Hurricane-induced beach change derived from airborne laser measurements near Panama City, Florida

William Robertson V a,b,⁎, Keqi Zhang a,c, Dean Whitman b

a International Hurricane Research Center, Florida International University, Miami, FL 33199, USA
b Department of Earth Sciences, Florida International University, Miami, FL 33199, USA
c Department of Environmental Studies, Florida International University, Miami, FL 33199, USA

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Abstract

This study used airborne laser data to investigate spatial variations in shoreline migration, beach width, subaerial volume, and subaqueous volume change due to a hurricane event. Five separate airborne laser data sets of Panama City, FL area beaches were collected during a seven-month period before and after landfall of Hurricane Ivan. Contour shorelines were extracted from digital elevation models interpolated from these laser measurements and were used to measure changes in shoreline position and beach width. The shoreline migrated 16 m landward due to Hurricane Ivan and migrated 10 m seaward following Hurricane Ivan. No significant spatial relationship was found between shoreline migration before and after the hurricane. Linear relationships between a time series of beach width and subaerial volume were found at many locations. However, utilization of a single coefficient to represent all relationships is problematic due to the spatial variability in the linear relationship. Differences in two bathymetric data sets for summer and fall show that only a small portion of sediments were transported beyond an active zone and most sediments remain within the active zone despite the occurrence of a hurricane.

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1. Introduction

Storm impacts, sea level rise, and human modification make beaches one of Earth’s most dynamic landforms. Quantification of storm-induced beach erosion and subsequent recovery is essential for understanding beach response to abrupt changes in hydrodynamics and appropriately designing coastal engineering projects such as beach nourishment. Shoreline position mapping (Crowell et al., 1991; Thevenot and Kraus, 1995; Pajak and Leatherman, 2002; Leatherman, 2003) and beach profile monitoring (Thom and Hall, 1991; Aagaard et al., 2005) are the two primary methods for quantifying coastal change. Shoreline data derived using remote sensing techniques and kinematic GPS surveys are an excellent source for analyzing large scale beach change temporally and spatially (Moore, 2000; Zhang et al., 2002; Sallenger et al., 2003). Previous studies have found that shoreline response to storms is highly variable along the shore (Stockdon et al.,
measurements on California coasts, Shepard (1950) found that sediments from berms were transported offshore to form sandbars during the winter when storm waves were dominant. Sediment moved toward the shore to form berms during the summer when swell waves were dominant. This cyclic behavior of beach profiles has been found to occur at many coasts during storm weather and the subsequent fair weather periods (King, 1972; Winant et al., 1975; Aubrey, 1979; Komar, 1998). It appears that onshore and offshore sediment movement during a cycle occurs mostly within the active profile zone, defined as the zone landward of the depth where sediment movement by waves is insignificant (Hallermeier, 1977). However, quantitative data on the amount of sediment redistributing within the active profile zone and the amount of sediment exchanged between the active and outside zones are lacking because most beach profile surveys do not extend adequately seaward. Data measuring the active and outside zones are rare, and only a few beaches in the world such as Duck, North Carolina contain data capturing most of the active zone (Lee et al., 1998).

Beach profiles have also been used to document the recovery processes. Based on analysis of beach profiles on the Texas coast before and after Hurricane Alicia, Morton et al. (1994) found that the backshore took longer to recover than the foreshore. Thom and Hall (1991) showed that it took several years for the volume of subaerial beaches to recover. In combination with the study of shoreline response to storms from List et al. (2006), these results imply that shoreline and beach volume may recover at different rates. However, the relationship between shoreline and volume change has not been examined in detail.

Beach profiles are an effective method for estimating sediment volume change, but cost limitations usually require that profiles be widely spaced alongshore to quantify large scale changes. The large spacing between profiles limits the accuracy of volume change estimates. Alternatively, subaerial beach volume changes can be estimated by assuming that volume changes are proportional to variations in beach width. Several studies have established a linear relationship between the subaerial volume \( V \) and beach width \( W \) at a specific location:

\[
V = KW
\]

(1)

where the coefficient \( K \) is estimated using \( V \) and \( W \) from a time series of beach profile measurements at individual transects. In Australia, Thom and Hall (1991) measured \( K \) values ranging from 2.55 to 2.76 \( m^2 \) for 4 beach profiles. In Monterey Bay California, Dingler and Reiss (2002) found that \( K \) values vary considerably from 1.95 to 4.42 \( m^2 \) for 7 different beaches. The number of profiles that were used to determine \( K \) in these two studies was limited, thus the alongshore variability of \( K \) for a single beach has yet to be determined. If there is significant alongshore variation in \( K \), then \( K \) cannot be treated as a constant and Eq. (1) would become location specific. In such a case, it would be very difficult to use temporal variations in beach width to quantify subaerial beach changes at a larger scale. Therefore, it is critical to know how \( K \) changes alongshore when applying shoreline positions to estimate subaerial volume.

Panama City on the Florida Gulf of Mexico coast was impacted by Hurricane Ivan in 2004. Five airborne laser surveys measured Panama City beaches before and after Ivan, which produce a unique, high-resolution data set to study the response of low-energy beaches to a storm. The objectives of this study are:

1) to determine if there is a correlation between landward shoreline migration induced by a storm and its subsequent seaward migration during recovery,

2) to determine the relationship between beach width and subaerial volume changes, and

3) to quantify sediment redistribution in the active zone and sediment exchange between the active and outside zones.

2. Study area

The Panama City area is located within the Coastal Lowlands (White, 1970) of the Gulf Coastal Plain.
Physiographic Province (Hunt, 1974). The Province is a wide coastal plain that contains Late Cretaceous to Holocene sedimentary deposits, and this study focuses on the Holocene sediments that have been reworked by waves and currents. Panama City is located between the Apalachicola Delta to the east and detached offshore barrier islands with large dunes to the west. The Apalachicola Delta received much its sediments from the Appalachian Mountains, and the Delta region is a primary source of sediment to Panama City beaches due to the dominant east to west littoral transport (Davis, 1997).

Panama City beaches are on the northwest coast of Bay County, Florida facing the Gulf of Mexico. The study area is located between the Walton-Bay County line and St. Andrews Inlet (Fig. 1). The shoreline orientation is northwest to southeast, and slightly concave toward the Gulf. This study investigates more than 23 km of sandy beaches consisting of fine sand to silty sand with shell fragments and a mean grain size of 0.24 mm. The beaches were renourished in 1999 throughout most of the study area, and 4 km east of the eastern section was further renourished in 2002. The mean tidal range is 0.37 m, making the coast microtidal but not necessarily wave dominant. The average deep-water (290 m) significant wave height at NOAA buoy 42039 is 1 m, with September through April greater than 1 m, and May through August below 1 m.

Hurricane Ivan made landfall east of Mobile, Alabama on September 16, 2004 with maximum sustained winds of 58 m/s (Leadon, 2004). Panama City was over 100 km to the east of the hurricane’s landfall with estimated sustained wind speeds of 27 m/s (Fig. 2). The storm surge in the study area was less than 2.5 m resulting in minor overwash and dune erosion (Fig. 3). Beach change was primarily caused by large waves generated by the hurricane. Significant wave heights greater than 12 m were measured during Hurricane Ivan from a NOAA buoy (42039) 150 km offshore. There were two high wave events following Hurricane Ivan, but both were in the offshore direction.
During early fall, Panama City experienced at least four large onshore wave events.

3. Data and methods

Beach response to a storm occurs three dimensionally, and two dimensional shoreline and profile measurements limit our understanding of beach response to storms. Until the advent of airborne laser mapping technology (also known as LIDAR), it has been extremely difficult to derive three dimensional measurements of beach change with sufficient resolution and accuracy. Airborne laser measurements can satisfy many of the needs for quantifying three dimensional coastal change with horizontal resolutions less than several meters and vertical accuracies near 0.15 m RMS (Sallenger et al., 2003). Past coastal studies have shown that shoreline position, beach profile, and beach volume change can be obtained by comparing multiple airborne laser data sets (Irish and White, 1998; Stockdon et al., 2002; Robertson et al., 2004, 2005; Zhang et al., 2005).

3.1. Airborne laser data

Airborne laser mapping is an active remote sensing technology that utilizes a pulsed laser to measure the range between an airborne platform and the Earth’s surface. Five airborne laser data sets (Fig. 4) were collected in 2004 using three systems: the University of Florida and Florida International University’s airborne laser swath mapper (ALSM), NASA’s experimental airborne advanced research LIDAR (EAARL), and the United States Army Corps of Engineers compact hydrographic airborne rapid total survey (CHARTS). Each system operates somewhat differently, and thus produces a different type of airborne laser data set.
The ALSM instrument is an Optech ALTM 1233 topographic airborne laser system that fires a laser in the near-infrared spectrum (1.1 μm). The laser pulses cannot penetrate the water column, so the ALSM instrument is only capable of deriving terrestrial surface measurements. A pulse rate of 33 kHz was used which produced less than 1 m point spacing on the ground for each flight line. The EAARL system sampled at 3 kHz, yielding a relatively sparse 5 m nominal point spacing per flight line. EAARL utilizes a green laser (0.532 μm) which can penetrate water and measure bathymetry. In this study, however, the EAARL data did not extend sufficiently offshore and only terrestrial measurements were used. The CHARTS system uses two lasers, one green and one near-infrared. The green laser is fired at 1 kHz to measure bathymetry, and the near-infrared laser measures topography at 9 kHz. This produced a nominal 8 m point spacing for the bathymetry and a 2 m point spacing for the topography for each flight line. Due to multiple flight lines, the resulting point density for each airborne laser data collection is slightly higher.

Airborne laser elevations often contain systematic errors that produce offsets between different data sets. Primary sources for airborne laser errors are erroneous laser calibration parameters and inaccurate GPS trajectories. End users are not able to correct laser calibration errors due to unattainable raw data and the proprietary software needed to produce laser points. GPS errors are often generated by incorrect monument elevations and GPS drift caused by inadequate modeling of the changing GPS satellite geometry. If the laser system is properly calibrated and the GPS drift is not large, then the offsets due to GPS errors throughout the data sets for a shoreline less than 50 km are usually systematic and constant. Fixing systematically shifted data to a known elevation significantly reduces errors in the laser elevations.

We compared all five airborne laser data sets to a GPS surveyed profile on a road surface not influenced by overwash and at multiple locations throughout the study area similar to the technique used by Zhang et al. (2005) and Robertson et al. (2005). The surveyed profile is an independent, high accuracy data set that was collected using rapid-static GPS with a short baseline and consisted of 312 points over 5 km. The GPS profile was located at the western end of the study area approximately 100 m landward of the shoreline. Mean differences between airborne laser surfaces and the surveyed profile ranged between 0.04 and 0.28 m. The same offsets were found at multiple locations throughout the study area indicating that the differences between laser surfaces were constant. Offsets were removed by vertically shifting the airborne laser data sets to match the GPS survey data under an assumption.
that the road surface did not change during the short study period. This procedure resulted in RMS errors of less than 0.10 m between the LIDAR gridded surfaces and the GPS survey.

Filtering the airborne laser data was necessary since several of the data sets were collected during mid-day hours when the beach was scattered with people and beach accessories. These objects can contribute to inaccurate shoreline positions and volume change. Based on previous studies, a progressive morphological filter with a 3 m window and 0.05 slope was used to effectively remove the non-terrestrial data without altering the natural beach morphology (Zhang et al., 2003; Zhang and Whitman, 2005).

The final step in processing airborne laser data involved interpolating the irregularly spaced laser measurements onto a regularly spaced grid to produce a set of digital elevation models (DEMs). The data were gridded at 1 m resolution using kriging interpolation with a linear variogram. DEMs for each flight were produced with a common origin and cell size to ensure registration. The DEMs were then analyzed to produce elevation contours and transects, or differenced to produce measurements of shoreline and volume change.

3.2. Shoreline and beach width change

The calculation of shoreline change is dependent upon a shoreline that can be measured with consistent methodologies over time. Unfortunately, airborne laser data do not directly measure the wet–dry interface that has historically represented the shoreline position. Recent studies have shown that an elevation contour derived from airborne laser data can represent the shoreline position (Stockdon et al., 2002; Sallenger et al., 2003; Moore et al., 2006). Robertson et al. (2004) found that a contour generated at the mean higher high water (MHHW) tidal datum is compatible to the wet–dry line for North and South Carolina. For this study, the local MHHW datum of 0.30 m (all elevations in this study are referenced to the NAVD88 datum) produced a noisy contour in some of the laser data sets due to being located seaward of the land–water interface. To avoid this problem, the shoreline contour was located at the 0.60 m elevation which is below the measured berm crest observed in the study area. The horizontal difference in shoreline positions corresponding to the MHHW datum and 0.60 m contour was on average less than 3 m due to a steep beach face slope at the foreshore.

Beach width is defined as the distance from the dune toe to the shoreline. Grids representing degrees of slope were visually compared in a GIS to digitized dune toe positions from DEMs and orthophotographs. A 6.5° slope most closely matched the digitized dune toe positions, but we were unable to use slope because the 6.5° contours generated from the slope grids were not continuous. Therefore, dune toe positions were determined using a contour of 3 m because dune toe positions match this continuous contour well. Calculations of beach width were the horizontal difference between the dune toe and shoreline position for each respective airborne laser survey.

Spatial changes in shoreline and beach width were analyzed using a GIS based metric mapping system (Robertson et al., 2005; Zhang et al., 2005). This system generates a set of transects perpendicular to the shoreline and calculates the intersection of each transect to shorelines or other linear features. Two hundred and thirty-seven transects (numbered 18–255, Fig. 1) spaced at 100 m intervals were analyzed over the area of beach covered by all 5 airborne laser data sets. Distances for each transect from a fixed offshore reference line to each dune toe and shoreline position of the 5 temporal surveys were measured, and the distances were exported to an ASCII table. Differences between distances were then used to calculate changes in beach width and shoreline over time.

3.3. Volume change

The DEMs derived from multiple airborne laser data allow an estimation of beach volumes. Volume change was quantified by differencing the DEM surfaces. Analysis of the difference grid allows for the quantification of sediment movement through the series of bins bounded by adjacent transects (Fig. 1). Two types of volume change were calculated in this study: subaerial and active beach (profile) zones. The subaerial zone was measured between the dune toe and the shoreline location for each respective data set (Fig. 5). Subaerial
Volume was calculated using all 5 airborne laser data sets. Active beach zone change was limited to the two bathymetric CHARTS data sets. The active beach profile was measured from the dune toe to the furthest seaward extent of the December CHARTS data (Fig. 5). The December CHARTS data measured to a distance of about 500 m offshore and an approximate depth of 11 m, whereas the May CHARTS data measured to a distance of about 1000 m offshore and an approximate depth of 19 m.

Volume change within each bin was summarized in terms of the total positive, negative, and net volume change (Zhang et al., 2005). The volumes were then normalized by the bin width (100 m) resulting in a table of positive, negative, and net volume change per alongshore length (m$^3$/m). Positive grid values in a bin
represent areas of accretion whereas negative grid values represent areas of erosion. Since little overwash occurred in the study area due to the low surge height and high dunes, sediment exchange across the landward boundary of the bin was negligible. The sediment exchange mainly occurred across the seaward boundary of the bin and across the two lateral boundaries.

4. Results

The alongshore variations in beach width and volume calculated from the five airborne laser data sets are shown in Figs. 6 and 7. There is a high alongshore variability in beach width and subaerial volume. In general, areas of large beach width and volume correspond to coastlines with less coastal infrastructure, while areas of small beach width and volume tend to be adjacent to infrastructure that is close to the shoreline and often protected by hard and soft stabilization. In addition, beaches in the western section of the study area are on average about 10 m narrower with standard deviations 4 m smaller than in the eastern section (Fig. 6). The boundary separating the west and east section is located approximately at the 13 km distance. The alongshore variability in beach volume exhibits a similar spatial pattern (Fig. 7). These general spatial relationships changed little throughout the study period.

4.1. Shoreline migration, beach width change, and subaerial beach volume change

The five data sets formed the basis for quantifying beach change into four time intervals between the data acquisitions (Fig. 4): May 4 to August 27 for summer change (115 days), August 27 to September 18 for change caused by Hurricane Ivan (22 days), September

Fig. 8. (a) Alongshore shoreline, (b) beach width, and (c) subaerial volume change calculated over four time periods in 2004. Lines correspond to the time intervals defined in Section 4.1: dashed line (summer, 5/4 to 8/27), medium line (Ivan, 8/27 to 9/18), thick line (recovery, 9/18 to 10/8), and thin line (fall, 10/8 to 12/1). Distance along shoreline is from west to east.
18 to October 8 for change during the post-Ivan recovery period (20 days), and October 8 to December 1 for fall change (54 days). Summary statistics for each time period are provided in Table 1. Hurricane Ivan caused significant landward shoreline migration with a reduction of the average beach width from 58 m to 42 m (Fig. 6, 8/27/04 to 9/18/04). In addition, subaerial volume was reduced from an average of 73 m$^3$/m to 42 m$^3$/m (Fig. 7, 8/27/04 to 9/18/04). This period of shoreline retreat and erosion was followed by a relatively rapid recovery in beach width from 42 m to 53 m (Fig. 6, 10/8/04). Somewhat surprisingly, a corresponding recovery in subaerial beach volume did not occur (Fig. 7, 10/8/04).

Shoreline, beach width, and subaerial volume differences between sequential data sets over 4 time periods provide more details of the alongshore beach change (Fig. 8, Table 1). For this analysis, a 500 m moving average filter was applied to each differenced data set to reduce the noise caused by high frequency spatial variations. Shoreline and beach width change signals were similar, which was expected because beach width was calculated using shoreline position, and the dune toe position changed little during the study period. Comparison of shoreline and subaerial beach volume change in Fig. 8 illustrates that both measures show seaward shoreline migration and profile accretion during summer months and significant landward migration along with erosion due to Hurricane Ivan. Following Hurricane Ivan, the relationships between shoreline migration and volume change differ remarkably. The shoreline shows significant seaward migration during recovery, while subaerial volume increased only 2.7 m$^3$/m (Table 1). Shoreline and subaerial volume change differed during fall as well, with a landward migration of shoreline, but an increase in subaerial volume.

Previous studies have found strong correlations between shoreline migration caused by hurricanes and the subsequent recovery periods (List et al., 2006). Linear correlation coefficients were calculated to test the relationships between change in shoreline position, beach width, and subaerial volume (Table 2). Shoreline migration caused by Hurricane Ivan and its subsequent recovery were weakly correlated ($-0.38$). Slightly higher correlations were found with the change in beach width ($-0.44$) and subaerial volume ($-0.46$) in the same period. For this data set consisting of 137 transects, the critical $t$-value at the 95% significance

<table>
<thead>
<tr>
<th></th>
<th>$dS \ R^2$</th>
<th>$dW \ R^2$</th>
<th>$dV \ R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer – Ivan</td>
<td>$-0.20$</td>
<td>$-0.22$</td>
<td>$0.02$</td>
</tr>
<tr>
<td>Ivan – Recovery</td>
<td>$-0.38$</td>
<td>$-0.44$</td>
<td>$-0.46$</td>
</tr>
<tr>
<td>Recovery – Fall</td>
<td>$-0.37$</td>
<td>$-0.28$</td>
<td>$-0.18$</td>
</tr>
</tbody>
</table>

Fig. 9. Alongshore (a) $K$ values and their respective (b) $R^2$ values for the 237 transects measured on Panama City beaches, from west to east. Dashed horizontal line (a) is the mean. Circles represent statistically significant $K$ values discussed in Section 4.2. Solid horizontal line (b) is the critical $R^2$ value of 0.77 at 95% significance.
level is 1.98. This corresponds to a critical value of ±0.17 for the correlation. Therefore, the correlations between each relationship with the exception to the summer to Hurricane Ivan change in subaerial volume are statistically significant.

4.2. Relationship between beach width and subaerial volume

Previous studies have proposed a temporal linear relationship between beach width and subaerial volume (Thom and Hall, 1991; Dingler and Reiss, 2002) where $K$ is the constant of proportionality between beach width and volume (Eq. (1)). This study utilized the high spatial resolution of airborne laser measurements to examine the alongshore variation in $K$. Beach width and subaerial volume were regressed over the five data acquisitions in each of the 237 bins.

Fig. 9a shows that $K$ varies considerably alongshore, ranging between 0.75 and 1.79 m$^2$ with a mean of 1.09 m$^2$. However, this study utilizes only five airborne laser data sets during 2004; therefore not all $K$ values are significant due to the limited sample size. The critical $t$-value at the 95% significance level with 5 samples is 3.18. This corresponds to a critical $R^2$ value of 0.77, and values below 0.77 indicate linear relationships are not significant between beach width and subaerial volume. When only analyzing transects above the critical $R^2$ value (66 of 237), the high variability in $K$ remained, ranging from 0.75 to 1.79 m$^2$ with a mean of 1.10 m$^2$.

4.3. Active zone sediment movement

The two CHARTS airborne laser data sets allow quantification of both onshore and offshore sediment movement. The net sediment exchange ($V_N$) represents the amount of sediments added or removed from a bin and is equal to the sum of the deposition ($V_D > 0$) and erosion ($V_E < 0$):

$$V_N = V_D + V_E$$

(2)

Results show that on average 27 m$^3$/m of sediments left the measured area during the summer to fall time period (Table 3). Net sediment exchange is helpful when quantifying changes for an entire study area, but it includes both removal and deposition of sediments and cannot distinguish the magnitudes of erosion and accretion that occur within the active profile zone. The amounts of sediment redistribution within the active profile zone and the relative magnitude of sediment exchange with the outside zone are critical for designing Coast. Eng. projects. If all sediments are contained in a given bin, then $V_N=0$. For this case, $V_D$ and $V_E$ are equal in magnitude, all sediment movements are due to redistribution, and the volume of redistributed sediments is equal to $V_D$ (or $|V_E|$). For most cases, the net sediment exchange is not zero. Therefore, the volume of redistributed sediment is equal to the lesser of the volumes of deposition or erosion. Thus, the volume of redistributed sediments ($V_R$) within the bin can be expressed as:

$$V_R = \min(V_D, |V_E|)$$

(3)

We propose to use the ratio:

$$R_V = \frac{V_N}{V_R}$$

(4)

to measure the relative magnitude of sediment exchange with outside areas to the sediment redistribution within a bin. When the majority of sediments are contained within a bin, $V_R$ is greater than $V_N$ and $R_V$ is less than 1. When the majority of sediments are deposited in or eroded from a bin, $V_N$ is greater than $V_R$, and the absolute value of $R_V$ is greater than 1. The sign of $R_V$ indicates if the net change was deposition (positive) or erosion (negative). In the rare case when the entire profile sustains deposition or erosion, then $V_R$ would be equal to zero. This would result in $R_V$ equaling positive or negative infinity, representing complete deposition or erosion. Based on change of the $R_V$ value, sediment movement for a bin can be separated into four categories: accretion dominated when $R_V$ is greater than 1, mix of accretion and redistribution when $R_V$ is greater than zero but less than 1, mix of erosion and redistribution when $R_V$ is less than zero but greater than −1, and erosion dominated when $R_V$ is less than −1 (Fig. 10).

### Table 3

<table>
<thead>
<tr>
<th></th>
<th>$V_N$ (m$^3$/m)</th>
<th>$V_R$ (m$^3$/m)</th>
<th>$R_V$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Min</td>
</tr>
<tr>
<td>All bins</td>
<td>−27</td>
<td>59</td>
<td>−238</td>
</tr>
<tr>
<td>Borrow pit bins excluded</td>
<td>−13</td>
<td>47</td>
<td>−153</td>
</tr>
</tbody>
</table>
The difference grid from two CHARTS DEMs was further analyzed to examine the spatial change of $R_V$. $R_V$ for the entire study area is $-0.21$, indicating that the movement of sediments was dominated by redistribution and a relatively small amount of sediments moved further offshore or alongshore (Table 3, Fig. 10). This agrees with the pattern of sediment movement in the active zone from the summer and winter conceptual model. For 224 out of the 237 transects, the magnitude $R_V$ is less than 1 and greater than $-1$, indicating that...

Fig. 10. Alongshore $R_V$ caused by Hurricane Ivan, from west to east. Vertical solid lines are the western bounds of a borrow pit. Vertical dashed lines are the eastern bounds of a borrow pit. Horizontal lines separate change environments, from mostly accretion at top to mostly erosion at bottom. Distance along shoreline is from west to east.

Fig. 11. Shaded relief map of May CHARTS data. Black line is the approximate location of zero change when differencing December CHARTS data from May CHARTS data. Notice the large depressions which are borrow pit locations. Rectangle is the bounds for Fig. 12.
most sediments were redistributed within the same bin. In 12 locations, however, the active zone shows mostly erosion ($R_V < -1$). $R_V$ values less than $-1$ are proximal to borrow pits excavated for a 1999 beach replenishment project (Figs. 10 and 11). The offshore bar inshore of a borrow pit is more eroded than offshore bars west and east of the borrow pits (Fig. 12). It is not possible to compute the exact amount of sediment trapped by the borrow pit because the December CHARTS data do not extend seaward enough to measure the entire borrow pit.

Since incomplete coverage for a borrow pit will produce abnormally large $R_V$ values for bins containing borrow pits, it is necessary to remove the bins influenced by borrow pits for an estimation of the average $R_V$ for the study area. The locations of borrow pits were identified with the May CHARTS data and the mean $R_V$ was recalculated by using transect bins that did not contain borrow pits (Figs. 10 and 11). Removal of bins that did not contain borrow pits reduced $R_V$ to $-0.07$ (Table 3). The lower ratio indicates that most sediments remained within the study area from summer to fall in 2004 even with the impact of Hurricane Ivan.

5. Discussion

Beach recovery following storm events is essential for beach sustainability. If beaches recover more at areas of higher erosion, then the natural recovery of beaches could slow landward migration of the shoreline. For North Carolina and Cape Cod coasts, List et al. (2006) found that the magnitude of shoreline recovery was small at locations with less erosion and large at locations with severe erosion. It appears qualitatively that a similar relationship also exists between the Ivan-induced landward shoreline migration and recovery at Panama City beaches (Fig. 8a). However, the correlation between landward and seaward shoreline migration is $-0.38$ (Table 2), which is low compared to those reported in the List et al. (2006) study that range from $-0.31$ to $-0.80$. The major reason for this difference is there are many erosion hot spots along North Carolina and Cape Cod coasts. Erosion hot spots are sections of coastline that erode significantly more than adjacent sections. It is the large magnitudes of landward migration at these hot spots and corresponding seaward migration during recovery that improve the correlation between shoreline changes found in the List et al. study. Our study area does not contain large alternating erosion hot spots. The spatial variability of shoreline change is small with a standard deviation less than 3.4 m (Table 1).

Estimation of subaerial volume from shoreline change appears problematic due to the differences between shoreline and subaerial volume change curves (Fig. 8a and c). Examination of individual beach profiles demonstrates why shoreline and subaerial volume do not change at the same rate. Transect 95 is representative...
of many profiles in the study area (Fig. 13). Prior to Hurricane Ivan, the profile shows a well defined berm. On the September profile, the berm is significantly eroded and flattened by Hurricane Ivan with a corresponding landward migration of the shoreline and a decrease in subaerial volume. The October and December profiles show the progressive formation and landward migration of a sand ridge. The sand ridge buildup resulted in an increase in subaerial volume along with a landward migration of shoreline position during the fall period. This demonstrates that using shoreline migration to represent subaerial volume change after a storm could lead to incorrect results.

Previous studies have found a temporal linear relationship \((K, \text{Eq. (1)})\) between beach width and subaerial volume (Thom and Hall, 1991; Dingler and Reiss, 2002). These relationships were based on a time series of beach profile measurements for individual transects that were spaced far apart, often on entirely different beaches. The spatial limitation of beach profiles did not allow researchers to test alongshore variability in \(K\). Airborne laser data greatly increase the spatial resolution of beach measurements, but few airborne laser data sets measuring overlapping areas exist. This study was temporally limited to 5 data sets measuring the same beaches in 2004. It was determined that 66 of the 237 transects were statistically significant at the 95% significance level.

For the statistically significant transects, the high \(R^2\) values indicate that a strong linear relationship between beach width and subaerial beach volume exists, but the spatial variability of \(K\) values suggests that the linear relationship is different from one transect to another. \(K\) values for adjacent Transects 150 and 151 (15.0 and 15.1 km for Fig. 9a) differ by 0.53, more than 70% of the 0.75 \(K\) value for Transect 151. Estimation of subaerial beach volume from beach width using Eq. (1) with a constant \(K\) value could yield large uncertainties depending on where transects were measured. Future airborne laser surveys are needed to increase the sample size to produce a more strict statistical analysis. The increased confidence will aid in determining the effectiveness of Eq. (1).

There appears to be a “depth of closure” along the beach profile as suggested by Hallermeier (1977, 1981) and sediment movement is small beyond this depth. The most seaward zero change contour for the difference grid of two CHARTS DEMs is located around 10 m in depth (Fig. 11). Estimated depth of closure for the study area is unavailable due to lack of wave data. However, the depth of closure was estimated to be 6.3 m at Destin Beach in terms of extreme wave height and period exceeding 12 h/yr, about 50 km west of the study area (Hallermeier, 1981). Hallermeier’s estimate of the depth of closure is determined by an average wave condition. Hurricanes often induce storm waves with large heights and long periods, therefore the depth of closure for storm wave condition is larger than those from a typical annual wave condition. The borrow pits close to the depth of closure are acting as a sediment sink, thus...
leading to more erosion from adjacent landward bars. Since having borrow pits close to the closure depth can lead to large sediment loss from nourished beaches, it may be more effective to place borrow pits further seaward to avoid trapping sediment from nourished beaches. However, poor quality sand beyond the depth of closure may limit the shift of borrow pits.

The depth of closure concept forms the basis for designing coastal engineering projects such as beach nourishment, but this concept remains controversial. In general, a number of coastal geologists refute the existence of the depth of closure due to a significant sediment exchange between the active beach zone and continental shelf (Pilkey et al., 1993). Coastal engineers defend the depth of closure concept and suggest that sediment exchange between the active zone and continental shelf is insignificant over the time frame of an engineering project (less than 50 yr). One key reason for this controversy is the lack of accurate large scale three-dimensional field observations of bathymetry for the active zone. Airborne laser measurements provide unprecedented high resolution measurements of bathymetry that can reach a depth of 60 m in clear water environments such as the Florida coast (Finkl, 2004). Repeat surveys before and after storms will provide critical information for solving the depth of closure controversy. The noise in airborne laser measurements makes it difficult to accurately measure small changes (<0.15 m). However, the signal of sediment loss from an active zone will be much stronger because significant amounts of sands have to be eroded from the active zone to deposit a thin layer of sands in the offshore area. Therefore, three-dimensional decadal monitoring of sand loss and gain in an active zone will allow quantification of sediment exchange between the active zone and continental shelf.

6. Conclusions

Large scale beach response to Hurricane Ivan was quantified using five airborne laser data sets measuring Panama City beaches. On average, Hurricane Ivan caused 16 m of landward shoreline migration across the study area, and the shoreline recovered by 10 m in a 20-day period following the storm. The hurricane also caused similar erosion in subaerial beach volume. However, unlike the shoreline position, a corresponding recovery in subaerial volume magnitude was not observed. Sediment sources to the east combined with additional sediments from beach replenishment projects would form a beach profile vulnerable to storm-induced erosion. It appears that at least some of the eroded sediments were being returned to the beach face during the low wave environment following Hurricane Ivan.

Weak spatial relationships were found between shoreline migration caused by Hurricane Ivan and the subsequent recovery period. Beach width reduction and subaerial volume erosion due to Ivan and accretion after the storm event had low correlations as well. Spatial change in subaerial beach volume differed from shoreline and beach width changes, and the change was often opposite in sign. This suggests that using shoreline migration during and immediately after a storm to predict subaerial volume change can yield incorrect results. For 66 of the 237 transects, beach width and subaerial volume showed a linear relationship. However, the variation of the linear relationship alongshore suggests that the coefficient ($K$) for a linear equation between beach width and subaerial volume is not spatially constant. The sample size for estimating $K$ is limited by 5 data sets. Future airborne laser surveys will provide a more strict analysis to determine if a linear relationship can be used to effectively estimate subaerial volume change from changes in shoreline position.

Sediment movement in the active zone during the summer and fall seasons was analyzed using water penetrating airborne laser measurements. A negative net volume change suggests sediment loss, but a $−0.21 R_v$ value suggests that most sediments remained in the measured area. Further analysis found that borrow pits, which supplied sediments for beach nourishment projects, trapped sediments transported offshore, and lead to more erosion of sand bars next to the borrow pits. The $R_v$ value was reduced to $−0.06$ when analyzing beaches not influenced by borrow pits, indicating that most sediment movement was confined to the active zone despite the impact of Hurricane Ivan. However, there appears to be some change seaward of the airborne laser data coverage, thus the full extent of sediment migration was not quantified in this study. Additional bathymetric airborne laser measurements are needed further offshore to confirm the depth of closure measurement and to fully understand the sediment exchange between the active zone and continental shelf.

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