Using Vessel-Based LiDAR to Quantify Coastal Erosion During El Niño and Inter-El Niño Periods in Monterey, CA

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USING VESSEL-BASED LIDAR TO QUANTIFY COASTAL EROSION
DURING EL NIÑO AND INTER-EL NIÑO PERIODS IN MONTEREY
BAY, CA

A Thesis
Presented to the
Faculty of the
Division of Science and Environmental Policy
California State University Monterey Bay

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
in
Coastal and Watershed Science and Policy

by
Steven Quan - Fall 2011
CALIFORNIA STATE UNIVERSITY MONTEREY BAY

The Undersigned Faculty Committee Approves the

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USING VESSEL-BASED LIDAR TO QUANTIFY COASTAL EROSION
DURING EL NIÑO AND INTER-EL NIÑO PERIODS IN MONTEREY, CA

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ABSTRACT

USING VESSEL-BASED LiDAR TO QUANTIFY COASTAL EROSION DURING EL NIÑO AND INTER-EL NIÑO PERIODS IN MONTEREY BAY, CA

by

Steven Quan

Master of Science in Coastal and Watershed Science and Policy
California State University Monterey Bay, 2011

Vessel-based LiDAR was employed to measure shoreline geomorphology, and quantify the rates of erosion and spatial distribution of coastal retreat around Monterey Bay, California during the 2008–2009 normal (non-El Niño) winter and 2009–2010 El Niño winter. These data were compared with pre- and post- El Niño airborne topographic LiDAR data from 1997 and 1998 to assess shoreline change since 1997 and test the hypotheses that: 1) segments of the coastline exhibiting considerably higher rates of erosion than adjacent areas (erosional hotspots), exhibit a predictable alternating spatial pattern alongshore between consecutive El Niño and inter-El Niño periods, and 2) the spatial distribution of erosion rates is positively correlated with the spatial distribution of wave energy.

As predicted, coastal erosion was found to be significantly higher during the 2009–2010 El Niño versus the 2008–2009 non-El Niño period (1.8 m average versus 0.1 m average in the southern bay and 0.5 m average versus 0.04 m average in the north bay). The spatial distribution of erosion rates during the 2009–2010 El Niño was positively correlated with that of wave energy. In southern Monterey Bay, these rates increased along a gradient from south to north in response to wave refraction over Monterey Submarine Canyon and the sheltering effect of the south bay by the Monterey peninsula, whereas in the northern bay, erosion was highest at the single location where wave energy was focused by a combination of wave refraction and sheltering from the bay’s northern headland from northwest waves.

Erosional hotspots were found to occur along the Monterey Bay coastline during the 1997–1998 and 2009–2010 El Niño winters, as well as during the 1998–2008 inter-El Niño period. Moreover, these hotspots were found to be significantly correlated with a 100–140 m spatial lag in southern Monterey Bay. Erosion hotspots that occurred during one El Niño or inter-El Niño period shifted spatially 100–140 m alongshore during the subsequent El Niño or inter-El Niño period. Vessel-based topographic LiDAR proved to be an efficient, cost-effective method for detecting sea cliff geomorphic change. This approach revealed that over El Niño and inter-El Niño periods, the majority of the coastline exhibited fine scale retreat in the form of variable erosional hotspots and enabled the quantification of a predictable erosional hotspots spatial pattern, highly useful for coastal planning.
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I would like to thank my thesis committee members: Dr. Rikk Kvitek, Dr. Doug Smith and Dr. Gary Griggs for all of their support, expertise and invaluable feedback throughout this long iterative thesis process. I would also like to thank the members of the CSUMB Seafloor Mapping Lab for all of their support and assistance. Special thanks to Steve Moore of CSUMB for technical assistance, Dr. Corey Garza of CSUMB for aid in statistical analyses and Dr. Daniel Fernandez for aid in frequency analyses. This research would not have been possible without the high resolution vessel-based LiDAR data and digital elevation maps generated for the California Ocean Protection Council’s California Seafloor Mapping Project by the CSUMB Seafloor Mapping Lab. Finally, I would like to thank my family for their never-ending support and Mich for her endless encouragement through tough times.
USING VESSEL-BASED LIDAR TO QUANTIFY 
COASTAL EROSION DURING EL NIÑO AND 
INTER- EL NIÑO PERIODS IN MONTEREY 
BAY, CA

INTRODUCTION

Holocene sea level rise has produced coastal retreat on a global scale. Erosion is expected to worsen with global warming induced accelerated sea level rise (Varekamp et al., 1992; Zhang et al., 2004; Church and White, 2006) and an increased frequency and intensity of storm events predicted for the 21st century (Meehl et al., 2007).

The primary forcing parameters for coastal erosion along the United States west coast (elevated sea levels, increased wave height, and higher precipitation) are associated with moderate to high intensity El Niño Southern Oscillation (ENSO) events (Storlazzi and Griggs, 2000; Allan and Komar, 2006). Recent documentation of wave height increases along the west coast suggest that one effect of global climate change may be more frequent high intensity storms, similar to those experienced during significant ENSO events (Seymour, 2011; Storlazzi and Wingfield, 2005; Ruggiero et al., 2010). These ENSO events may therefore serve as proxies for anticipated 21st century weather patterns, and an opportunity to explore the potential effects of sea level rise and high intensity storms on shoreline erosion. With an estimated 184 million dollars in losses, including the destruction of 33 ocean front houses and damage to 2000 homes and business along the US west coast during the 1982–1983 El Niño period (Griggs and Johnson, 1985; Griggs et al., 2005), preventative measures and pro-active coastal management are needed to minimize societal impacts of impending climate change.

The ability to more accurately predict where, and at what rates, coastal erosion is likely to occur will be important to these planning efforts. Here we use vessel-based mobile topographic LiDAR for shoreline mapping in Monterey Bay, California to determine at what spatial and temporal scales our understanding of primary forcing parameters can be used to quantify and predict patterns of coastal erosion.
MONTEREY BAY

The arcuate shoreline of Monterey Bay along the central California coastline (Figure 1) presents a uniquely suited location to study spatial variations in coastal retreat. The shoreline has large gradients in wave exposure with the central bay shoreline fully exposed, and the north and south extremes partially shielded by their headlands under certain wave conditions. The head of Monterey Submarine Canyon lies just offshore from Moss Landing in the center of the bay, and refraction over the canyon focuses wave energy to the north and south (Thornton et al., 2007). The large spatial gradients in wave exposure make the bay an ideal laboratory for testing hypotheses on the relationship between wave energy and patterns of coastal erosion. The hooked shape of the headlands located at both ends of the bay is in an equilibrium configuration, the result of dominant wave approach from the northwest (Griggs and Jones, 1985).

Monterey Bay is rimmed by wide sandy beaches that are backed by coastal dunes in the southern section and Tertiary sedimentary rock cliffs and weaker bluffs in the northern section. The north and south headlands consist of more resistant marine sedimentary rocks and granodiorite, respectively (Griggs and Patsch, 2005, California Geologic Survey, 2002). The strength of the coastal rocks and sediments determines the erodability of the coastline, with softer sediment types having higher susceptibility to erosion versus hard sediment types (Benumof et al., 2000). For this study, sites were restricted to sections of the coastline backed by coastal dunes and bluffs to control for geologic variation in lateral erosion rate analyses.

Long-term erosion rates around Monterey Bay can be traced back to the 1940s and have been found to be persistent and relatively uniform (~0.3–2 m/yr) over long timeframes (Thornton et al., 2006; Hapke et al., 2006). These studies, based on analysis of historic aerial photographs (Sklavidis and Lima-Blanco, 1985) were focused on broad scale, long-term assessment of the coastline at the kilometer scale.

Short-term erosion, however, does not occur uniformly around Monterey Bay, but rather in spatially variable “hot spots”; segments of the coastline exhibiting considerably higher rates of erosion than adjacent areas. This small scale erosion pattern has been well documented for the 1997–1998 El Niño period, with the most extreme rates located in the exposed central section of the bay and decreasing in magnitude towards the more
protected southern and northern ends of (Egley, 2002; Thornton et al., 2006; Thornton et al., 2007). Bluff erosion during the 1997–1998 El Niño winter (Oct 1997–April 1998) ranged from 0 to 4 m. Rates at Sand City ranged from 0 to 2 m and at Fort Ord from 0.5 to 13 m with net volume loss calculated to be nearly seven times the historic annual average (Thornton et al., 2006).

Direct links were found between hotspot erosion and the formation and location of rip channels and large mega-cusps (Thornton et al., 2007), with the relationship hypothesized to be due to narrowing of beach width at mega-cusp embayments, allowing wave run-up to easily reach and erode coastal bluffs (Shih and Komar, 1984; Revell et al., 2002; Thornton et al., 2007). The location and formation of rip channels, mega-cusps and subsequently, dune hotspots are hypothesized to migrate and regenerate along the coastline, but are not expected to return to their same location the following year because southern Monterey Bay exhibits nearly uniform long-term erosion along sections of the coastline subject to uniform wave exposure (Thornton et al., 2007). Given the framework of past studies, we can predict where erosion will occur on long time scales and large spatial scales, but we cannot accurately predict the location and rate of erosion on short time scales within local areas due to the spatially variable characteristic of hotspot erosion and the episodic nature of intense storms which appear to control these hotspots. Considering the impacts to the coastline that occurred during previous El Niño periods, the study and prediction of small-scale spatial erosion patterns can be useful to anyone concerned with shoreline retreat rates.

The quantitative detection of fine-scale geomorphic hotspot change in recent studies was only achievable through the use of high-resolution digital surface models produced from aerial LiDAR data. LiDAR is optical remote sensing using the measurement of time delay between transmittance and return of laser pulses, providing the ability to rapidly and efficiently measure surface geomorphology in three dimensions. In 1997 and 1998, NASA, USGS, and NOAA collaborated to conduct pre- and post-El Niño airborne LiDAR surveys of the California coastline, providing researchers with digital surface models of the coastline. This data set provided the first clear assessment of El Niño erosion rates in Monterey Bay (Thornton et al., 2006; Thornton et al., 2007; Hapke et al., 2006; Hapke and Reid, 2007). Since then, there have been no further,
publically available comprehensive LiDAR surveys of the Monterey Bay shoreline, leaving the measurement of non-El Niño period erosion rates to be derived by less precise means. While airborne LiDAR has been an effective and groundbreaking method for measuring coastal geomorphology by providing high resolution, precision, and broad coverage, the technique has its limitations. Availability, cost, the ability to respond on short notice to significant environmental events, and atmospheric conditions (e.g. low cloud ceilings and fog) that either preclude the use of aircraft or effectiveness of the sensor can limit the use of airborne LiDAR.

Our study employed a vessel-based LiDAR system as an alternative to airborne LiDAR to measure sea cliff morphology. This approach combines the high resolution characteristics of LiDAR data with an efficient and effective platform for measuring coastal geomorphology. Our expectations were that the high resolution datasets produced using this system would provide insight into the short-term and fine-scale patterns of change that have occurred since the 1998 LiDAR survey and the impacts of the most recent 2009–2010 El Niño winter, relative to the 2008–2009 normal (non-El Niño) winter.

The project had four objectives: 1) to evaluate the utility of a vessel-based topographic LiDAR system as a rapid response alternative to airborne LiDAR for measuring coastal geomorphology and quantifying the spatial distribution of coastal retreat; 2) to use the vessel-based system to quantify and compare the rates and spatial distribution of coastal erosion during the 2008–2009 normal (non-El Niño) year and 2009–2010 El Niño year, and to compare these findings with the results from pre- and post-El Niño airborne LiDAR surveys in 1997 and 1998 (Egley, 2002); 3) to test the hypothesis that erosional hotspots exhibit a changing, but predictable alternating alongshore spatial pattern between consecutive El Niño and inter-El Niño periods, and 4) to test the assumption that the occurrence of erosional hotspots is correlated with the spatial distribution of the highest wave energy.
METHODS

VESSEL-BASED LiDAR

We used a Riegl LMS-Z420i terrestrial laser scanner mounted sideways on a hydrographic survey vessel to produce high-resolution shoreline terrain data at a relatively low cost compared to conventional airborne LiDAR. The Riegl LMS-Z420i (hereafter 420i), originally designed as a static terrestrial laser scanner, was mounted on the 10 m research vessel *R.V. VenTresca*. The 420i has a range of 1 km, a positional accuracy of 10 mm, and a scan swath angle of 135°. While the 420i was designed to
rotate through 360°, in our mobile application the scanner head is fixed in one position and set to line scan mode. This allows for adjacent measurement of coastal relief while the vessel travels parallel to the coast. The scan and acquisition rates for the 420i in a fixed line scan position are 20 Hz and 8,000 points per second respectively.

Vessel trajectory data were collected to correct the 420i data for platform position and attitude during post processing. An Applanix POS/MV 320 was used to collect sensor position and attitude data at 200 Hz. These data were then post-processed and corrected in Applanix POSPac software with GPS ephemeris from a network of continuously operating GPS reference stations to yield a tightly coupled inertial-GPS Smoothed Best Estimated Trajectory (SBET) of the 420i’s position and attitude (pitch, roll, yaw) referenced to the NAD83 (CORS96 epoch 2002) UTM coordinate system and NAVD88 (Geoid 2003) datum.

Vessel-based LIDAR data were collected along the shoreline of Monterey Bay on December 9 and 10, 2008, November 4, 2009, and on July 15, 16, and 17, 2010 during low tide and relatively calm seas (Figure 1). These conditions are optimal for vessel-based LIDAR measurements as collection during low tide provides the fullest coverage of the shoreline relief. Rough seas increase boat motion and can therefore reduce data density as the laser sensor’s swath covers relatively more sky and water and less shoreline when rolling heavily.

The vessel-based LIDAR data were subject to a series of post processing procedures as the raw 420i data contained no geo-referenced position data, only position data relative to the scanner’s geometrical center, with attributes consisting of time, range, bearing and intensity. Riegl RiScanPro software was used to apply SBET solutions to the raw LIDAR data, yielding correctly geo-referenced XYZ data in NAD83 (CORS96 epoch 2002) UTM coordinate system and NAVD88 (Geoid 2003) datum. The XYZ data densities were generally 5 points per m². Fledermaus (IVS3D) software was used for editing and 3D visualization of vessel-based LIDAR data. Editing involves the manual rejection of outliers on a point by point basis. ArcGrids were generated in Fledermaus at 1 m resolution using the mean squares algorithm. These grids were subsequently used in ArcGIS (ESRI) for analysis.
Pre-existing data from the collaborative USGS, NASA, and NOAA airborne LiDAR surveys conducted on October 12 and 13, 1997 and April 15, 17, and 18, 1998 were also used in conjunction with the vessel-based LiDAR from this study for long-term shoreline change analyses. These earlier LiDAR data sets were downloaded as xyz point data and processed using the same editing and gridding techniques used with the 420i data, but with an output resolution of 2 m due to their lower point densities.

GIS ANALYSES

Previous researchers have used different geomorphic characteristics to measure lateral coastal erosion. Monitoring the location of the intersection of the back beach and dune apron (Thornton et al., 2006) and top of the seacliff face (Hapke et al., 2006 and 2009, Hapke and Reid, 2007) are the two most commonly used approaches. The decision to measure these different geomorphic characteristics may lie in the type of data used, coastal topography, access, or personal preference. The intersection of the back beach and dune can oscillate back and forth seasonally, so it is not an optimal feature to monitor. The seacliff top captures bedrock erosion, but can be difficult to delineate in ArcGIS. “Bedrock” represents the local geologic material that best resists erosion. In this study area, bedrock locally includes weak marine sandstone, poorly-lithified Quaternary dunes, and modern dunes. Landward retreat of the shoreward edge of local “bedrock” is the basis for monitoring long-term coastal erosion.

The use of vessel-based LiDAR provided significant flexibility in selecting the geomorphic feature to monitor. Our chief criteria in selecting a feature included,

1) it must be the most resistant material present in order to capture monotonic, parallel retreat of the eroding coastline,

2) it must foster reproducibility for future marine LiDAR studies, and

3) it must have a high density of LiDAR strikes to ensure high precision.

We chose to measure coastal position and change on the seacliff face at a vertical position of 10 meters elevation (NAVD88). We selected that elevation as representing the local geologic bedrock with field inspection, well above the seacliff apron, but not so high as to overshoot short seacliff faces (Figure 2).
Figure 2. Shore-normal profiles of 1998 and 2008 LIDAR digital elevation maps showing lateral change measurement at 10m elevation NAVD88.

Comparisons of the locations of various coastal structures along the Monterey Bay coastline were used to validate registration between datasets. The Digital Shoreline Analysis System (DSAS; Thieler et al., 2005) was used to calculate lateral change along the coastline at the 10 m elevation line (NAVD88) using contour lines derived in ArcGIS for each dataset. Transects were spaced at 20 m intervals and oriented normal to the coastline to accommodate any crenulated cliffs and to facilitate comparison with previous USGS (Morton and Miller, 2005, Hapke et al., 2006, Hapke and Reid, 2007) and DSAS (Hapke et al., 2009) cliff change analyses. The analysis was broken up into 2 sections (Figure 1), southern and northern Monterey Bay, about 10 km and 11 km in length, respectively. Net shoreline movement was calculated for each transect based on the horizontal shift in the 10 m contour line position. In order to achieve the most accurate measure of net shoreline change along each transect, the otherwise shoreline-normal orientation of individual transect was edited to be normal to the seafloor face in deeply crenulated cliffs according to the methods of Hapke et al., (2006). One way Analysis of Variance (ANOVA) and Welch’s Two Sample t-test was used to test for significant differences between the 1997–1998 El Niño, 1998–2009 inter- El Niño, 2008–2009 non-El Niño and 2009–2010 El Niño periods for Southern Monterey Bay and Northern Monterey Bay respectively.
Errors for net shoreline movement calculations were derived using methods from Hapke et al., (2006) and Stockton et al., (2002). Net shoreline movement uncertainty was calculated as the square root of the sum of the squares of the shoreline position error (±1.4 m), an error derived from existing LiDAR shoreline data (Stockton et al., 2002). Uncertainty for this study was calculated as ±1.4 m for each transect.

Running averages were conducted on the results of the DSAS net shoreline movement analysis to minimize noise and reveal the spatial periodicity of erosion hotspots. A shoreline segment length of 100 m for the running average was used to give a clear signal. This distance also fell within the spatial scales of the estimated 200 m–300 m mega cusp length hotspots located in Monterey bay (Thornton et al., 2007). Cross-correlation analysis was used to test the hypothesis that erosion hotspots exhibit a predictable alternating spatial pattern alongshore between consecutive El Niño and inter-El Niño periods. DSAS results for consecutive El Niño and inter-El Niño periods from 1997–2010 were cross-correlated to identify significant phase variations in hotspot erosion alongshore.

To compare swell height distribution with seaciff erosion rate values in Monterey Bay, Coastal Data Information Program (CDIP) swell height distribution NOWcast models (250 m resolution) were used to generate a mean composite for the 2009–2010 El Niño period. The 5 strongest El Niño storms were selected using a compilation of National Buoy Data Center significant wave height and tidal height data. The greatest combination of high significant wave height and high tidal height at any given period was used to determine the 5 strongest El Niño winter storms (10/15/09, 11/28/09, 01/19/10, 02/13/10 and 02/28/10). CDIP swell height distribution NOWcast models for each of the 5 selected El Niño winter storms were downloaded as 8 bit bitmap images, reclassified, and merged in ArcGIS to create a mean composite of wave height distribution of the 5 strongest storms for the 2009–2010 El Niño year at 250 m spatial resolution. DSAS results were binned to closely match the 250 m resolution of the mean composite swell height distribution model and statistically compared with regression analyses.
RESULTS

Inter-survey comparison of various coastal structures along the Monterey Bay coastline through all of the LiDAR datasets yielded ±1.2 m horizontal and ±12 cm vertical precision which remained consistent with previously published estimated positional uncertainties for LIDAR data at ±1.4 m (Stockton et al., 2002) (Figure 3). Sources of error may be attributable to a combination of LiDAR system measurement error, grid generation or changes in coastal vegetation.

Figure 3: Shore normal profiles of 2008 vessel based LiDAR and 1998 aerial LiDAR to assess inter-survey precision. Location: Monterey Bay Beach Resort.

Erosion results for this study are reported on a per period basis (i.e. survey date to survey date) as we are focusing on U.S. west coast erosion, which occurs predominantly during winter periods and where annualized rates may be misleading. In keeping with previous work, results show numerous spatially variable erosional hotspots which increase in occurrence and magnitude along a gradient from south to north along southern Monterey Bay during the 2009–2010 El Niño period (Figure 4). Although moderate in severity compared to the 1997–1998 El Niño period, substantial erosion occurred during the 2009–2010 El Niño. The highest rates of lateral erosion were detected between Fort Ord Dunes State Beach at the old Stillwell hall site (~14 m) and at Marina Beach (~8 m) during the 2009–2010 El Niño (Figure 4 and 5) with an average of 1.8 m (Table 1). In
comparison with a normal year, considerably higher rates of erosion were found during the 2009–2010 El Niño period (1.8 m average) than the 2008–2009 normal non-El Niño period (0.1 m average) (Table 1). Significant differences were found between erosion during the 1997–1998 El Niño, 1998–2009 inter-El Niño, 2008–2009 non-El Niño and 2009–2010 El Niño periods for Southern Monterey Bay (Table 1). In addition, spatially variable erosional hotspots were also detected in southern Monterey Bay during the inter-El Niño period (1998–2009) with an erosion average of 3.7 m (Table 1). Multi El Niño cycle (1997–2010) analyses reveal a stronger south to north gradient signal, which was only slightly apparent in the 2009–2010 El Niño for the southern analysis region (Figure 4). During the multi El Niño cycle (1997–2010), erosion magnitude increased at an approximate rate of 5 m of retreat per kilometer alongshore for the first 0 to 4 km of coastline with Sand City as the central point, depicted with the solid black arrow (Figure 4). The following 8 km of coastline north of Sand City to Marina, exhibited signs of progressively uniform erosion.
Figure 4. Southern study area plot of lateral change with a 100 m running average at 10 m elevation (NAVD88). X axis represents alongshore distance (m) starting in Sand City and ending at Marina State Beach. Y axis represents lateral change (m). Dashed line depicts the asymptotic nature of erosion magnitude found in this stretch of coastline.
In northern Monterey Bay, erosion during the 2009–2010 El Niño period was minimal compared to the southern bay, with as much as 2.5 m of retreat occurring in the form of erosional hot spots centered at La Selva beach (Figure 6) with an average of 0.5 m (Table 1). Erosion during the 2008–2009 normal year averaged 0.04 m for northern Monterey Bay (Table 1). Significant differences were also found between erosion during the 2008–2009 non-El Niño and 2009–2010 El Niño periods for Northern Monterey Bay (Table 1).
Figure 6. Northern study area plot of lateral change with a 100 m running average at 10 m elevation (NAVD88). X axis represents alongshore distance (m) starting from Sunset Beach and ending at Seacliff State Beach. Y axis represents lateral change (m).

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Table 1. Summary of average shoreline change rates for Monterey Bay derived from DSAS results. Asterisks denote p-values (0.01*, 0.001**, <0.001*** for ANOVA (Southern Monterey Bay 97–98, 98–09, 08-09 and 09–10 periods) and Welch Two Sample t-test (Northern Monterey Bay 08–09 and 09–10 periods) tests.)
A comparison of the spatial locations of El Niño and inter-El Niño hotspots in southern Monterey suggests an inverse correlation between the spatial location and magnitude of hotspots that occurred during consecutive 1997–1998 El Niño to 1998–2009 inter-El Niño periods and 1998–2009 inter-El Niño to 2009–2010 El Niño periods (Figure 7). For the majority of the coastline, hotspots that occurred during one period tend to be low or no activity spots in the consecutive period.

Cross correlations of El Niño and inter-El Niño erosion hotspot variations were found to be significantly correlated at 95% confidence with a 100–140 m spatial lag in southern Monterey Bay (Figure 8). Erosion hotspots that occurred during one El Niño or inter-El Niño period, shifted spatially 100–140 m alongshore during the subsequent El Niño or inter-El Niño period.
Figure 7. Plots of lateral change after consecutive El Niño to inter-El Niño periods (top) and inter-El Niño to El Niño periods (bottom) with a 100 m running average at 10 m elevation (NAVD88) for Southern Monterey Bay. X axis represents alongshore distance (m) starting in Sand City and ending at Marina State Beach. Y axis represents lateral change (m). Anomalously high lateral erosion values at Stillwell Hall were omitted.
Figure 8. Cross-correlations between consecutive El Niño and inter-El Niño period hotspot erosion for Southern Monterey Bay. The most significant cross correlation values were found at a spatial lag of 140 m (top) and 100 m (bottom), representing a strong out of phase relationship in hotspot location between periods. Horizontal dashed lines represent 95% confidence levels. Anomalously high lateral erosion values at Stillwell hall were omitted.

The composite swell height distribution model revealed hotspots and gradients in Monterey Bay (Figure 9). In Northern Monterey Bay, a concentrated large km scale swell height hotspot was found at La Selva Beach with the reminder of the northern coastline exhibiting relatively uniform wave energy exposure. In Southern Monterey Bay, a strong gradient of increasing swell height from south to north was found centered at Sand City.
This gradient leads to a coastline with uniform wave energy exposure from north of Sand City to the Salinas river mouth. The largest waves occurred at the muted delta of the Salinas River, where the southern half of the bay bulges. As expected, results from both El Niño and inter-El Niño analyses indicate that locations with the highest rates of erosion coincided with the locations of greatest wave energy. Spatial wave gradient patterns also coincided with the increasing gradient found in the southern Monterey Sand City region and the large km scale hot spot at La Selva (Figure 4, 6 and 9).

![Swell Height](image)

**Figure 9.** Coastal Data Information Program mean swell height distribution NOWcast model composite derived from the 5 strongest 09/10 El Niño winter storms (10/15/09, 11/28/09, 01/19/10, 02/13/10, and 02/28/10). Coordinate system: UTM zone 10N NAD83.
Figure 10. Bluff erosion (m) plotted against average wave height (m) for southern Monterey Bay (left) and northern Monterey Bay (right) during the 2009–2010 El Niño period with their respective non-linear (left) and linear (right) regression lines.

DSAS results are plotted with wave height data for both southern and northern Monterey Bay (Figure 10). Wave height values were selected at 100 m offshore relative to the shoreline to omit erroneous breaking wave zone data. Non-linear (southern Monterey Bay) and linear (northern Monterey Bay) regression results indicate significant relationships between lateral erosion and wave height (p < 0.05, northern Monterey Bay adjusted $R^2 = 0.1621$).

DISCUSSION

Consistent with previous pre/post El Niño shoreline assessments (Thornton et al., 2006), spatially variable erosion hotspots occurred during the 2009–2010 El Niño period, and at significantly higher annual rates of change than during the 2008–2009 normal year. The southern Monterey Bay coastline had changed considerably from 1997 to 2010, with both El Niño and inter-El Niño periods playing equally important roles in coastal dynamics. Erosion during the two El Niño periods (1997–1998, 2009–2010) produced the greatest change over short time frames, but erosion during the 11-year inter-El Niño period (1998–2009) contributed to substantial net change over longer timeframes. Previously, hotspot erosion was found to occur only during El Niño or extreme storm events (Thornton et al., 2006, Thornton et al., 2007), but in this study, short-term hotspot
erosion was shown to occur during both El Niño and inter-El Niño periods with no indication of uniform erosion along the southern and northern sections of the Monterey Bay coastline during any single El Niño or inter-El Niño period. The detection of hotspots during the inter-El Niño period suggests a longer term persistence of mega cusps and rip currents on the decadal scale.

Net alongshore erosion at the decadal time scale spanning two El Niños and the inter-El Niño period from 1997 to 2010 in southern Monterey Bay was found to be essentially uniform for the 8 km of shoreline north of the identified wave energy gradient at Sand City (Figure 4). The one anomaly in this trend of progressively uniform long-term retreat occurred at Stillwell Hall in Fort Ord. Once an armored sandy bluff, riprap was removed at Stillwell in 2004 and the bluff was allowed to erode and quickly equilibrated with the adjacent undisturbed bluff (Figure 4 and 11). Analysis of swell height distribution with results from the DSAS yielded significant correlation between swell height and lateral erosion. Along the southern bay shoreline, where the sandy bluffs are uniformly weak and susceptible to erosion, wave distribution models may prove to be a reliable predictor for future coastal erosion on broad scales in this region.

The northern Monterey Bay analysis lacks the multi-El Niño period data available for southern Monterey Bay because the airborne LiDAR data from 1997 and 1998 were found to have mis-registration issues along certain sections of the northern coastline with our vessel-based LiDAR data. Nevertheless, hot spot erosion occurred on the northern bay and was primarily centered over La Selva beach during the 2009–2010 El Niño. Multi-El Niño cycle analyses could be performed in the north bay to test for similar alternating hotspot erosion patterns if registration issues can be resolved.
Figure 11: Aerial photographs of Stillwell Hall at Fort Ord captured in 2002 and 2010. (Photos copyright (c) 2010 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.californiacoastline.org). This location is a good example of passive erosion fronting coastal armoring, which can be recovered with armor removal.

Inverse correlations between the spatial distribution and magnitude of erosion hotspots were found in southern Monterey when comparing consecutive El Niño and inter-El Niño periods (1997–1998 El Niño to 1998–2009 inter-El Niño to 2009–2010 El Niño), suggesting the occurrence of an alternating hotspot pattern, where the spatial location of erosion hotspots alternate between consecutive El Niño and inter-El Niño periods. Cross correlation of El Niño and inter-El Niño erosion hotspot variations were found to be significantly correlated at the 95% confidence with a 100–140 m spatial lag in southern Monterey Bay. Erosion hotspots that occurred during one El Niño or inter-El Niño period shifted in location spatially 100–140 m alongshore during the following El
Niño or inter-El Niño period. Subsequently, the initial hotspots are not expected to occur in the same spatial location during the subsequent El Niño or inter-El Niño period.

The inverse correlation between the spatial location of consecutive El Niño and inter-El Niño hotspots suggests a pattern of alternating spatial hotspots, where promontories are left post-hotspot erosion and are subsequently the first to erode during the following El Niño or inter-El Niño period. Previous work has shown that the formation and location of large mega-cusps play a significant role in the amount of wave run-up and subsequently the location of dune hotspot erosion (Thornton et al., 2007). In agreement with the estimated 200–300 m estimated mega cusp lengths alongshore (Thornton et al., 2007), the cross correlation result of a 100–140 m spatial lag, roughly half of the mega cusp wavelengths, confirms the theory of an alternating hotspot pattern. Furthermore, the cross correlation results between El Niño and inter-El Niño periods suggest that bluff topography may be another major parameter in the role of future locations of hotspot erosion, a topic for further research.

The 100–140 m lag found in the spatial variation of erosion hotspots between consecutive El Niño and inter-El Niño periods sheds new light on short-term coastal management decisions for Southern Monterey Bay. Previously interpreted as primarily episodic and variable, occurring during extreme storm periods characteristic of El Niño episodes, results from this study demonstrate that relatively rapid erosion can also occur during quiescent periods and have a predictable spatial pattern. In regards to short-term coastal management, resource managers can begin to make accurate and reliable predictions on where and when these erosion hotspots will occur. For coastal management on multi-El Niño period timeframes, the approximately uniform eroding coastline along sections of the shore subject to uniform wave exposure simplifies long-term management. It seems apparent when looking at the overall gently curving nature of the shoreline/bluff edge at both ends of the bay, that over the long-term the erosion smooths or evens out spatially (Griggs and Jones, 1985). Although we see indication of uniform erosion in our 1997–2010 timeframe, annual rates from multi-event analyses should be used with caution for long-term coastal planning as it is important to not only include the most current erosion rates and patterns, but the effects of future sea level rise and climate change in the planning processes.
The effects of coastal retreat are evident now as numerous structures along the Monterey Bay coastline are at risk to erosion and coastal managers are faced with making difficult response decisions. Stillwell Hall at Fort Ord is a prime example of the effects of coastal erosion and armoring (Figure 11). Repeated armoring protected the bluff immediately in front of the building from erosion for several decades, but the loss of beach fronting the armor and passive erosion (continued erosion maintaining a beach on either side of the armor) occurred, creating a peninsula effect (Stamksi, 2005). Beach width nearly disappears in front of armored properties and with time, these properties protrude outward towards the water blocking beach access and ultimately the natural movement of sediment in the littoral cell. With various structures at risk and currently in an armored state in Southern Monterey Bay (i.e. Ocean Harbor House Condominiums and Monterey Beach Hotel; Figure 12), the beginning stages of the peninsula effect are already taking place. Although we can estimate when these armor structures will begin to result in a peninsula effect, it is ultimately up to coastal management to weigh the costs and benefits to mitigation. In both cases, permitting agencies have already allowed new armor to be constructed.

Future climate change is expected to bring increased sea level rise, and accelerated coastal erosion, complicating the decision of coastal permitting agencies. For example, efforts have been made to address and plan for future coastal change along the southern Monterey Bay shoreline with the Coastal Regional Sediment Management Plan (Coastal RSM Plan, 2008). This comprehensive plan contains historic average retreat rates (1910–2005) as a backbone to aid in the decision making process for localized areas along the southern Monterey Bay coastline. As a result of historically variable, but increasing average erosion rates over time and the evidence for hotspot erosion through both El Niño and/or inter-El Niño periods documented in this study, historic average rates may not be representative of our coastline for long-term planning. For instance, recent planning for a proposed resort in southern Monterey Bay used an average erosion rate to estimate dune cutback for 50 years, the life of the resort. With evidence of an increasing trend in erosion rates, the occurrence of hotspot erosion, and the anticipation of increased and more frequent storms due to climate change, that estimate may not be valid.
As a result, there is great need for new, efficient and cost effective tools for precisely monitoring the distribution and rates of coastal erosion over shorter time frames to enable more nimble adaptive management in response to accelerating climate change and sea level rise. The flexible, rapidly mobilized vessel-based LiDAR system used in this study produces high-resolution terrain data, in a relatively cost effective manner compared to traditional airborne LiDAR surveys; for which high cost is one of the biggest limiting factors for repeat aerial LiDAR surveys. Indeed, no further comprehensive airborne LiDAR flights were conducted following those in 1998 and the
vessel based data collected during this study. Due to its low, horizontal view point, vessel-based LiDAR, unlike airborne LiDAR, can miss flat spots above the level of the sensor and topographic lows behind berms and dunes. While this limitation precludes the ability to measure back dunes, vessel-based LiDAR is optimal for measuring lateral erosion, deposition, and topography of sea cliff faces. This horizontal viewpoint is exceptionally effective for measuring marine terraces and steep seacliff faces, topographic features that aerial LiDAR’s down looking viewpoint can miss and/or misrepresents due to sparse data density. We therefore conclude that the vessel-based LiDAR approach employed here is suitable for the detection and quantification of small scale coastal processes, highly useful for coastal planning.

CONCLUSIONS


Episodic El Niño erosion occurred during the 1997–1998 El Niño and 2009–2010 El Niño in Southern Monterey Bay and was found to be significantly higher during the 2009–2010 El Niño versus the 2008–2009 non-El Niño period (1.8 m average versus 0.1 m average in the southern bay and 0.5 m average versus 0.04 m average in the north bay). Spatially variable hotspots were found post 2009–2010 El Niño, and although moderate compared to 1997–1998, substantial erosion occurred during the 2009–2010 El Niño. El Niño and inter-El Niño erosion hotspot variations were found to be significantly correlated at the 95% confidence with a 100–140 m spatial lag in southern Monterey Bay. Erosion hotspots that occurred during one El Niño or inter-El Niño period, shifted in location 100–140 m alongshore during the subsequent El Niño or inter-El Niño period. DSAS lateral erosion results during the multi El Niño cycle (1997–2010) indicate the progression of approximately uniform erosion along the southern Monterey Bay coastline with net erosion consistent with significant wave energy. Wave energy distribution
models are a reliable predictor for future coastal erosion on broad scales as erosion rates were found to be significantly related to that of wave energy.

The utilization of vessel-based LIDAR proved to be an effective and efficient method to measure sea cliff geomorphology with very high resolution. The coverage and high point density vessel-based LIDAR provides is very useful for accurate and precise quantification, analysis, and modeling of small scale geomorphic coastal processes. With the effects of global warming and sea level rise projected to exacerbate erosion, the effective and efficient attributes of this approach provides the opportunity to conduct annual or seasonal repeat surveys, a benefit to both future long and short-term coastal change analyses.

The distinct geographical extent of the Monterey Bay coastline contains diverse geology and spatially distinct physical oceanographic processes. Successful spatially explicit erosion modeling of the Monterey Bay shoreline will create products that will be invaluable to not only local coastal resource managers, but have the potential for extrapolation to coastlines with similar demographics throughout the world. Providing the most up to date research on where, when and at what rate coastal erosion is occurring to resource management agencies and coastal communities will be helpful in their efforts to efficiently plan for the inevitable changes associated with climate change, sea level rise and El Niños.
LITERATURE CITED


APPENDIX

R CODE

REGRESSION ANALYSIS

\[ \text{SMB} <- \text{read.csv(file.choose(), header=TRUE, sep="",)} \]
\[ \text{f <- function(x,a,b) \{a * exp(b * x)} \]
\[ \text{dat <- data.frame(x, y)} \]
\[ \text{smbf <- nls(y ~ f(x,a,b), data = dat, start = c(a=1, b=1)} \]
\[ \text{co <- coef(smb)} \]
\[ \text{plot(y-x, xlab="Wave Height (m)", ylab="Lateral Erosion (m)",}
\]
\[ \text{xlim=c(0, 5), ylim=c(0, 7)} \]
\[ \text{curve(f(x, a=co[1], b=co[2]), add = TRUE)} \]
\[ \text{summary(smbf)} \]

\[ \text{NMB} <- \text{read.csv(file.choose(), header=TRUE, sep="",)} \]
\[ \text{nmb<-lm(yy~xx)} \]
\[ \text{plot(yy~xx, xlab="Wave Height (m)", ylab="Lateral Erosion (m)",}
\]
\[ \text{xlim=c(0, 5), ylim=c(0, 7)} \]
\[ \text{abline(nmb)} \]
\[ \text{summary(nmb)} \]

CROSS CORRELATION

\[ \text{CC} <- \text{read.csv(file.choose(), header=TRUE, sep="",)} \]
\[ \text{ccf(x,y,main="1997-1998 El Niño vs. 1998-2009 Inter-El Niño Period",xlab="Lag (m)",}
\]
\[ \text{ylab="Cross Correlation")} \]
\[ \text{par(xaxt="n")} \]
\[ \text{ccf(x,y,main="1997-1998 El Niño vs. 1998-2009 Inter-El Niño Period",xlab="Lag (m)",}
\]
\[ \text{ylab="Cross Correlation")} \]
\[ \text{lablist.x<-as.vector(c(-400:400,by=200))} \]
\[ \text{lablist.x<-as.vector(c("-400", "-200", "0", "200", "400"))} \]
T-TESTS AND ANOVA

NMB <- read.table(file.choose(), header=TRUE)
attach<-NMB
ttestNMB<-t.test(erosion, year, data=NMB)
summary(ttestNMB)
boxplot(erosion~year)

EMB <- read.table(file.choose(), header=TRUE)
attach<-EMB
aovEMB<-aov(erosion~period, data=EMB)
summary(aovEMB)
boxplot(erosion~period)