an important influence on localized shoreline changes. However, we find no evidence that littoral processes and sediment availability are substantially different between Oahu and Maui in an overall, island-wide sense. Beaches on both islands are fronted by similar fringing reef platforms supporting nearshore sediment bodies contained in depressions and channels. Beaches on both islands are typically backed by carbonate sand-rich coastal plains. As the older of the two volcanic islands and having undergone more fluvial erosion, Oahu features two deep bays (submerged stream valleys) with accreting beaches unlike found in the Maui beach study regions. Removing the historical shoreline data for the accreting beaches on Oahu at Kahana and Kailua bays we find that Oahu remains less erosional than Maui. Prominent emerged fossil reef formations on the Oahu coast have not been identified on Maui. These formations typically do not support accretional beaches on Oahu and, therefore, are not likely to be an important contributor to differing shoreline trends between the islands.

Differing rates of relative SLR around Oahu and Maui remain as the best explanation for the difference in overall shoreline trends between the islands after examining other influences on shoreline change including waves, sediment supply and littoral processes, coastal geomorphology, and human impacts. The results of this study show that SLR is an important factor in historical shoreline change in Hawaii and that historical rates of shoreline change are about two orders of magnitude greater than SLR.

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References

Bayley, G.V., Hammersley, J.M., 1946. The effective number of independent observations in an autocorrelated time series. Supplement to the Journal of the Royal Statistical Society 8 (2), 184–197.

Bochicchio, C., Fletcher, C., Dyer, M., Smith, T., 2009. Reef-top sediment bodies: Windward Oahu, Hawaii. Pacific Science 63 (1), 61–82.

Brunel, C., Sabatier, F., 2009. Potential influence of sea-level rise in controlling shoreline position on the French Mediterranean Coast. Geomorphology 107, 47–57.

Caccamise, D.J., Merrifield, M.A., Bevis, M., Foster, J., Firing, Y., Schenewerk, M., Taylor, F., Thomas, D., 2005. Sea level rise at Honolulu and Hilo, Hawaii: GPS estimates of differential land motion. Geophysical Research Letters 32.

Calhoun, R.S., Fletcher, C.H., Harney, J.N., 2002. A budget of marine and terrigenous sediments, Hanalei Bay, Kauai, Hawaiian Islands. Sedimentary Geology 150 (1–2), 61–87.

Church, J.A., White, N.J., 2006. A 20th century acceleration in global sea level rise. Geophysical Research Letters 33 (L01602).

Conger, C.L., Fletcher, C.H., Hochberg, E.J., Frazer, N., Rooney, J.J., 2009. Remote sensing of sand distribution patterns accross an insular shelf: Oahu, Hawaii. Marine Geology 267 (3–4), 175–190.

Efron, B., 1981. Nonparametric estimates of standard error: the jacknife, the bootstrap, and other methods. Biometrika 68, 589–599.

Efron, B., Tibshirani, R., 1993. An Introduction to the Bootstrap. Chapman & Hall/CRC, Boca Raton, FL.

Fletcher, C.H., Mullane, R.A., Richmond, B.M., 1997. Beach loss along armored shorelines on Oahu, Hawaiian Islands. Journal of Coastal Research 13 (1), 209–215.

Fletcher, C.H., Rooney, J.J.B., Barbee, M., Lim, S.-C., Richmond, B.M., 2004. Mapping shoreline change using digital orthophotogrammetry on Maui, Hawaii. Journal of Coastal Research, Special Issue 38, 106–124.

Fletcher, C.H., Bochicchio, C., Conger, C.L., Engels, M., Feirstein, E.J., Grossman, E.E., Grigg, R., Harney, J.N., Rooney, J.B., Sherman, C.E., Vitousek, S., Rubin, K., Murray-Wallace, C.V., 2008. Geology of Hawaii Reefs. In: Springer (Ed.), Coral Reefs of the U.S.A. pp. 435–488.

Fletcher, C.H., Romine, B.M., Barbee, M.M., Dyer, M., 2011. Oahu Shoreline Study: Data on Beach Changes. University of Hawaii Coastal Geology Group for the City and County of Honolulu Department of Planning and Permitting under contract # F27934.

Fletcher, C.H., Romine, B.M., Genz, A.S., Barbee, M.M., Dyer, M., Anderson, T.R., Lim, S.C., Vitousek, S., Bochicchio, C., Richmond, B.M., 2012. National Assessment of Shoreline Change: Historical Shoreline Changes in the Hawaiian Islands. U.S. Geological Survey Open-File Report 2011-1051.

Frazer, L.N., Genz, A.S., Fletcher, C.H., 2009. Toward parsimony in shoreline change prediction (I): basis function methods. Journal of Coastal Research 25 (2), 366–379.

Genz, A.S., Frazer, L.N., Fletcher, C.H., 2009. Toward parsimony in shoreline change prediction (II): applying basis function methods to real and synthetic data. Journal of Coastal Research 25 (2), 380–392.

Hapke, C.J., Himmelstoss, E.A., Kratzmann, M.G., List, J.H., Thieler, E.R., 2010. National Assessment of Shoreline Change: Historical Shoreline Changes Along the New England and Mid-Atlantic Coasts (57 pp.).

Harney, J.N., Fletcher, C.H., 2003. A budget of caronate framework and sediment production, Kailua Bay, Oahu, Hawaii. Journal of Sedimentary Research 73 (6), 856–868.

Harney, J.N., Grossman, E.E., Richmond, B.M., Fletcher, C.H., 2000. Age and composition of carbonate shoreface sediments, Kailua Bay, Oahu, Hawaii. Coral Reefs 19, 141–154.

Hwang, D., 1981. Beach Changes on Oahu as Revealed by Aerial Photographs. Prepared by the Urban Regional Planning Program and the Hawaii Institute of Geophysics and Sea Grant Program, University of Hawaii for the Dept. of Planning and Economic Development, State of Hawaii (Technical Supplement 22 — Hawaii Coastal Zone Management Program, Hawaii, USA, 146 pp.).

Leatherman, S.P., Zhang, K., Douglas, B.C., 2000. Sea level rise shown to drive coastal erosion. Eos, Transactions of the American Geophysical Union 81 (6), 55–57.

List, J.H., Sallenger, A.H., Hansen, M.E., Jaffe, B.E., 1997. Accelerated relative sea-level rise and rapid coastal erosion: testing a causal relationship for the Louisiana barrier islands. Marine Geology 140 (3–4), 347–365.

Makai Ocean Engineering and Sea Engineering, 1991. Aerial Photograph Analysis of Coastal Erosion on the Islands of Kauai, Molokai, Lanai, Maui and Hawaii. Office of State Planning Coastal Zone Management Program, Honolulu, HI.

Mcquarrie, A.D.R., Tsai, C.-L., 1998. Regression and Time Series Model Selection. World Scientific, Singapore.

Merrifield, M.A., Maltrud, M.E., 2011. Regional sea level trends due to a Pacific trade wind intensification. Geophysical Research Letters 38 (21).

Merrifield, M.A., Merrifield, S.T., Mitchum, G.T., 2009. An anomalous recent acceleration of global sea level rise. Journal of Climate 22 (21), 5772–5781.

Moberly, R., Chamberlain, T., 1964. Hawaiian Beach Systems. Prepared for Harbors Division, Department of Transportation, State of Hawai'i (contract no. 6496, 95 pp.).

Moore, J.G., 1987. Subsidence of the Hawaiian Ridge. In: Decker, R.W., Wright, T.L., Stauffer, P.H. (Eds.), Volcanism in Hawai'i. United States Geological Survey Professional Paper pp. 85–100.

Muhs, D.R., Szabo, B.J., 1994. New uranium-series ages of the Waimanalo Limestone, Oahu, Hawaii: implications for sea level during the last interglacial period. Marine Geology 118 (3–4), 315–326.

National Academy of Sciences, 1990. Managing Coastal Erosion. National Research Council, Committee on Coastal Erosion Zone Management, National Academy Press, Washington D.C.(182 pp.).

Resig, J.M., 2004. Age and preservation of *Amphistegina* (*foraminifera*) in Hawaiian beach sand: implication for sand turnover and resource renewal. Marine Micropaleontology 50, 225–236.

Romine, B.M., Fletcher, C.H., 2012. Armoring on Eroding Coasts Leads to Beach Narrowing and Loss on Oahu, Hawaii. In: Cooper, J.A.G., Pilkey, O.H. (Eds.), Pitfalls of Shoreline Stabilization: Selected Case Studes. Coastal Research Library, 3. Springer Science and Business Media, Dordrecht, Netherlands.

Romine, B.M., Fletcher, C.H., 2013. A summary of historical shoreline changes on beaches of Kauai, Oahu, and Maui, Hawaii. Journal of Coastal Research 29 (3), 605–614.

Romine, B.M., Fletcher, C.H., Frazer, L.N., Genz, A.S., Barbee, M.M., Lim, S.-C., 2009. Historical shoreline change, Southeast Oahu, Hawaii: applying polynomial models to calculate shoreline change rates. Journal of Coastal Research 25 (6), 1236–1253.

Shalowitz, A.L., 1964. Shore and Sea Boundaries. U.S. Department of Commerce, Publication 10-1.U.S. Government Printing Office, Washington D.C.

Sherrod, D.R., Sinton, J.M., Watkins, S.E., Brunt, K.M., 2007. Geologic Map of the State of Hawaii. U.S. Geological Survey Open-File Report 2007-1089.

U.S. Army Corps of Engineers, Honolulu District, State of Hawaii Department of Land and Natural Resources, Office of Conservation and Coastal Lands, 2009. Southeast Oahu, Hawaii, Diamond Head to Pearl Harbor, Preliminary Regional Sediment Management Plan. Prepared by Moffat & Nichol and EA/HHF Joint Venture.

U.S. Army Corps of Engineers, Honolulu District, State of Hawaii Department of Land and Natural Resources, Office of Conservation and Coastal Lands, 2011. Maui Preliminary Regional Sediment Management Plan, Kahului and Kihei Regions. Prepared by Moffat & Nichol and EA/HHF Joint Venture.

Vermeer, M., Rahmstorf, S., 2009. Global sea level linked to global temperature. Proceedings of the National Academy of Sciences 106 (51).

Vitousek, S., Fletcher, C.H., 2008. Maximum annually recurring wave heights in Hawaii. Pacific Science 62 (4), 541–553.

Webb, A.P., Kench, P.S., 2010. The dynamic response of reef islands to sea-level rise: evidence from multi-decadal analysis of island change in the Central Pacific. Global and Planetary Change 72 (3), 234–246.

Zhang, K., Douglas, B.C., Leatherman, S.P., 2004. Global warming and coastal erosion. Climatic Change 64, 41–58.