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Geospatial analysis of vulnerable beach-foredune systems from decadal time series of lidar data

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Abstract Time series of lidar data, acquired over the past decade along the North American East Coast, provide opportunities to gain new insights into 3D evolution of barrier islands and their beach and dune systems. GIS-based per grid cell statistics and map algebra was applied to time series of Digital Surface Models representing two sections of North Carolina barrier islands to quantify elevation change trends, map dynamic and stable locations, identify new and lost buildings, measure relative volume evolution in the beach and foredune systems and analyze shoreline dynamics. Results show a relatively small stable core in both study areas, with beaches and the ocean side of the dunes exhibiting systematic high rates of elevation loss while areas landward from the dunes increase slightly in elevation. Significant number of new homes have been built at locations with very small core surface elevation, and homes built within the shoreline dynamics band have already been lost. The raster-based methodology used in this study can be applied to perform similar analyses in other coastal areas where time series of lidar data are available.

Keywords Barrier islands · Beach erosion · Sand dunes · GRASS GIS · Outer Banks North Carolina

Introduction

Understanding short term barrier island evolution, identification of areas susceptible to high rates of erosion and accurate mapping of elevation and sand volume change is critical for responsible coastal planning and management (Stockdon et al. 2007; Houser et al. 2008; Saye et al. 2005). Previous studies have demonstrated advantages of lidar surveys for evaluating beach changes and assessment of shoreline and dune erosion (Stockdon et al. 2002; Sallenger et al. 2003; Overton et al. 2006; Burroughs and Tebbens 2008). Lidar-based, bare earth Digital Elevation Models (DEMs) have been widely used for quantification of beach and dune volume change (e.g. Mitasova et al. 2004; Overton et al. 2006; White and Wang 2003), including assessment of major storm and hurricane impacts (Sallenger et al. 2006). The high density of lidar data points and near-annual frequency of coastal mapping provide time series of elevation data that can be used for extraction of new information about spatial patterns of coastal dynamics using raster-based techniques (Mitasova et al. 2009a). However, rapid evolution of lidar technology during the past decade produced data sets with different accuracies, scanning patterns, and point densities; therefore, geospatial analysis, when applied to decadal lidar time series, needs to address the issues of accurate data integration and computation of a consistent set of elevation models. The objective of this paper is to

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provide quantitative geospatial information about the dynamic state and recent evolutionary trends in coastal topography in vulnerable locations using raster-based analysis of elevation surfaces.

Study sites

Decadal evolution of coastal topography was investigated for two sites on the Outer Banks, North Carolina (NC), USA. The Outer Banks are a series of barrier islands extending from Cape Henry, Virginia to Cape Lookout, North Carolina. This area has proven to be an ideal place to observe and study coastal dynamics due to rapid evolution of geomorphic features. Further, the interplay between natural and anthropogenic influences on the coastal dynamics provides a rich context in which to consider management alternatives. In the last hundred years, inlets have opened and closed, shorelines have eroded and accreted, and dunes have been built and lost.

The two study sites (referred to as Hatteras and Rodanthe) chosen for this paper have a history of beach and dune evolution for which anthropogenic modifications have occurred. These two areas were formally identified (along with five other locations) as the “NC 12 Hotspots” with respect to the coastal highway NC 12 vulnerability in a study by Stone et al. (1991). Management alternatives to decrease the vulnerability of NC 12 to storms and long-term erosion such as road relocation, beach nourishment, and dune maintenance have all been utilized in subareas of these locations with varied success dependent on local and temporal conditions.

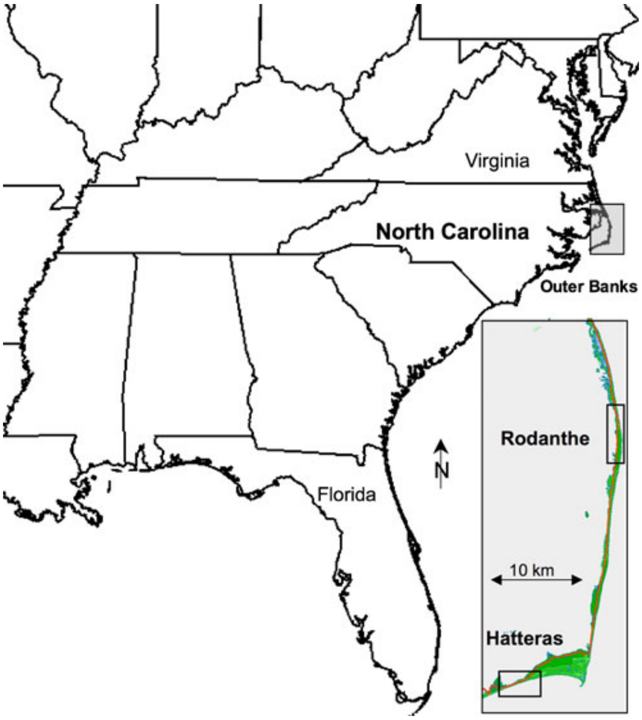


Fig. 1 Location of the study sites Hatteras and Rodanthe on the Outer Banks, North Carolina, USA

The Hatteras Hotspot is between Frisco and Hatteras Village on the southeasterly facing portion of Hatteras Island (Fig. 1) and is part of the Cape Hatteras National Seashore. This area was reported by Stone et al. (1991) to have long-term erosion rates of 0.6 to 1.0 meters per year. Given the proximity of NC 12 to the active shoreline and the long term erosion rate, relocating the road landward in approximately 2008 was recommended. Short-term events were not considered in the analysis by Stone et al. (1991). These long term erosion rates provided realistic projections until September 2003 when Hurricane Isabel overwashed Hatteras Island at this location and a breach developed (Wamsley and Hathaway 2004; Overton and Fisher 2004). After the breach was closed (Wutkowski 2004), the road was relocated landward of its pre-Isabellocation, and a protective dune was constructed on the ocean side of the road. The Hatteras study site extends approximately 2.7 km, beginning just northeast of Hatteras Village.

The Rodanthe Hotspot (Fig. 1) is 4.7 km long with 2.4 km within the Village of Rodanthe and 2.3 km in the Pea Island National Wildlife Refuge (PINWR) that is undeveloped, with the exception of NC12. The area north of Rodanthe has long been known as the ‘S’ Curves due to the curvature in the road alignment. The road has been moved landward multiple times in the last 30 years in response to shoreline change driven by high long term erosion rates (upwards of 4.3 m/yr, NC Division of Coastal Management 2003). Today, management priorities within the PINWR restrict moving the road landward. Thus, sand management practices after storm-induced overwash events are critical to understanding the changing morphology of the beach and dune system.

Methods

To characterize dynamics of beach-foredune systems, time series of lidar-based elevation data was processed and analyzed using GIS-based workflow proposed by Mitasova et al. (2009a) and Overton et al. (2006) with enhancements developed specifically for application to the studied sites. The workflow includes integration of data from various lidar surveys, computation of new types of maps that characterize terrain evolution, as well as quantification of changes in volumes and shorelines relative to the site dynamics.

Data acquisition

The analysis was based on time series of lidar data acquired by several agencies for a variety of mission objectives:

- September 1997, September 1998, October 1999: the National Oceanic and Atmospheric Administration (NOAA) / National Aeronautics and Space Administration (NASA) / U.S. Geological Survey (USGS) Airborne Lidar Assessment of Coastal Erosion project;
- February 2001: the North Carolina Floodplain Mapping Program (NCFMP);
- September 2003: the NASA / USGS Experimental Advanced Airborne Research Lidar (EAARL) pre- and post- Hurricane Isabel survey;
- July 2004 and November 2005: the U.S. Army Corps of Engineers National Coastal Mapping Program Topo/ Bathy Lidar;
- March 2008: the NOAA Integrated Ocean and Coastal Mapping (IOCM) Lidar for North Carolina and Virginia.

The point data were downloaded from two online distribution sites (USGS Center for Lidar Information Coordination and Knowledge 2009; NOAA Coastal Services Center 2010) in the NC State Plane North American Datum 1983 coordinate system with North American Vertical Datum 1988 (NAVD88) and units in meters. The published vertical accuracy of most of the data is 0.15–0.2 m and the horizontal accuracy is published as 2 m and better or as 0.7 m at 700 m airplane altitude that was the approximate altitude for most of the surveys used in this study (NOAA Coastal Services Center 2010).

Point data analysis and computation of digital surface models

To quantify changes in beach and sand dune systems and identify new construction or loss of structures, first return lidar points were used to generate Digital Surface Models (DSM) that combine bare earth surface with structures and vegetation (as opposed to DEM that represents bare earth only). The following workflow (Mitasova et al. 2009a) was employed to produce a consistent, high resolution time series of DSMs, with minimized systematic error and noise:

- per grid cell statistical analysis of the input point data was performed for each survey at a hierarchical set of resolutions ranging from 10 m to 0.5 m, with the aim to extract information about the properties of the point cloud data, such as number of points and range of elevations within each grid cell;
- preliminary DSMs were created at 5 m resolution by computing the mean elevation value from the points located within each cell; these DSMs were used to map the spatial extent of each survey and derive a mask for the study area;
- regularized spline with tension (RST, Mitasova et al. 2005) was used for simultaneous computation of DSMs at 0.5 m resolution and for smoothing of noise. To preserve important topographic features and structures, resolution was chosen such that the average range per cell was less than the published vertical accuracy in the lidar data;
- the interpolated DSMs were compared with high accuracy, time invariant ground based data: NC Department of Transportation (DOT) benchmarks established along the NC-12 highway centerline (Points #201–210 for Hatteras and Points #262–295 for Rodanthe) to identify and remove potential systematic errors, verify the published data accuracy, ensure that approximation has not introduced unacceptable errors and check data consistency. The median differences between the DSMs and NCDOT elevation benchmarks were used to derive systematic error correction. Although the values of the mean and median differences were close to each other, median was considered more appropriate for systematic error correction because of its lower sensitivity to outliers present in some of the data sets.

Resulting time series of DSMs were then used to derive standard measures of coastal change as well as novel type of maps characterizing coastal dynamics and vulnerability in the study areas. The processing and analysis were performed using open source Geographic Resources Analysis Support System (GRASS GIS, Neteler and Mitasova 2008).

Geospatial and temporal analysis

The spatial pattern of trends in elevation was mapped by applying summary statistics on per cell basis to DSM time series, with each output cell value computed as a function of the values in the corresponding cells across the time domain (Wegmann and Clements 2004). Using this approach, the following raster maps were computed: (a) core surface, representing the minimum elevation recorded at each grid cell over the study period; (b) envelope surface, representing the maximum elevation recorded at each grid cell over the study period; (c) standard deviation as a measure of elevation change; (d) linear regression slope, representing spatial pattern of elevation increase/decrease rates; (e) linear regression offset (equivalent to the initial elevation map) and coefficient of determination representing measure of the strength of linear dependence between time and elevation; (f) time of minimum and time of maximum raster maps. The volume bound by the core surface and the mean high water level represents the volume of mass that has remained stable throughout the study period. The volume bound by the core and envelope surfaces represents the space within which the actual elevation surface evolved during the study period. This 3D space is referred to as dynamic layer (Fig. 2, also see animation associated with Mitasova et al. 2009b).

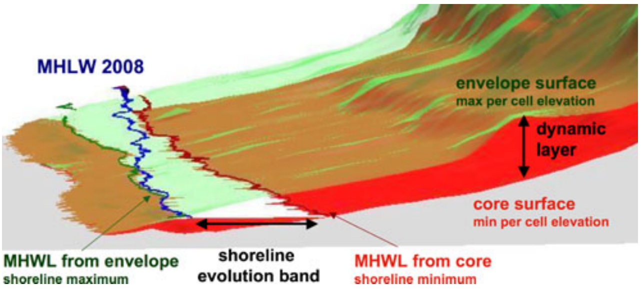


Fig. 2 Relation between the core and envelope surfaces, dynamic layer, and shoreline evolution band. Mean high water level (MHWL) is 0.36 m at our study sites

The two dimensional analog to dynamic layer is shoreline evolution band (Fig. 2). It defines an area within which the shoreline evolved over the study period and it is extracted as a mean high water elevation contour from the core and envelope surfaces ($z=0.36$ m, where z is elevation registered to NAVD88). Width of this band was used as a quantitative measure of shoreline dynamics at any given location. To quantify stability / dynamics at different elevation levels, contours at elevations 1.5 m (upper beach) and 3.0 m (mid-dune) were extracted from the core and envelope surfaces. Stability for a selected elevation level z_k at a given location was then measured as distance between the z_k contours derived from the core and envelope surfaces.

To analyze and compare sand volume change within selected areas the volume ratio R_i was computed for each elevation surface as follows:

$$R_i = (V_i - V_c)/(V_e - V_c) \qquad (1)$$

where V_i is the volume between the i^{th} elevation surface in the time series and the core surface, V_c is the volume between the core surface and mean high water level, and V_e is the volume between the envelope surface and mean high water level. Relative volume R_i, expressed as a percent of the dynamic layer as opposed to the entire volume above mean high water level, permits comparison of volume change trends in areas with different size.

The structures that were built or lost during the study period were identified as locations where the difference between the the core and envelope surfaces (minimum and maximum elevations for each cell over the entire time period of 12 years) exceeded a given threshold (Mitasova et al. 2009b). The time interval when a given house was built or destroyed was retrieved by analysis of elevation change at the centroids of the identified homes. New structures that were built at locations where the core surface elevation was much lower than the present elevation surface were considered at higher risk because they have been built on relatively unstable surface that may further evolve. Similarly, homes located in an area where the core surface elevation is lower than a minimum threshold that is considered safe (e.g. based on storm surge, or sea level rise) or the homes located within the shoreline dynamic band were identified as vulnerable.

Results

Point data analysis and DSM correction

The results of lidar point cloud analysis at a hierarchy of resolutions is summarized in Table 1. At 10 m resolution mean range of elevations within the grid cells exceeds 1 m for all surveys and 2 m for the last three surveys indicating that important features may be lost at this resolution. At 2 m resolution the mean range was between 0.08 and 0.65 m and the number of points per grid cell was less than one for older surveys, indicating need for interpolation. At 0.5 m resolution, the within-cell mean range was less than the published data accuracy and interpolation was necessary for all surveys. To preserve the shape of the buildings,

Table 1 Mean number of points and mean elevation range per grid cell at 0.5 m, 2 m and 10 m resolution for each lidar survey used at the Rodanthe site

	Grid size [m]	Points per cell	Range [m]		Grid size [m]	Points per cell	Range [m]		Grid size [m]	Points per cell	Range [m]
1996	0.5	0.07	0.09	1999	0.5	0.07	0.01	2004	0.5	1.18	0.06
	2	0.16	0.08		2	1.21	0.13		2	18.84	0.65
	10	3.95	1.11		10	30.23	1.52		10	471.92	2.62
1997	0.5	0.245	0.02	2001	0.5	0.02	0.00	2005	0.5	0.65	0.06
	2	0.61	0.24		2	0.33	0.06		2	10.36	0.59
	10	15.03	1.79		10	8.42	2.79		10	257.16	2.70
1998	0.5	0.05	0.01	2003	0.5	0.05	0.00	2008	0.5	0.22	0.01
	2	0.21	0.15		2	0.80	0.08		2	3.51	0.41
	10	5.28	1.53		10	20.06	1.63		10	88.03	2.65

0.5 m resolution was selected and the time series of DSMs were interpolated for both study areas.

To assess and remove potential systematic errors, elevation differences between the DSM and NCDOT benchmarks were calculated and the median difference for each year was then applied to the entire DSM, assuming uniform spatial distribution of the systematic error. The median differences ranged from −0.38 to 0.25 m for the Hatteras area and from −0.24 to 0.23 m for Rodanthe. Systematic errors for the Rodanthe site were similar to those at Hatteras, with the average of the median difference in systematic error between the two sites less than 0.06 m. The largest median values for the systematic errors were associated with the older surveys (1997 and 2001), the systematic errors for more recent surveys (2004, 2005, 2008) were much smaller with the medians ranging between −0.07 and +0.03 m. The improvement gained by the DSM correction was verified by computing the differences between the corrected DSMs and the NCDOT benchmarks (Fig. 3).

Impact of the Hatteras Island breach due to Hurricane Isabel in 2003 required special attention when computing systematic errors in this area. The median values of the DSM-NCDOT benchmark differences were used as correction values for the years 1997, 1998, 1999 and pre-Isabel 2003. Examination of the high resolution post-Isabel orthophotos revealed that the NCDOT benchmark points 201 through 204 and the points 206 through 210 were covered with an extensive amount of sand caused by the overwash. Furthermore, the NCDOT benchmark point 205 was the only point standing clear of sand, and the correction value for the post-Isabel 2003 DSM had to be calculated by the elevation difference between the NCDOT benchmark point 205 and the elevation of the DSM at that point. Since the highway was destroyed during the breach and then reconstructed at different elevation, NCDOT benchmark points 204 through 206 were removed from the calculation of the elevation difference median for years 2004, 2005 and 2008.

Raster-based time series analysis

The corrected 0.5 m resolution DSMs for the Hatteras study site were used to extract the minimum (core) and maximum (envelope) elevations for each cell over the entire time period of 12 years. The average elevation of the envelope was 2.85 m, while the average elevation of the core was only 1.21 m. The volume of the core above the mean high water level accounted for only 42% of the envelope space volume indicating significant dynamics in elevation. Cross sections of the core and envelope surfaces show the dynamic layer in Fig. 4, with core completely missing in the breach area.

The standard deviation map was used to identify the stable and dynamic areas in terms of elevation change (Fig. 5). The values of the standard deviations were extracted for each NC DOT benchmark, resulting in an average value of 0.14 m, almost equal to the published accuracy of the lidar data. However, approximately 88% of the area has the standard deviation value greater than 0.14 m indicating the highly dynamic nature of elevation surface at this site, with the highest values of standard deviation found along the foredune (1.0 m to 2.5 m) and at new buildings (5.0 m to 5.6 m).

The map representing the rate of elevation change (Fig. 6a) showed nearly uniform, high rates of elevation loss due to erosion along the beach while a relatively low rate of elevation increase was observed inland from the foredunes. The high rates of elevation change were close to linear according to the coefficient of determination map (Fig. 6b). Between areas of severe, near-linear change were

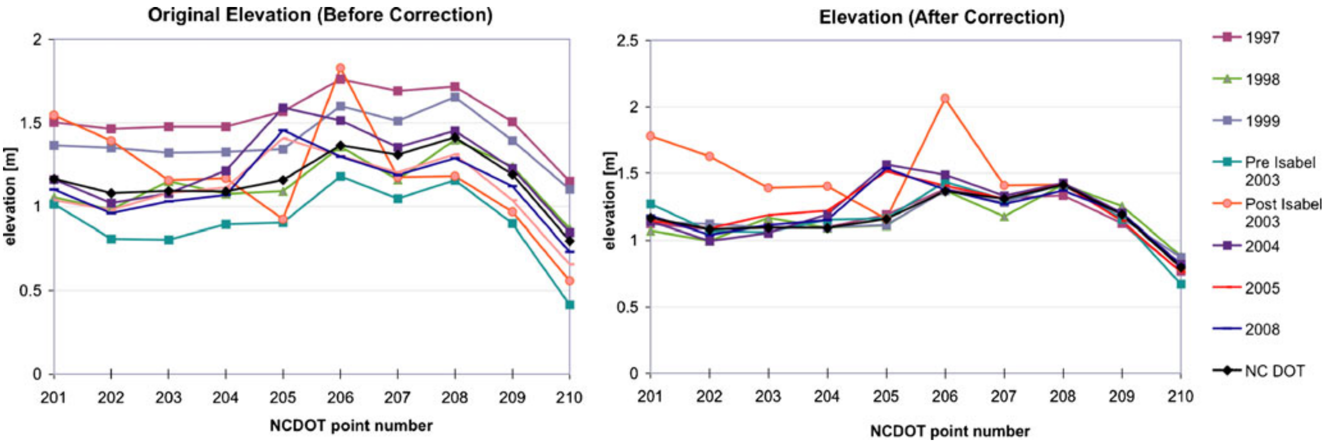


Fig. 3 Hatteras Island site: elevations at the NCDOT benchmarks derived from the original and corrected DSMs. Large differences in the 2003 post Hurricane Isabel data reflect the impact of overwashed sand

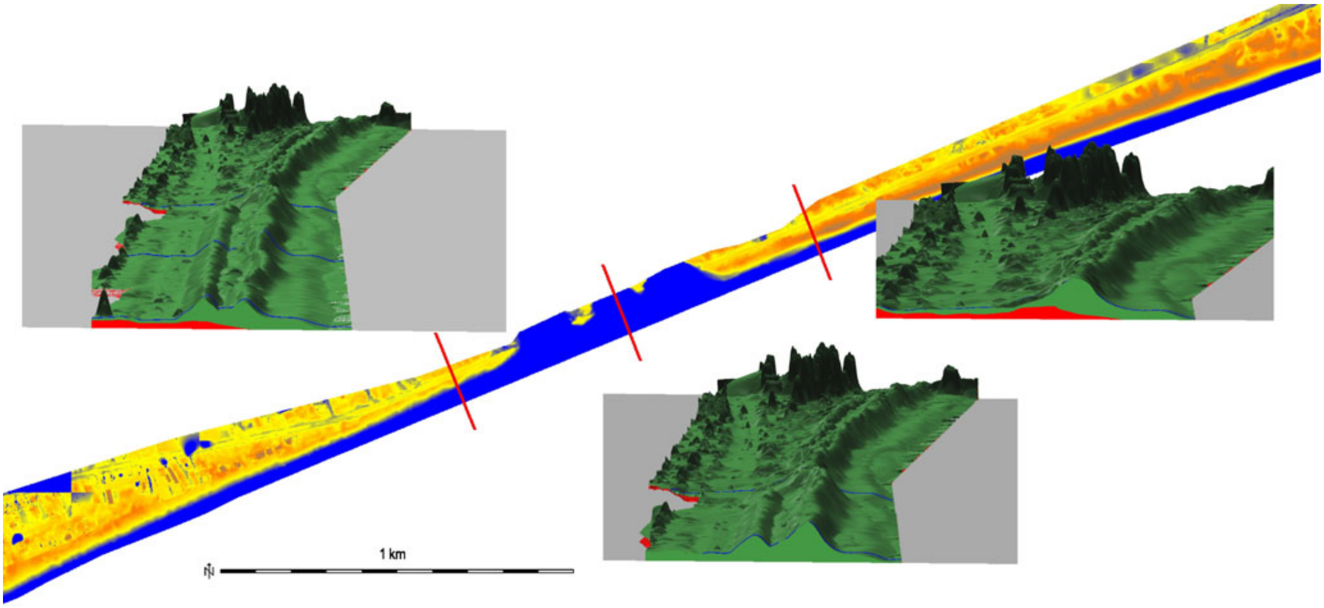


Fig. 4 Core surface (*red*) below which elevation never decreased and envelope surface (*green*) above which elevation never increased. The cross section in the area that was breached during the Hurricane Isabel in 2003 has no core surface

areas with zero net rate of change that had low coefficients of determination indicating that the rate of change was reversing direction or was periodic.

Temporal aspects of terrain change were captured by a map representing the year when each grid cell was at its highest elevation (Fig. 7a) and a map representing the year when each grid cell was at its lowest elevation (Fig. 7b). A third map, representing year at minimum elevation derived without the 2003 DSM is also presented (Fig. 7c) to highlight the effect of Hurricane Isabel on the island (Fig. 7b). The temporal maps clearly show that the maximum elevations on the beach come primarily from dates before the year 1999. In the inland area, nearly all of the maximum elevations are from dates after the year 2003. This suggests that at least a portion of the sand from the beach has been redistributed inland. The map representing the year of minimum elevation (Fig. 7b) highlights the location where the breach occurred during Hurricane Isabel (the lowest elevation in the year 2003). However, most of the study area along the beach had its lowest elevation in the year 2008 which indicates the impact of recent erosion.

Similar analysis performed in the Rodanthe study area (Fig. 8) leads to results consistent with the Hatteras site. The mean elevation of the core and envelope surfaces

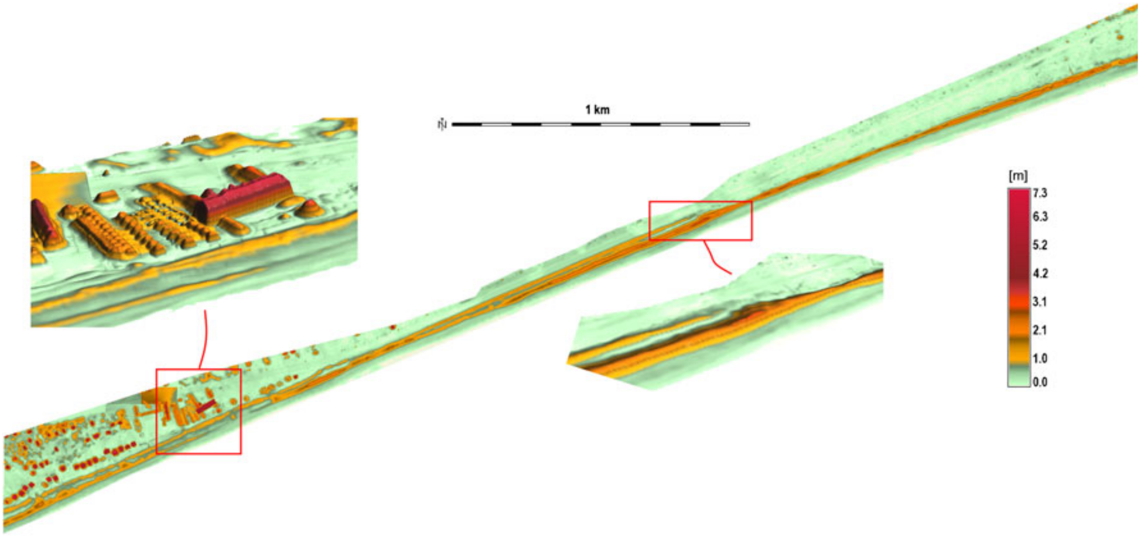


Fig. 5 Spatial pattern of standard deviation represents the variation of elevation based on more than decade of lidar surveys. Insets show the standard deviation draped over the 2008 year DSM, with the local maxima on dunes and new buildings

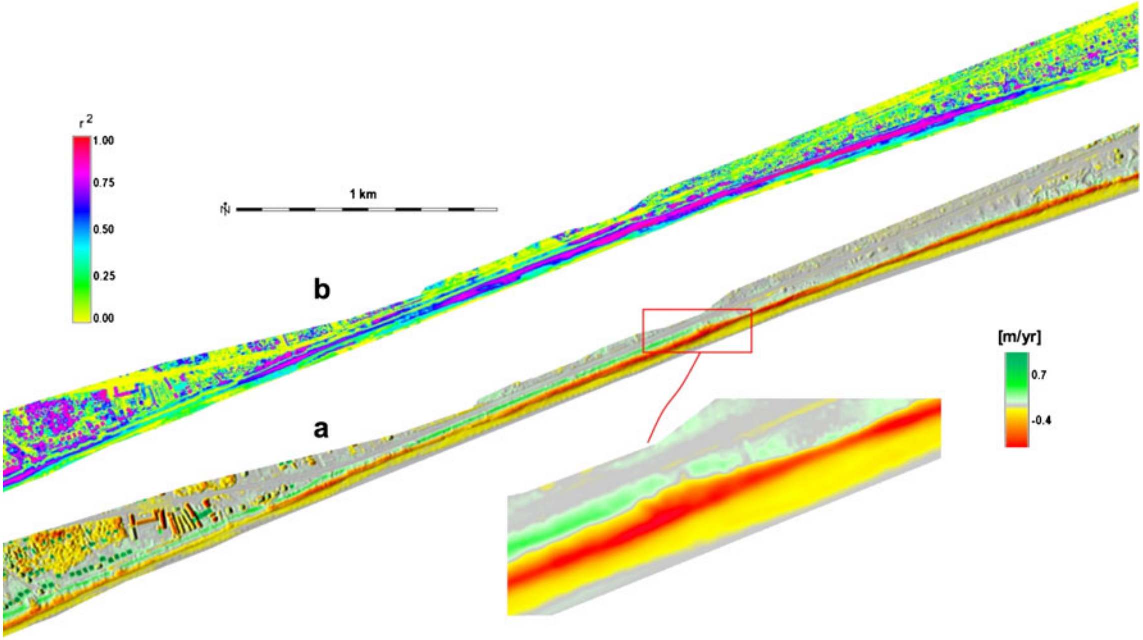
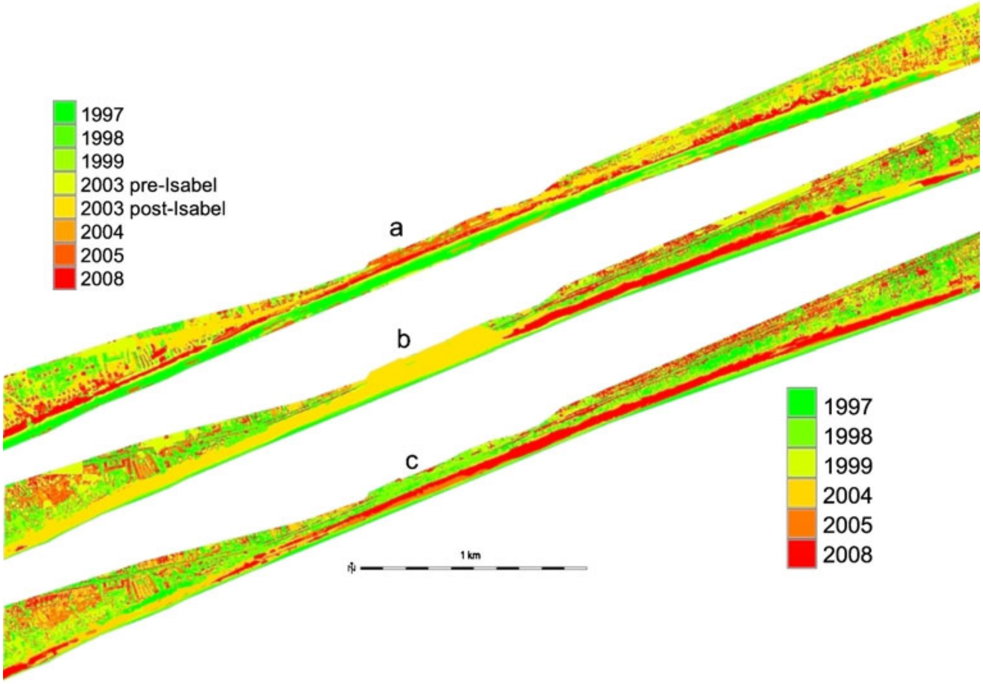


Fig. 6 Linear-regression results at the Hatteras site: **a** regression slope map, representing elevation increase (*green*) and decrease (*red*) rates, with stable areas shown in grey; **b** map representing spatial pattern of coefficient of determination r^2 where the areas with high r^2 experienced strong linear trend of elevation decrease (in our case due to beach and dune erosion) or increase (due to wind transport and overwash)

(computed as minimum and maximum elevations for each cell over 12 years) was 1.66 m and 3.29 m respectively, slightly higher than at the Hatteras site, but the core represented only 34% of the envelope volume and 56% of the most recent (2008) elevation surface volume. Mean standard deviation was 0.64 m, with the highest values observed on dunes and due to the new or lost homes (Fig. 8a). The regression coefficient map (Fig. 8b) showed the highest rates of elevation loss along the beach and oceantfront side of the dunes, while the inland area experienced modest rates of elevation growth. The standard deviation and regression slope values in Rodanthe were influenced by construction of new homes and loss of some older structures in the southern part of the study area.

Fig. 7 Maps representing: **a** the year of maximum elevation, **b** the year of minimum elevation with the dark yellow area representing locations where the elevation was at its lowest level after Hurricane Isabel (note that the dune north of the breach was not at its lowest post-hurricane in 2003, but more recently, in 2008), **c** year of minimum elevation derived without 2003 DSMs



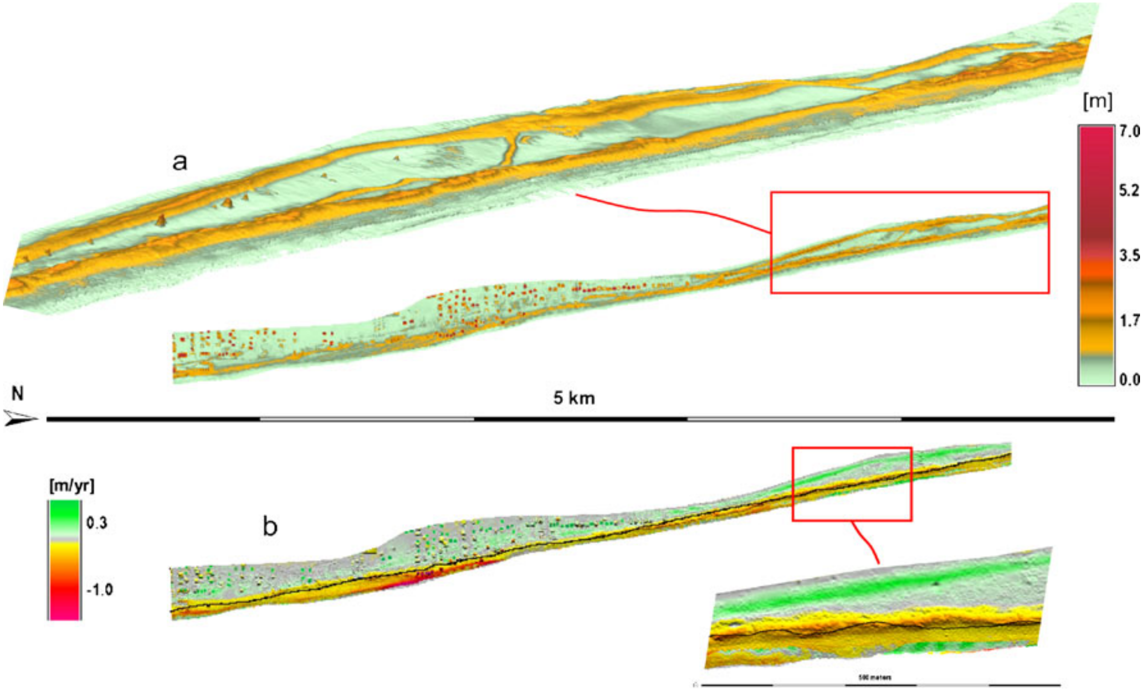


Fig. 8 Maps representing spatial pattern of elevation change at the Rodanthe site: **a** standard deviation map showing the most dynamic areas in red and stable areas in green; **b** linear regression slope map with elevation increase trends in green areas and elevation decrease trends in red areas

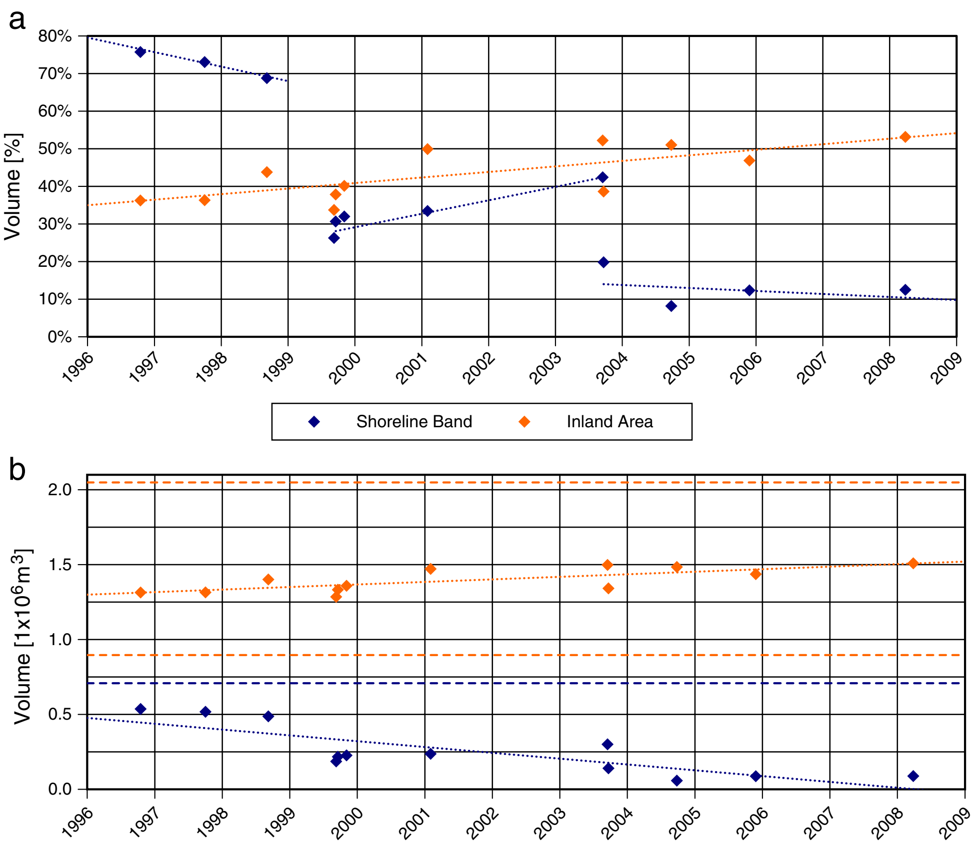


Fig. 9 Evolution of **a** relative volume as % of dynamic layer volume, and **b** total volume above the mean high water level within the shoreline evolution band (*blue*) and inland area (*yellow*). The three data points in 1999 are based on the post Hurricane Dennis surveys, the two points in 2003 are pre and post Hurricane Isabel surveys. The total volume of the inland area envelope and core is 2.05×10^6 m^3 and 0.90×10^6 m^3 respectively (*yellow dashed line*), while the total envelope volume within the shoreline evolution band is 0.71×10^6 m^3 (*blue dashed line*), and there is no core volume in the shoreline evolution band. The regression lines are not predictive but are only derived as an aid to the eye

However, their impact on standard deviation and regression slope values was negligible because the structures in Rodanthe only accounted for approximately 2% of the area and only a small fraction of homes were constructed or destroyed in any given year.

Relative volume change

In addition to the raster-based analysis, the relative volume of sand within the dynamic layer (Eq. 1, Fig. 8a) and total sand volume above the mean high water level (Fig. 8b) were computed for each year for two areas at the Rodanthe site:

- 0.222 km^2 beach area within the shoreline evolution band
- 0.548 km^2 inland area with dunes, located landward of the core (minimum) shoreline and bounded by the inland line of lidar data availability, to ensure full spatial and temporal data coverage.

Both the relative and total volumes measured within the shoreline evolution band decreased over time (Fig. 9). This was expected, as shore erosion is dominant through this study area. Only about 16% of the sand volume located within the shoreline band in 1996 remained in 2008, representing a loss of about 450,000 m^3. On the other hand, the volume within the inland area increased both as total volume and as percentage of the dynamic layer (envelope minus core). Approximately 15% more volume covered the area in 2008 than in 1996, an increase of about 200,000 m^3. Clearly the volumes were not offset and the overall trend was a net volume loss of about 250,000 m^3 between the years 1996 and 2008. The fate of the lost sand volume cannot be fully documented without incorporation of nearshore bathymetry measured simultaneously with topography (Browder and McNinch 2006) but there is evidence that at least a portion of this sand could be stored nearshore and transported back onto the beach (Fig. 9, post 1999 Hurricane Dennis volume increase). It is also possible that portion of the lost sand has been transported by overwash inland beyond the mapped area and remains on the island.

Changes in the relative volume (Fig. 9) were gradual for certain time intervals (e.g., years 1996 through 1998) and at times episodic (years 1999 and 2003). In the years 1999 and 2003, the area was subject to overwash as well as dune and shoreline erosion due to Hurricanes Dennis and Isabel. The rate of volume change was constant within the inland area (Fig 9a) while the rates within the shoreline band were highly variable without clear linear trend or acceleration.

Separating the shoreline evolution band area from the inland area brings to light a trend of dramatic loss of volume within the shoreline band and a modest increase in volume landward from the shoreline band, indicating possible island transgression. It also reveals the episodic loss and periods of recovery associated with hurricanes. This result is consistent with the result from regression slope analysis for both the Hatteras and Rodanthe sites that indicates systematic loss of elevation on the oceanside of the foredunes and modest increases in elevation on the landward side. Increased volume in the landward zone is consistent with both natural and anthropogenic activities. Overwash events carry sediment landward as do aeolian processes in the case of dune build-up. While post storm cleanup activities simply move sand around within the area, breach reconstruction and beach nourishment add sand to the system. In the Rodanthe study area, post storm cleanup was required after the two hurricanes, but no beach nourishment projects occurred during the time frame of the study.

Dynamics at selected elevation levels and shoreline band

To assess and compare dynamics at different elevation levels, contours were derived from the individual DSMs for each year, as well as for the core and envelope surfaces. Contour displacements were then measured for elevations relevant for beach and foredune processes, specifically the mean high water level elevation of 0.36 m, upper beach elevation of 1.5 m, and mid-dune 3 m elevation. The displacements were measured at 100 m intervals along a distance of 4.6 km using series of 46 parallel transects (Fig. 10). The shoreline displacement between the most recent lidar surveys, 2005 to 2008, was dramatic in some locations, eroding as much as 27.2 m (9.1 m/yr) and accreting more than 31.8 m (10.6 m/yr). However, the average displacement over the 4.6 km length of the study site was a minor 0.3 m (0.1 m/yr) of accretion. The shoreline displacement over the entire study period, 1996 to 2008, showed significant net erosion with an average of 35.0 m (2.9 m/yr), reaching maximum erosion of 73.9 m (5.7 m/yr) and only one spatially isolated instance of accretion of less than 5 m (0.4 m/yr). The shoreline displacement between the core and envelope (a band within which the shoreline evolved during the study period) was nearly 77.0 m at its widest and 26.7 m at its narrowest point, the average width of the band was 48 m.

The 2008 shoreline accounted for almost 80% of the core (minimum) shoreline, its remaining 20% length was associated with the post hurricane shorelines of the years 1999 and 2003 (Fig. 11). The 1996 shoreline overlapped with most of the envelope (maximum) shoreline. This is reflected in the graph (Fig. 10) where the shoreline displacement between 2008 and 1996 was close to the maximum displacement reflected in the difference between the core and envelope shorelines. There was a notable

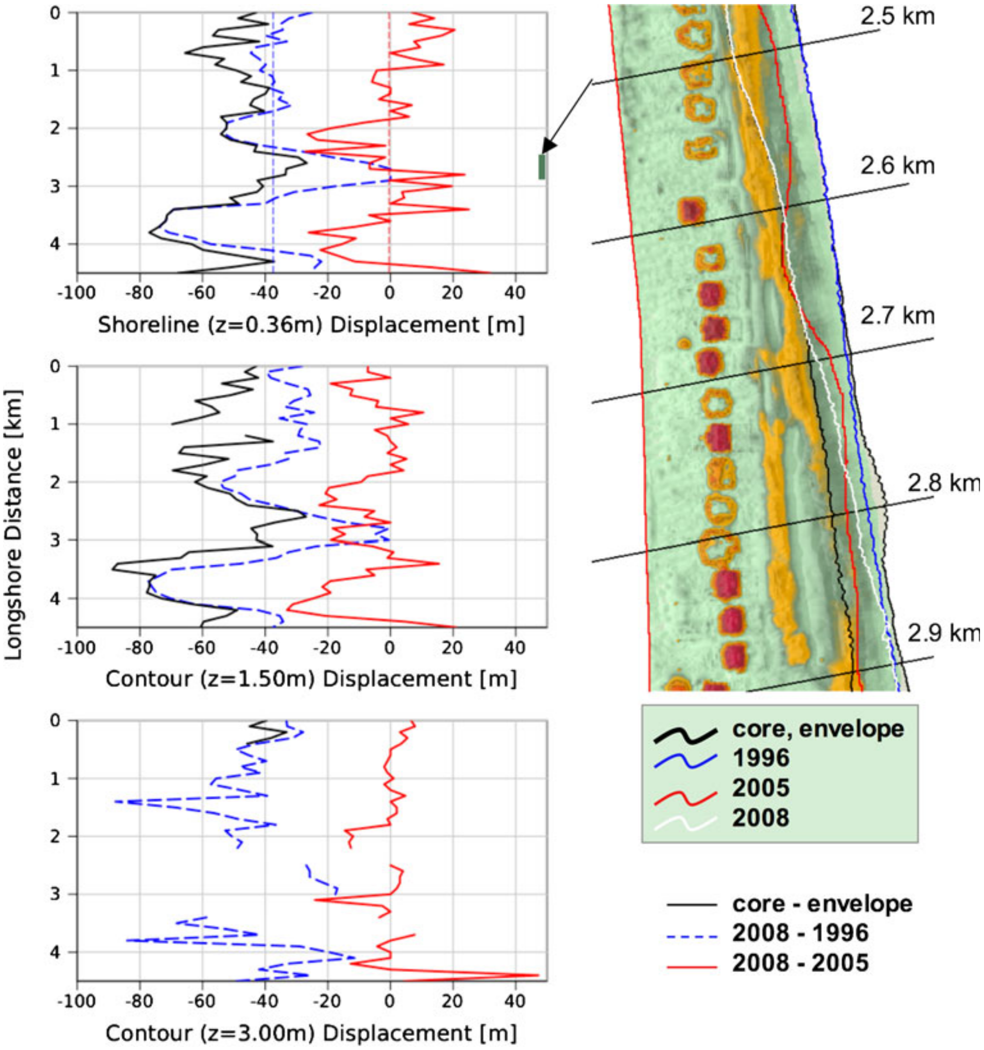


Fig. 10 Graphs (*left*) showing the displacement of elevation contours (0.36 m, 1.5 m, 3.0 m) over three time intervals: 1996 to 2008 (*blue*) representing change in the given contour over the entire study period; 2005 to 2008 (*red*) representing differences between the contours extracted from the two most recent lidar surveys; and difference between the contours extracted from the core and envelope (*black*) representing the maximum displacement. The negative values are erosion and positive values are accretion. Displacement locations are reported in km from the most northern measurement. The image inset illustrates the shorelines and transects used to compute the displacement at small subsection of the study site

exception at the 2.9–3.0 km section, where the 2008–1996 displacement was close to zero and the 2008 shoreline approached the 1996 shoreline (Fig. 10). However, the core-envelope displacement indicated that, at some point during the study period, the displacement at this location was more than −20 m (Fig. 11 shows that it was in 1999 and 2003). The displacement between the years 2005 and 2008 was closer to zero, with a small section around the 3 km

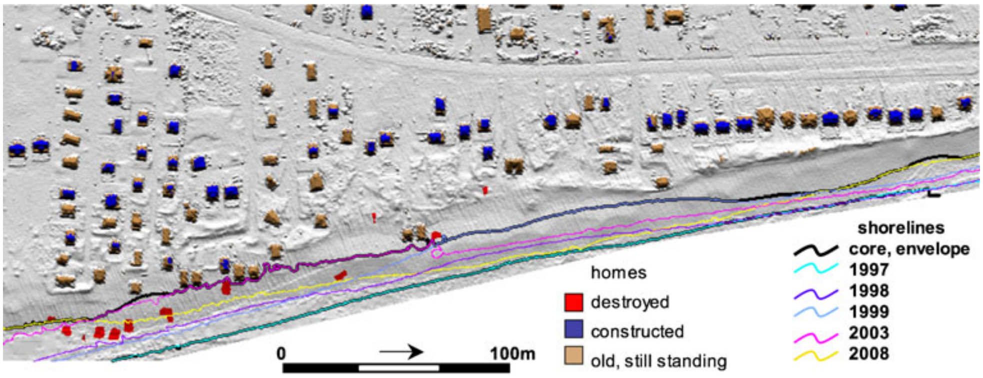


Fig. 11 Classification of homes as constructed or destroyed between the years 1997–2008 as identified by raster analysis of decadal series of lidar surveys. Envelope shoreline is in this section practically identical with the 1997 shoreline (*cyan over black line*) while the core (minimum) shoreline includes sections of 1999, 2003 (*post hurricane*) and 2008 shorelines. Apparently, the homes were destroyed by the 2003 Hurricane Isabel

marker of longshore distance experiencing significant accretion. The rate of shoreline change was highly spatially and temporally variable and was influenced by hurricane activity, no clear acceleration or deceleration in rates of shoreline erosion was observed during the 12 year study period, longer time series would be needed to identify such trends.

Areas of accretion and erosion along the shore appeared to be spatially periodic. This was evident in both the 1996 to 2008 and 2005 to 2008 displacements crossing the average displacement at approximately the same location. Elevation change in areas of the most dramatic erosion and accretion typically ranged between 0.5 and 1.6 m. The shoreline evolution analysis illustrates the significance of including short term variation in shoreline change assessments. Locations where the short term change is large and long term change is small can be misrepresented as stable if long term shoreline change rates are used.

The 1.5 m contour exhibited similar pattern of dynamics as the mean high water shoreline (Fig. 10) with the contour moving inland over most of its length except for a small section at the 3 km marker which appeared to be stable. A core-envelope difference curve for the mid-dune elevation (3 m) could be extracted only in the far north of the study region because the core of Rodanthe rarely exceeded an elevation of 3 m. This contour has also moved inland and its location has been relatively stable since 2005. The relatively uniform retreat of all three contours indicates that the entire beach-foredune system is retreating while the slope of the migrating beach remains relatively stable.

Buildings

The map algebra operations applied to core and envelope surfaces (Mitasova et al. 2009b) were used to efficiently extract locations of homes that were built or lost during the study period (Fig. 11). The homes where the difference between the core and envelope exceeded 10 m and, at the same time, the year of maximum elevation was smaller than the year of minimum elevation were classified as lost, while the home locations where the year of maximum was larger than the year of minimum were considered new construction. Of the 110 structures identified in the area, 47 were stable through the entire study period, 43 were constructed, and 20 were destroyed. Automated query at the centroids of the extracted buildings was used to identify the years when these buildings were lost or built, based on the change in elevation that exceeded the given threshold. The southern section of the Rodanthe study site that is experiencing rapid erosion contains many of the lost buildings, including the seven homes that were built within the current shoreline evolution band—an area that has been after the Hurricane Isabel in 2003 below mean high water level (Fig. 11).

Conclusion

Application of modern mapping technology and robust geospatial analysis provided new insights into short term evolution of coastal topography at two barrier island sections on the North Carolina coast. The raster-based approach extended the assessment of coastal dynamics beyond the traditional shoreline change by identifying stable core surface and dynamic layer and by mapping spatial patterns of decadal trends in elevation change using per cell linear regression. The trends were further quantified by deriving the shoreline evolution band and comparing volume change within this band with volumes landward from the core shoreline. The raster-based approach was also used to identify buildings that were built or lost over the past decade without the need for manual digitizing from imagery.

In the studied locations, the results highlight a very small stable core with mean elevation less than 1.7 m and a large proportion of the existing sand volume relocated or lost within the study period: an environment posing continuous serious challenges to development of buildings and road maintenance. Analysis of buildings revealed that many structures were built in locations with very small core and several homes located within the shoreline band were already lost. The results also indicate that a portion of the lost sand volume is transported inland, with beach and ocean side of foredunes experiencing decadal trend of decreasing elevation while the landward side of the dunes exhibits moderate increasing elevation trends, a pattern consistent with barrier island transgression. At the same time, the foredunes were identified as the most dynamic geomorphic features in terms of variation in elevation. Spatial and temporal variability in volume and shoreline change captured by this short term 12 year data is significant, driven by major storms as well as tides and seasonal variations without an apparent acceleration or stabilization of erosion rates. Although it was possible to map the erosion/accretion patterns at high level of detail, the underlying sand transport processes cannot be fully explained without incorporation of nearshore bathymetry measured simultaneously with topography (Browder and McNinch 2006) and aeolian processes.

The presented methods provide data analysis tools and procedures to establish detailed spatial patterns of short term change. These analyses and related visualizations such as the core surface and shoreline evolution band can communicate relative coastal hazard in a way that the traditional metric, averaged shoreline erosion rate, does not and can inform both engineering and public policy decisions. At present the international attention to climate change and the associated projections for sea level rise warrant increased monitoring of shoreline areas. Repeated lidar elevation surveys together with the proposed methodology would provide robust documentation of change upon which engineering and management decisions could be based.

Postscriptum note: while this paper was under review Rodanthe experienced major impact by a north eastern storm that ended the relatively stable period of 2005–2008 documented in this paper.

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