RUSS, EMILY REBECCA. Geospatial Techniques for Analyzing Storm Impacts and Visualizing Coastal Topographic Change on the Outer Banks. (Under the direction of Dr. Helena Mitasova).

Natural and anthropogenic processes are continuously shaping the North Carolina (NC) Outer Banks. As these barrier islands have been developed, it has become necessary to understand the effects of these different processes on the topography. Although human predictive capability of landscape evolution is limited, people can observe coastal change through remotely sensed data. Repeated light detection and ranging (LiDAR) surveys collected over the Outer Banks, which have both high accuracy and resolution, have presented an opportunity to study terrain evolution due to different processes such as storms, wind and wave transport, and anthropogenic modifications. This data can be imported into a geographic information system (GIS) and analyzed to better understand coastal geomorphology.

The NC Outer Banks are susceptible to storm impacts and, subsequently, storm surge flooding. In this study, a storm surge impact analysis was performed to assess and predict coastal vulnerability at the Outer Banks. The first component of this analysis was to reconstruct maximum water levels by identifying wrack lines in remotely sensed data collected after Hurricane Irene (2011). Although assessing inundation is useful, the ability to predict storms can influence emergency management decisions. Therefore, the wrack line analysis was used to verify the Advanced Circulation (ADCIRC) numerical model storm surge predictions. It was discovered that ADCIRC underestimates the maximum water level because it does not consider wave effects. However, these models are necessary in order to be prepared for storm events. ADCIRC is a computationally demanding model, and it is
applied over a low-resolution grid. Therefore, we coupled ADCIRC with a high-resolution spread inundation model, implemented using the open source Geographic Resource Analysis Support System (GRASS) GIS, to elucidate areas that are vulnerable to storm surge flooding. Grid resolution significantly impacted flooding extent, and the high-resolution digital elevation model (DEM) showed an intricately detailed inundation map.

Inundation modeling alone does not show coastal morphological changes. The multi-temporal LiDAR data over the Outer Banks were combined in a space-time (STC) to visually summarize coastal surface evolution. This STC method goes beyond previous analyses, such as feature extraction and 2D raster based methods because it allows the user to display a 3D surface in order to see spatiotemporal changes simultaneously. Isosurfaces were extracted in order to visualize evolution of an elevation contour and coastal landscape trends. These trends could then be associated with known processes such as storm impacts and anthropogenic activities.

Despite these advancements, our ability to predict how coastal processes will alter terrain is limited. Therefore, an exploratory vector field analysis, which depicts change was developed. These vectors illustrate the change in gradient direction and magnitude, as well as elevation at each grid cell. This analysis is still in a preliminary stage of development, but the goal is to use these vector fields to identify landscape patterns to aid in understanding morphological change in coastal settings.
Geospatial Techniques for Analyzing Storm Impacts and Visualizing Coastal Topographic Change on the Outer Banks

by

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DEDICATION

I would like to dedicate this thesis to my parents and brother who have always been my greatest supporters. I also would like to dedicate this to my boyfriend Andy who is the most levelheaded person I have ever met and encouraged me every step of this process. I appreciate each of you for keeping me focused, and I love you all.
BIOGRAPHY

Emily Rebecca Russ was born in the foothills of North Carolina in Morganton, NC, but developed a love for the NC Outer Banks at a young age through vacations to Ocracoke. This interest led her to obtain her Bachelor’s Degree from North Carolina State University in Natural Resources with a Marine and Coastal Concentration in May of 2011. She continued her education at NCSU in the Fall of 2011 to pursue a Master’s Degree in Earth Science.
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CHAPTER 1: Introduction

Barrier islands are narrow strips of land that make up nearly 15% of the world’s coastlines. These islands act as a buffer between the open ocean and back barrier estuarine systems and protect mainland areas from direct storm impact. The North Carolina (NC) Outer Banks are a 320-kilometer stretch of barrier islands between Cape Henry, Virginia and Cape Lookout, North Carolina (Inman and Dolan, 1989, Riggs et al. 2011). The Outer Banks are high-energy environments, and are continuously being shaped by wind, waves, astronomical tides, gravity, sea level rise, storm impacts, vegetation, animals, and humans.

A struggle has formed between these natural systems and anthropogenic activities as these barrier islands become more developed, and structures have been built with the intention of establishing permanence. The migratory nature of the Outer Banks, especially as a result of storm impacts, is in conflict with this development and poses major challenges to infrastructure management (Riggs et al. 2011).

Since record keeping began in the 1850s, over 300 tropical storm systems have come within 150 miles of North Carolina (NC Climate Office 2013). Coastal storms can cause billions of dollars’ worth of damage and loss of life. Low-lying areas are flooded, protective foredunes are flattened, stabilizing vegetation is destroyed, and new inlets are opened as a result of severe storms. Aeolian transport, vegetation growth, and human intervention also alter coastal landscapes. Due to the complex, multiscale interactions between these processes and landscape features, our understanding of coastal landscape evolution is incomplete and, predicting coastal topographic change is a challenge. Therefore, new technology and tools
are being utilized to study coastal terrain. Airborne light detection and ranging (LiDAR) data have been collected to represent topography at a snapshot in time. Since the mid-1990s, several LiDAR point clouds have been collected over North Carolina coastal areas, providing more than a decade’s worth of topographic data. Many of these collections were post-storm reconnaissance missions used to assess surface changes caused by storms. This unprecedented amount of LiDAR data, along with the improvement in data analysis tools, has allowed us to gain a better understanding of coastal geomorphology at the Outer Banks.

Geographic information systems (GIS) include powerful sets of tools that can be used to analyze surface changes through space and time. The purpose of the research presented in this work was to analyze storm impacts and visualize barrier island change caused by various natural and anthropogenic processes using elevation models derived from LiDAR data. In this study, all geospatial analyses were performed using the open source Geographic Resource Analysis Support System (GRASS) GIS (Neteler and Mitasova et al. 2008).

The second chapter of this thesis describes a storm surge impact analysis, which was developed using GIS methods, to assess and predict storm surge extent and potential inundation levels. The first component of this analysis was to employ high-resolution LiDAR data and orthoimagery to identify vegetative debris deposited after Hurricane Irene and reconstruct maximum water levels during the storm. This chapter also describes two models that can be used to estimate flooding from storm surge. The first is a simple spread inundation model that is applied to a high-resolution digital elevation model (DEM), and the second is Advanced Circulation (ADCIRC), a complex numerical model. The inundation
depths predicted by these models were assessed to evaluate whether they could be coupled to identify vulnerable areas in the terrain.

However, this storm surge analysis does not consider morphological changes from storm impacts or other coastal processes. Therefore, chapter three describes a spatiotemporal analysis, using the space-time cube approach, which was applied to visually summarize changes in coastal topography through both space and time in a single image. This approach was used to give a more comprehensive look at how coastal landscapes evolved, and help identify topographic patterns that could then linked to different coastal processes.

The space-time cube approach can show spatial and temporal surface changes, but these methods do not predict how different coastal processes will transform the surface. Therefore, an exploratory vector analysis method was developed in chapter four to help understand the deformation and migration of a coastal dune system. This analysis created a three dimensional (3D) vector field that showed the change in surface gradient and elevation between two years. The patterns in the vector field were used to identify how coastal processes shape terrain.

These analyses were applied at four study sites along the NC Outer Banks (Figure 1). Pea Island was selected to analyze storm surge impacts (Figure 2); Rodanthe was used for studying storm surge impacts and surface evolution through space and time (Figure 3); Cape Hatteras was chosen to visualize spatial and temporal terrain evolution (Figure 4); and Jockey’s Ridge was used to examine surface evolution and create vector fields that help identify coastal processes facilitating this change (Figure 5). The aim of these analyses was
to better understand processes impacting and shaping the NC Outer Banks and illustrate these changes through effective visualizations.

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CHAPTER 2: Geospatial Analysis of Storm Surge Impact: Reconstruction, assessment and prediction

2.1 Introduction

Flooding, or the inundation of normally dry land, is one of the most expensive and dangerous natural disasters that affects coastal areas. The North Carolina (NC) Outer Banks are highly susceptible to flooding from storm surges, as a result of their low elevation and frequent hurricanes, tropical storms, and nor’easters. The position of the Outer Banks causes these barrier islands to endure the brunt of storm surge impacts when a storm comes from offshore.

Storm surge levels are measured across the NC Outer Banks at three tidal stations from Duck to Cape Hatteras. However, the water levels recorded at these tidal stations are not necessarily representative of surge elevations across the entire Outer Banks because they can be highly variable. Another limitation to using tide gauges for storm surge measurements is that during the peak of a storm there is a strong possibility for stations to lose power (NHC 2013).

An alternative to using tide gauges to estimate the maximum water level is to survey high water marks. One type of high water mark is the deposition of vegetative debris, referred to as a wrack line. It usually represents the highest elevation the storm waters reached, including wave runup and setup, so the elevation is usually higher than a static surge elevation (NHC 2013). However, these high water marks are not collected during the storm, and they can be washed away by rain or cleaned up, so it is important to collect this...
information as soon as possible after the storm. Previous studies on the impacts of Hurricanes Emily (Bush et al. 1996) along the NC Outer Banks, Katrina in Alabama and Louisiana (FEMA 2006) and Tropical Cyclones Vance and Chris in Australia (Nott and Hubbert 2005) used wrack lines to reconstruct storm surge elevations. In these studies, on-site surveys were conducted to determine the elevation of the wrack line using the surveyor’s best judgment about its location.

Although the previously performed wrack line analyses determined storm surge elevation on the ground, current remote sensing technology has improved the ability to obtain an accurate location of a wrack line from high-resolution (submeter) orthoimagery and light detection and ranging (LiDAR) data, flown within a short time period after storm impact. The high-resolution imagery can be used to determine the spatial location of the wrack line, and the elevation at which the debris was deposited can be extracted from the LiDAR data. This method based on remote sensing technology is less expensive and labor-intensive than on-site collection (Clinch et al. 2012; Barnes et al 2008; Lane et al. 2003). However, to date there have been very few studies where remote sensing was used to estimate storm surge elevation (Clinch et al. 2012).

Wrack line analyses allow us to assess maximum storm surge height reached in a storm event, but it is even more important to predict the surge level before the storm so emergency management decisions can be made, especially if the area needs to be evacuated. The maximum height of a storm surge, and subsequently the extent of flooding, are difficult to assess and predict because storm surge levels are not only dependent on wind intensity, but on the shape of the coastline, the forward speed of a storm, the direction a storm is traveling
with respect to the coastline, atmospheric pressure gradients associated with the low pressure system, and storm system width as well. Storm surge heights are maximized at lower atmospheric pressure levels, causing a larger bulge in water surface elevations centered beneath the low-pressure system, when strong winds push large volumes of water against the shore, and when storm surges arrive during high tides (NOAA 2013).

The vulnerability of barrier islands to storm impacts has previously been assessed using a storm impact scale for barrier islands. This scale proposes four different storm regimes based on the water elevations relative to the dune toe and dune ridge (Sallenger 2000). Hardin et al. (2012) modified this impact scale to better identify the dune toes and ridges using geospatial techniques. In addition to this storm impact scale, modeling is often used to predict storm surge and to better grasp how it can impact a coastal region. Complex models are necessary for understanding how both topography and storm dynamics affect storm surge flooding. The United States Army Corps of Engineers (USACE) and the Federal Emergency Management Agency (FEMA) use the Advanced Circulation (ADCIRC) model to forecast storm surge elevations for Atlantic storms. ADCIRC is a numerical process-based hydrodynamic circulation model designed to simulate water levels and currents over an unstructured finite element grid (USACE 2004).

While ADCIRC has the capacity to predict storm surges over large areas, including where there are no tide gauges, it does have limitations. ADCIRC grid resolution varies between 4 km and 50 m, with the higher resolutions along more complex topography, such as coastlines and river mouths (Blanton and Luettich 2008). The flooding extent is affected by the grid resolution, and in areas with complex topography and bathymetry, distinct features
that can only be resolved at higher resolutions (< 50 m) may be missed, or overestimated, depending on where the grid node is located. ADCIRC is capable of predicting water levels and currents at one-second time intervals for large-scale simulations of storm events. Therefore, the initial computation of water levels and currents over the Western North Atlantic ADCIRC grid takes nearly 45 days to complete, and outputs over 20 GB of data (Baugh et al. 2013). Although the ADCIRC model can be downscaled to simulate storm events over a smaller area, setting up and running the predictions of subdomain models can still take over a day to complete.

Therefore, the objective of this research is to investigate whether a simple spread inundation model can be applied to a 0.5 m resolution DEM to supplement the output from the computationally demanding, lower-resolution ADCIRC model to improve understanding of coastal vulnerability in a storm event. In order to capture the impact of using high-resolution grids on coastal vulnerability, the inundation levels from the simple spread inundation model can be compared to the ADCIRC model to determine if this can augment the ADCIRC model forecast when delineating potential storm surge flooding.

2.2 Study Sites

The assessment of storm surge elevation based on wrack line location was investigated using the impact of Hurricane Irene (2011) over Hatteras Island as a case study, where there are no tide gauges along the 65 km stretch between Oregon Inlet and Cape Hatteras (Figure 2.1). The narrow barrier islands that extend south of Oregon Inlet, through the Pea Island National Wildlife Refuge (PINWR) to the village of Rodanthe, contain areas
along NC Highway 12 referred to as “hotspots” due to their vulnerability to storm impacts and long-term erosion (Mitasova et al. 2010, Stone et al. 1991). Approximately 73% of the shoreline between Oregon Inlet and Rodanthe exhibit long-term erosion, when the 1933/52 shoreline composite was subtracted from the 2009 shoreline (APNEP 2012). The average long-term rate of change between Rodanthe and Oregon Inlet is a loss of 1.07 meters per year; however, areas near Oregon Inlet have shown a long-term rate of erosion as high as 6.68 meters per year (APNEP 2012; NCDCM 2011).

On August 27, 2011, Hurricane Irene, a category 1 storm on the Saffir-Simpson scale, made landfall near Cape Lookout, North Carolina and tracked northward through the Pamlico Sound (Figure 2.2). Hurricane Irene caused large storm surges, up to 2.1 m at Oregon Inlet, and up to 1.9 m at the USACE Duck Field Research Facility (FRF), directed from the soundside of the island, as winds pushed water east in the Pamlico Sound (Figure 2.3), subsequently leading to 2 breaches along NC Highway 12. The more severe breach occurred south of a series of freshwater ponds in the PINWR and is referred to as the Pea Island Breach. The other breach occurred on the north side of the village of Rodanthe, in Mirlo Beach, which will be referred to as the Rodanthe Breach (Clinch et al. 2012; NOAA 2011). Both breaches formed within two of these NC Highway 12 hotspots.

The Pea Island Breach formed within the “Old Sandbag Area” hotspot, which is a 4.1 km stretch within the PINWR, approximately 13 km north of the village of Rodanthe and 10 km south of Oregon Inlet, where erosion rates are between 3 and 4 meters per year (OBTF 2013a). PINWR contains beach, dunes, upland areas, fresh and brackish water ponds, salt flats, and salt marshes, which provides nesting, resting, and wintering habitats for migratory
birds as well as protection for endangered species. The island is minimally developed and only contains three U.S. Fish and Wildlife Service buildings and NC Highway 12. The lack of development is ideal for conducting a wrack line analysis so the debris will not be obstructed by any structures (USFWS 2013). The Pea Island Breach opened where topography was low, near the marsh islands west of Hatteras Island and within the historic New Inlet complex that last opened from 1933 to 1945 (NCDOT 2012; Mallinson et al. 2008). Despite continued shoreline erosion and the formation of the Pea Island Breach, NC Highway 12 cannot be moved west of its current location due to its proximity to the PINWR (Mitasova et al. 2010). A temporary bridge, constructed by NCDOT, covers the breach, which filled with sand as of May 2013, but more permanent solutions are being considered (NCDOT 2012).

The Rodanthe Breach formed within the “Rodanthe ‘S’ Curves” hotspot, which is a curved 3.9 km section on NC Highway 12, approximately 1 km north of the village of Rodanthe, where erosion rates reach up to 4.6 meters per year (OBTF 2013a). The barrier islands south of PINWR along the “S Curves” are mostly undeveloped, until Mirlo Beach, just north of the village of Rodanthe, an area that has experienced a significant increase in development over the past 20 years. The Rodanthe Breach, almost 8 km south of the Pea Island Breach on NC Highway 12, formed after Hurricane Irene, due to flooding of a man made channel that runs between NC Highway 12 and the Pamlico Sound (NCDOT 2012). This breach filled in naturally shortly after storm impact (Clinch et al. 2012). NC Highway 12 has been moved landward several times in the past 30 years in response to high rates of shoreline erosion. Other practices have been implemented to protect NC Highway 12 such as

Figure 2.1 Study site images: Pea Island and Rodanthe Breach locations (Imagery obtained from Google Earth, August 29, 2011).
2.3 Data

High-resolution data and orthoimagery were analyzed to assess the peak storm surge level, and to model storm surge flooding. Light detection and ranging (LiDAR) data were collected over Hatteras Island after Nor’Ida in 2009 by United States Geological Survey.
(USGS) and after Hurricane Irene in 2011 by National Oceanic and Atmospheric Administration (NOAA) (Table 2.1). The LiDAR data point clouds were used to compute 0.5 m-resolution raster digital elevation models (DEMs) using the bivariate regularized spline with tension interpolation method (Mitasova et al. 2005a). The DEMs were projected in the North Carolina State Plane coordinate system, units (m), and referenced horizontally to the North American Datum 1983 (NAD83) and vertically to the North American Vertical Datum 1988 (NAVD88).

The accuracy of the interpolated DEMs was evaluated by extracting elevations along the NC Highway 12 centerline. This was done by comparing the elevation along the road centerline in the interpolated DEMs with high-accuracy NCDOT benchmarks (OBTF 2013b), which were located along the NC Highway 12 centerline as well, as described in Mitasova et al. 2009. The differences between elevations in each DEM and the benchmarks were calculated, and the median difference, a constant value, for each was subtracted from the corresponding DEM. After Hurricane Irene, several of the benchmarks at the Pea Island and Rodanthe sites were damaged or buried, as seen in post-Hurricane Irene imagery, and could not be used to correct the systematic errors associated with the DEMs. Therefore, instead of using benchmarks, points were digitized at equal intervals along the NC Highway 12 centerline throughout both study sites, and compared to the corrected 2009 DEM. Several of the digitized points were in areas where the road was damaged or where it was covered with sand, so many of these points were not used (Figure 2.4). The 2009 DEM was chosen as the baseline to compare the 2011 DEM since the road elevation should be similar, as it had not been paved between these two surveys. However, the systematic errors were not constant
in the 2011 data across the Pea Island study site, but followed a linear trend. This trend was subtracted from the 2011 DEM to produce a corrected DEM. A constant value, which was the median difference between the benchmark and DEM elevations, was subtracted from 2011 DEM at the Rodanthe study site.

Figure 2.4 Elevations along the NC 12 centerline derived from the uncorrected DEMs at Pea Island Study Site (top) and Corrected DEMs (bottom).

Table 2.1 Pea Island and Rodanthe Elevation Data

<table>
<thead>
<tr>
<th>Date</th>
<th>Agency</th>
<th>Collection Information</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/01/2009</td>
<td>NPS/USGS/</td>
<td>Experimental Advanced Airborne Research LiDAR (EAARL)</td>
<td>Vertical: 0.2 m</td>
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<tr>
<td></td>
<td>NASA</td>
<td></td>
<td>Horizontal: 0.75 m</td>
</tr>
<tr>
<td>08/29/2011</td>
<td>NOAA</td>
<td>Riegl Q680i-D system for Emergency Response Program</td>
<td>Vertical: &lt;0.30 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Horizontal: &lt;1.0 m</td>
</tr>
</tbody>
</table>

In addition to LiDAR data, 0.35 m resolution orthoimagery collected on August 28, 2011 after Hurricane Irene was acquired to identify the location of vegetative debris. This
imagery was also compared to pre- and post-Hurricane Irene 0.15 m resolution orthoimagery to assess vulnerability prior to Hurricane Irene and show how the study sites recovered after impact (Table 2.2).

Table 2.2 Pea Island and Rodanthe Orthoimagery

<table>
<thead>
<tr>
<th>Date</th>
<th>Agency</th>
<th>Collection Information and Purpose</th>
<th>Horizontal Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/11/2010</td>
<td>NC CGIA</td>
<td>NC Statewide; Provide up to date imagery for state agencies. Use for this project: Aid in emergency response, hazard mitigation, and flood insurance map delineation</td>
<td>0.15 m</td>
</tr>
<tr>
<td>8/28/2011 Post-Irene</td>
<td>NOAA</td>
<td>Support national security and emergency response following Hurricane Irene</td>
<td>0.35 m</td>
</tr>
<tr>
<td>2/28/2012</td>
<td>NC CGIA</td>
<td>Collected for NC coastal counties only to support 911 communications and base mapping in local governments</td>
<td>0.15 m</td>
</tr>
</tbody>
</table>

Digital line data in ArcGIS shapefile format were used to provide spatial context and to perform wrack line analysis, and these included:

- Dare County Boundary and shoreline, with Pea Island Breach (NCDOT)
- Deposited vegetative debris (wrack line) digitized at PINWR (Clinch et al. 2012)
- 45 transects spaced 50 m apart along study site (Clinch et al. 2012)

2.4 Methods

The Pea Island Breach wrack line analysis and inundation modeling methods were originally described in the paper *Hurricane Irene and Pea Island Breach: Pre-Storm site*
characterization and storm surge estimation using geospatial technologies (Clinch A.S, Russ, E.R., Oliver, R.C., Mitasova, H., and Overton, M.F. 2012). The methods described in the Clinch et al. (2012) paper were refined and independently rerun (outside of the Clinch et al. 2012 study) for the Pea Island Breach site and then applied to the Rodanthe Breach site.

2.4.1 Wrack Line Analysis

Georeferenced post-Hurricane Irene orthoimagery was used to digitize the location of the wrack lines near the Pea Island and Rodanthe Breaches. Wrack line points were selected manually by zooming into the imagery, at locations where the vegetative debris was visible. Then, a line representing the wrack line was digitized. Points were only digitized where man-made structures and thick vegetation did not obstruct the vegetative debris. Sometimes multiple wrack lines were identified, somewhat parallel to each other; in such case, the wrack line that was deposited at the highest elevation was chosen. Once significant wrack lines were digitized, parallel transects, nearly perpendicular to the shore and NC Highway 12, were generated at 50 m intervals across the study sites. The imagery, digitized wrack lines, and transects were draped over the pre- and post-Hurricane Irene DEMs. The elevation values for the wrack lines were then extracted from both DEMs along transects, where the digitized wrack line was present, and compiled into a table (Appendix A). Statistical analyses were performed to find the average, median and standard deviation of the wrack line elevations for both 2009 and 2011 DEMs.
2.4.2 GRASS GIS Spread Inundation Model

To further improve understanding of storm surge flooding extent, a simple inundation model was applied to the pre-Irene DEM using GRASS GIS software to visualize inundation. This simple inundation model was used to determine the spatial extent of potential inundation when a DEM was flooded to specific water levels (surge elevations). Poulter and Halpin (2008), describe three inundation techniques, which vary in raster cell connectivity, that were applied in a sea level rise study in the North Carolina coastal plain. The first method used the ‘zero-side rule’ where it is assumed there is no connectivity between cells; this is usually referred to as a bathtub model because only a single cell is being filled. The other two methods, the ‘four-side rule’ and the ‘eight-side rule’ assume flooding spreads based on cell connectivity. The ‘four-side rule’ assumes water only spreads to cells that share a full side with a flooded cell (directly north, east, south, or west), which usually underestimates flooding extent, while the greater connectivity method using the ‘eight-side rule,’ which assumes that flooding spreads to all eight cells that are connected, causes overestimates in the flooding extent (Poulter and Halpin 2008).

The inundation tool in GRASS, r.lake, is based on the ‘eight-side rule’ (eight flow directions, D8) and has been applied to model sea-level rise (Poulter and Halpin 2008, Gesch 2009). Mitasova et al. (2012); Starek et al. (2011); and Tateosian et al. (2010), investigated the application of coastal flooding as a result of landscape modification using the r.lake GRASS function. The required inputs for this model are the DEM that is being flooded, the water level applied to create a ‘lake’, and the coordinates of the seed point where the flooding will be initiated. The model uses a 3x3-moving window to determine if cells in the
DEM will be filled to the specified water level. To initiate flooding, the water level at the seed point, which is at the center of a 3x3 window, cannot contain a null value and the water level needs to be greater than the elevation at the seed point. The eight cells that surround the seed point in the 3x3 window are inundated if they are not null values and if the cell elevations are below the specified water level. Then, all of the cells that have been inundated become the center of their own 3x3 window (the moving window concept), where the eight cells in this new 3X3 window are checked to see if they fit the criteria in order to be filled. If one of the cells that is contiguous to a flooded cell has a higher elevation than the water level, it will not be filled, and the cells surrounding this cell will not be checked, since this cell acts as a barrier. The flooding will continue to spread as long as there is connectivity (inundated cells) between cells with elevations lower than the water level and the seed point because the flooded cells cannot be discontinuous (Figure 2.5). In this analysis, the most vulnerable areas are low-lying topography connected to either the ocean or sound, depending on the track of the storm. The output map that is produced will correspond to water depth, which is the elevation of the cell subtracted from the water level (Neteler and Mitasova 2008).
The pre-Irene DEM at the Pea Island and Rodanthe Breach sites were flooded from single, soundside seed points at 0.1 m increments, starting at 0.4 m, which is 0.04 m higher than mean high water relative to NAVD88 at the study sites, to the average maximum surge elevations obtained from the wrack line analysis to reconstruct Hurricane Irene surges.

### 2.4.3 Surge Inundation Modeling using wrack line elevation, ADCIRC and spread model

The average elevation of the wrack line was used to estimate the maximum water level during Hurricane Irene. Using the spread inundation model, the maximum wrack line elevation was applied to the 2009 DEM to reconstruct the flood extent during Irene. The maximum surge elevation predicted by ADCIRC during Hurricane Irene, which was found at Renaissance Computing Institutes’s (RENCI) Coastal Emergency Risks Assessment (CERA) website, was also applied to the 2009 DEM at both study sites. The inundation maps
constructed from the average wrack line elevation were compared to the maps created using the maximum ADCIRC prediction to verify model accuracy during Hurricane Irene.

The next part of the inundation analysis was to compare the ADCIRC inundation forecast results for Hurricane Irene, available through the CERA website, to the spread model inundation results and determine if the potential inundation depths between the models were consistent (CERA 2013). Although the ADCIRC model may not reflect the true water levels reached during storm conditions, comparing ADCIRC to a high-resolution inundation model can help improve flood predictions. ADCIRC uses a set of equations to describe ocean and coastal circulation. It requires three inputs to calculate the storm surge: a finite element mesh with bathymetric/topographic information, boundary conditions that define land and forcing boundaries, and meteorological forcing. Then, water velocities are calculated by solving momentum equations and water elevations are calculated by solving the depth integrated continuity equation in the generalized wave continuity equation (GWCE) (Pei et al. 2013; Luettich et al. 1992).

The pre-Irene DEMs at the two study sites were masked so only elevations above 0 m were shown. Random points were generated, using a random point generator in GRASS GIS, over the masked pre-Irene DEM at both study sites to ensure that the inundation depths were sampled evenly over the study sites. Then, the maximum water height (surge elevation) and the inundation depth above ground, predicted by the ADCIRC model, were recorded for each of the random points by inspecting the attributes on the CERA website. The inundation depth was the difference between the water level that the DEM was flooded to and the topography elevation. The DEM was flooded to the various surge elevations using the
spread inundation model, depending on the surge elevation at each random point predicted by ADCIRC. Then, the random points were queried on the flooded DEM to obtain inundation depths predicted by the spread model. The ADCIRC and the spread models inundation depths were compared to determine the variation in inundation between the models. If the spread model predicted the area to be inundated, but the ADCIRC model did not, it was recorded as an ADCIRC null, and if the ADCIRC model predicted flooding and the spread model did not, it was recorded as a spread null.

2.5 Results

The wrack line elevations were compiled into a table and the average elevation was used as an input for the maximum surge level in the spread inundation model to assess potential storm surge flooding during Hurricane Irene. Also, the inundation depths from the GRASS and ADCIRC models were compared to determine if running the models together could elucidate where topography is more vulnerable to flooding, and address how including a high-resolution DEM with ADCIRC can aid in predicting flooding extent.

2.5.1 Wrack Line

The wrack line analysis was applied at the Pea Island and Rodanthe Breach study sites to reconstruct the maximum surge elevations during Hurricane Irene. As illustrated in Figure 2.2, Hurricane Irene was a soundside storm, which caused debris to be carried from the Pamlico Sound and deposited as a semi-continuous wrack line on the soundside of the barrier island dunes.
Recent orthoimagery that was collected yearly between 2010 and 2012 was compared in Figures 2.6 and 2.7 to demonstrate how the land cover changed at the two study sites over a short time period. In Figure 2.6, the post-Irene shoreline is superimposed over the Pea Island imagery to show where the breach formed. In the Pea Island 2010 image, Figure 2.6A, there are three visible overwash fans, where the dunes were degraded due to Nor’Ida in 2009 (Clinch et al. 2012). The breach channels formed in the same area as the overwash fans as evidenced in Figure 2.6B. Figure 2.6C highlights the dynamic nature of the breach, where the southern channel filled in, and the main channel migrated south. Land cover differences can also be detected by comparing the three images at the Rodanthe site in Figure 2.7. Since the Rodanthe Breach filled in shortly after opening, there is no breach in the post-Irene shoreline at the Rodanthe site, and the shoreline shapefile was omitted from Figure 2.7. Figure 2.7B shows the breach, which formed along a ditch that can be seen in Figure 2.7A. The breach to the oceanside had closed by 2012, but the ditch remains visible in Figure 2.7C. It is important to note that the southern portion of the Rodanthe study site is highly developed, which is why the wrack line analysis was performed north of the Rodanthe breach, along a 1.5 km undeveloped section of the barrier island.
Figure 2.6 Orthophotographs of Pea Island study site taken on A) April 11, 2010, B) August 29, 2011, and C) February 28, 2012. The post-Irene shoreline is superimposed over the Pea Island Imagery (black lines) to show where the breach formed.

Figure 2.7 Orthophotograph of Rodanthe study site taken on A) April 11, 2010, B) August 29, 2011, and C) February 28, 2012.
Coastal evolution through time is also visible when comparing pairs of DEMs. The 2009 data was used in Clinch et al. 2012 for wrack line analysis since the 2011 LiDAR data was not available at the time of writing. However, the post-Irene orthoimagery and LiDAR data were collected within one day of each other making the 2011 DEM more representative of the maximum surge elevations resulting from Hurricane Irene. While the most distinct change at study sites between 2009 and 2011 were the breaches, Figures 2.8C and 2.9C shows subtler changes in elevation, such as a slight increase in elevation at the wrack line locations, between the DEMs at Pea Island and just north of Rodanthe, respectively.
Figure 2.8 DEM of Pea Island Study Site on A) December 1, 2009, B) August 29, 2011, and C) the difference between A and B with wrack line overlaid (black line).
Transects were generated every 50 m throughout both study sites to ensure that the wrack line elevations were extracted evenly over the whole study area (Figures 2.10 and 2.12). The high-resolution (0.35 m) orthoimagery provided sharp detail to aid in the digitization of the wrack lines. In the close-up imagery in Figures 2.11 and 2.13, the wrack lines are distinct from other land cover types.
Figure 2.10 Post-Irene orthophoto overlaid with digitized wrack line figure and transects at Pea Island study site.

Figure 2.11 A) Close up of deposited vegetative debris at Pea Island study site and B) Same image overlaid with wrack line.
Figure 2.12 Post-Irene orthophoto overlaid with digitized wrack line and transects at Rodanthe study site.

Figure 2.13 A) Close up of deposited vegetative debris at Rodanthe study site and B) Same image overlaid with wrack line.
The elevations of the digitized wrack lines were extracted from the 2009 and 2011 DEMs (Figures 2.14 and 2.15) and compiled into Table A.1 for Pea Island and into Table A.2 for Rodanthe (Appendix A). The wrack line elevations are compared at Pea Island and Rodanthe in Figure 2.16. The wrack line elevation statistics: average, median, and standard deviation for both the 2009 and 2011 DEMs are reported in Table 2.3 for Pea Island and in Table 2.4 for Rodanthe. The average and median wrack line elevations were higher by nearly 0.20 m in 2011 at 2.71 m and 2.72 m, respectively, than in 2009 at 2.50 m and 2.57 m, while the standard deviation was smaller in 2011 by 0.11 m, at 0.29 m, throughout the Pea Island study site. The difference between the 2009 and 2011 elevations at the Rodanthe site were comparable to the differences found at the Pea Island site. The average and median wrack lines elevations were 0.18 m higher, at 3.00 m and 2.93 m, in 2011 than in 2009, while there was a standard deviation of 0.26 m. The smaller standard deviations in 2011 suggest that the elevation was less variable at the wrack line location in the post-Irene DEM.
Figure 2.14 Wrack line and transects overlaid on A) 2009 DEM and B) 2011 DEM at Pea Island Breach, used to extract elevations.

Figure 2.15 Wrack line and transects overlaid on A) 2009 DEM and B) 2011 DEM north of Rodanthe site, used to extract elevations.
Figure 2.16 Hurricane Irene wrack line elevation comparison between 2009 and 2011 DEM at Pea Island (top) and Rodanthe (bottom).

Table 2.3 Pea Island Wrack Line Statistics

<table>
<thead>
<tr>
<th>Year</th>
<th>Average Elevation (m)</th>
<th>Median Elevation (m)</th>
<th>Standard Deviation (m)</th>
</tr>
</thead>
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<tr>
<td>2009</td>
<td>2.50</td>
<td>2.57</td>
<td>0.40</td>
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<tr>
<td>2011</td>
<td>2.71</td>
<td>2.72</td>
<td>0.29</td>
</tr>
<tr>
<td>Difference</td>
<td>0.21</td>
<td>0.15</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Table 2.4 Rodanthe Wrack Line Statistics

<table>
<thead>
<tr>
<th>Year</th>
<th>Average Elevation (m)</th>
<th>Median Elevation (m)</th>
<th>Standard Deviation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>2.82</td>
<td>2.75</td>
<td>0.36</td>
</tr>
<tr>
<td>2011</td>
<td>3.00</td>
<td>2.93</td>
<td>0.26</td>
</tr>
<tr>
<td>Difference</td>
<td>0.18</td>
<td>0.18</td>
<td>0.10</td>
</tr>
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</table>

2.5.2 Inundation Analysis

Figures 2.17 through 2.20 demonstrate how vulnerable the topography was to varying levels of inundation at the two study sites following Nor’Ida. The DEMs were flooded gradually, but it is evident that a 1 m surge can flood low-lying topography (Figures 2.17B and 2.18B). When Pea Island (Figure 2.17D) and Rodanthe (Figure 2.18D) were flooded to
2.0 m, the water spread from the sound to the ocean through a path where the foredunes were degraded below 2.0 m. These low foredunes were located at a small driveway, approximately 7 m wide, for the Fish and Wildlife buildings, along existing overwash fans at Pea Island, and in the highly developed area, where Rodanthe oceanfront homes were unprotected. Figures 2.19 and 2.20 are displayed in 3D to help visualize the potential inundation during maximum storm surge at Pea Island and Rodanthe during Hurricane Irene. While these results most likely overestimate flooding extent because they were generated using the D8 inundation algorithm, the maximum elevation of water on the dunes closely match the location of the digitized wrack line. This is because the spread model is dependent on topography and cell connectivity. At Pea Island, the maximum water level applied was 2.5 m, and the floodwaters reached this elevation on the backside of the foredunes, but these dunes acted as a barrier for the flood. However, there were areas on the foredunes that were below 2.5 m, and the water was able to spread through to the oceanside, flooding everything below 2.5 m.
Figure 2.17 2009 DEM at Pea Island flooded to A) 0.4m, B) 1.0m, C) 1.8m, and D) 2.0m.
Figure 2.18 2009 DEM at Rodanthe flooded to A) 0.4m, B) 1.0m, C) 1.9m, and D) 2.0m
Figure 2.19 3D 2009 DEM at Pea Island (overlaid with Post-Irene orthophoto and wrack line) flooded to the average wrack line elevation of 2.5m.

Figure 2.20 3D 2009 DEM at Rodanthe (overlaid with Post-Irene orthophoto) flooded to the average wrack line elevation of 2.82m.
2.5.3 Inundation Model Comparison

The maximum water level predicted by ADCIRC for Hurricane Irene was compared to the spread inundation model flooded to the average wrack line in order to verify model accuracy. Model output from ADCIRC predicted a maximum surge elevation of 1.4 m at the Pea Island site, while the average wrack line elevation was 2.5 m. At Rodanthe, the maximum surge elevation prediction was 2.0 m and the average wrack line elevation was 2.82 m. Also, known water levels, measured during or after Hurricane Irene, were compared to the inundation depths predicted by the ADCIRC model in Table 2.5 (USGS 2013). The ADCIRC model surge elevations and inundation depths are displayed at maximum zoom in Figure 2.21 for the Hurricane Irene forecast. In Figure 2.22, the Pea Island DEM was flooded to three different levels, based on the different surge elevations output by ADCIRC in the area, while Figure 2.23 shows the Rodanthe DEM flooded to three different surge levels, predicted by ADCIRC forecast. The inundation depths predicted by the ADCIRC storm surge model and reconstructed by the spread models were recorded in Table A.3 for Pea Island and A.4 for Rodanthe (Appendix A). The average difference between the spread model and ADCIRC inundation depths was 0.328 m, the median was 0.443 m, and the standard deviation was 0.308 m at the Pea Island study site. Also, 31% of the inundation depths were higher in the spread model, 12.5% were higher in the ADCIRC forecast, and 33% more of the points were inundated in the ADCIRC forecast. The average difference between the spread model and ADCIRC inundation levels was -0.093 m, the median was -0.232 m, and the standard deviation was 0.330 m at the Rodanthe study site. Also, 33% of the inundation depths were higher in the spread model, 22% were higher in the ADCIRC
forecast, 39% more of the points were inundated in the ADCIRC forecast, and only 5.6% more of the points were inundated in the spread model.

Figure 2.21 ADCIRC Surge Elevations (top) and inundations depths (bottom) at the Pea Island and Rodanthe study sites.

Figure 2.22 2009 Pea Island DEM with random points overlaid, flooded to 0.6m (left), 0.7m (center), and 1.4m (right).
Figure 2.23 2009 Rodanthe DEM with random points overlaid, flooded to 0.6m (left), 1.7m (center), and 2.0m (right).

<table>
<thead>
<tr>
<th>Measurement Source</th>
<th>Location</th>
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<th>ADCIRC Surge MSL (m)</th>
<th>Difference (m)</th>
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<td>1.6</td>
<td>0.84</td>
</tr>
</tbody>
</table>

2.6 Discussion

Wrack line analyses and inundation modeling can be important for understanding storm impacts on coastal areas. These can aid in delineating flood level boundaries, creating inundation maps for visualization, determining insurance premiums in flood prone areas and creating Flood Insurance Rate Maps (FIRMs), as well as helping coastal emergency managers develop effective evacuation plans.
2.6.1 Wrack Line Accuracy

Error is inherent to all remotely sensed data and can result from acquiring, processing, analyzing, and converting data (Lunetta et al. 1991). Although the LiDAR data had published vertical accuracies between 20 and 30 cm, it may contain errors due to collection and processing, which could significantly alter the topographic analysis results in coastal areas. The systematic error correction should remove those errors resulting from inaccuracies in data registration; however, since the value removed is based on the median, mean, or trendline of errors in the dataset, local error residuals remain, especially in locations with steeper slopes or vegetation (Mitasova et al. 2009).

Hurricane Irene caused approximately 6100 m$^3$ of sand to be deposited on NC Highway 12, north of Rodanthe, as calculated by summing up the difference in elevation between the 2009 and 2011 DEMs. This storm-deposited sand led to difficulties in correcting the systematic errors at the study site. Also, the 2011 LiDAR data contained vertical errors of 1 m in some areas. After removing the errors in the 2011 data, the residual errors along the road were only ±10 cm, which is within the vertical accuracy of the LiDAR data.

The average difference between the wrack line elevations in 2011 and 2009 is +20 cm at the Pea Island Breach and +18 cm at the Rodanthe Breach, which are within the LiDAR vertical accuracy. Since the difference in wrack line elevations is within the vertical accuracy, the difference in elevation between the years may be negligible. However, wrack line elevations at both study sites were consistently higher in 2011, and the difference in
elevation was in the outer limits of the LiDAR vertical accuracy, which could mean that the accumulation of debris that formed as a wrack line created a slight rise in elevation.

Although the post-Irene LiDAR data and orthoimagery were collected within one day of each other, the LiDAR data took longer to process before they became publically available. Therefore, it was beneficial to have a recent LiDAR dataset, the 2009 data in this example, to compare with post-storm orthoimagery and use to reconstruct storm surge elevations (Clinch et al. 2012). The statistical differences between the two datasets were within the LiDAR vertical accuracy, so the 2009 data was a reasonable proxy for determining maximum storm surge elevations using wrack line data. However, caution needs to be taken when using LiDAR data collected after a storm event, like Nor’Ida, where dune and shoreline erosion would have occurred, as it is likely that these areas were rebuilt by the USACE and NCDOT.

Another source of error results from the manual process used to digitize the wrack line from orthoimagery. Most high water mark elevations are dependent on the surveyor’s best judgment of its location, and this method using remote sensing data was no exception, since zooming into the imagery to manually digitize the wrack line points was used. The high-resolution orthoimagery allowed the user to easily distinguish the wrack line from other land cover types. However, methods by Barnes et al. 2008 and Lane et al. 2003, demonstrate that this process could be automated, using image processing, but it still required some manual input, like the clipping of the study area, to reduce incorrect classifications. In future studies, wrack line elevations extracted from the orthoimagery and DEMs should be
compared with elevations collected on site after storm impact to better understand the error from using remotely sensed data.

### 2.6.2 Inundation Analysis

The spread inundation model does not consider storm dynamics, such as wave effects or storm duration, but is dependent upon elevation and cell connectivity. The D8 spread algorithm typically overestimates the flooding extent because the same water level is applied to all cells that have lower elevations and are connected to an inundated cell (Poulter and Halpin 2008). Once the water level was greater than the lowest point in the foredunes, most of the area, on both sound and oceansides, was inundated. However, most of the area on the oceanside would not have been flooded from a soundside surge unless surge conditions were persistent over a long period of time. Therefore, the higher the surge, the more likely the inundation model will overestimate the storm surge extent because it assumes that all cells with elevations lower than the water level that are connected to the seed point will flood. Also, since this inundation model simulated Hurricane Irene, a soundside storm, there were few barriers that would have prevented the water from flooding the back barrier system, compared to an oceanside storm where the foredunes would protect the topography behind (to the west of) them. The 3D DEMs that were flooded to the average wrack line elevation inundate a large area of both of the study sites because of low points along the dunes, which is likely an overestimation of flood volume. However, since the wrack line matches up well with the flood elevation on the dune, this can be a useful visualization for understanding the potential flood extent that results from a storm surge (Clinch et al. 2012). Time could be
incorporated into the spread inundation inundation model, where areas that experience sustained storm conditions will be more likely to flood. A cost surface, which is a map that shows the cost of moving between geographic points, could be developed to reflect the amount of time it would take for different cells in the DEM to flood (Neteler and Mitasova 2008). This could provide a more realistic inundation map, rather than simply displaying the maximum flood extent.

The ADCIRC surge predictions, which take into account how storm duration will affect surge, were also used as input into the spread model. The ADCIRC model underestimated the maximum flooding extent, when compared to the inundation model results of using the average wrack line elevation, since the water level did not reach the elevation of the wrack line. However, ADCIRC only shows storm surge, and does not take into account increased water levels due to wave effects, unless it is coupled with a wave model, such as the simulating waves nearshore model (SWAN) (Dietrich et al. 2012).

2.6.3 ADCIRC error sources

The Hurricane Irene simulation in the ADCIRC model was run for the Western North Atlantic grid, which was developed to have resolutions between 50 m and 500 m along the North Carolina coast. These resolutions should be able to display major bathymetric and topographic features, such as inlets, dunes, and rivers, similar to those that are visible in satellite imagery, NOAA shoreline charts, and DEM shoreline datasets. However, other features that would affect flooding extent may be missed, or overestimated due to insufficient resolution, like ditches, beach access roads and trails, buildings, and driveways. Model
outputs were displayed via the Coastal Emergency Risks Assessment (CERA) viewer (Blanton and Luettich 2008)

Error is also present in this numerical model because of the model structure and parameters used to represent the inherently random conditions associated with any given storm event. ADCIRC often overestimates flooding for high surge elevations and underestimates flooding for low surge elevations (Pei et al. 2013). The accuracy of the ADCIRC model was tested by comparing the model results with the measured values of water levels. Pei et al. (2013) used this method to quantify the errors associated with the ADCIRC models with 169 hurricanes from 1922 to 2011 at nine tidal gauges along the North Carolina, South Carolina, and Georgia coasts. The resulting errors varied over the study sites, but the average error was usually less than 0.30 m. The difference between the measured and predicted surge elevations shown in Table 2.5 varied more than the errors found in the study by Pei et al. 2013. However, the measured water levels reported in Table 2.5 were collected from maximum wave height gauges and high water marks, and these measurements are typically higher than static surges, like those measured at tidal gauges (NHC 2013).

2.6.4 ADCIRC model coupled with GRASS GIS

The ADCIRC storm surge model and GRASS GIS spread inundation model were compared to determine if the inundation depths predicted by ADCIRC were comparable to the inundation depths output in the spread model. The CERA viewer had some limitations such as restricted zoom and no option to request specific coordinates. Therefore, locations of
the random points generated through GRASS were approximated in the CERA viewer. Since the area was small, there was not much variation in surge elevations predicted by ADCIRC. However, if performing this comparison over larger areas, several seed points may need to be specified in the spread inundation model to reflect spatial variations in the storm surge. The ADCIRC surge predictions were applied to the spread inundation model to test the extent of potential flooding. However, the ADCIRC surge elevation and inundation depths were output relative to mean sea level (MSL) on the CERA website, a tidal datum, while the DEM elevations and inundation depths in GRASS GIS were relative to NAVD88, a geodetic datum. The difference between NAVD88 and MSL datums is not constant across the Outer Banks, which leads to some uncertainty when comparing the data. At the Oregon Inlet Marina, MSL is 0.038 m lower than NAVD88, while at the FRF in Duck MSL is 0.12 m lower than NAVD88 (NOAA 2013c). As evidenced through the tables, there was a lot of variation between the ADCIRC and spread model inundation depths, though they were always within 65 cm (Appendix A, Tables A3 and A4) of each other. Also, the ADCIRC model predicted inundation in several places where the spread model did not. This is likely because the high-resolution (0.5 m) DEM represents even small features that will impact how something will flood, such as a home, while the ADCIRC grid is more generalized, missing all of this finer grid structure information.

The 0.5 m resolution DEM was able to pick up the man-made features that increased the vulnerability of flooding at the Pea Island and Rodanthe study sites. The foredunes were degraded at the Pea Island study site along a 7 m wide USFWS driveway. Unless the ADCIRC grid node was chosen in this area, it would not reveal this feature. The
susceptibility of the driveway to flooding was shown in the inundation analysis using the spread inundation model. The water was able to flood through the driveway to the ocean when the surge elevation reached 2.0 m because the foredunes, which should be a barrier to storm surge flooding, were lower than that. The inundation model predicted that the flooding would pass through this driveway, which is consistent with where the actual breach occurred, albeit over a more narrow area. The increased vulnerability due to man-made features suggests that there may need to be stricter regulations on how these are built.

Similarly, at the Rodanthe site there was an artificial ditch that ran from the Pamlico Sound, between two ponds, and parallel to NC Highway 12 for 300 m. This ditch was highly vulnerable to flooding, as indicated in the inundation images, where a 2.0 m surge was able to flood it. The inundation model did not predict that the flood would spread across the foredune directly east of the ditch, although the ditch was fully inundated, because the foredunes were between 3 and 4 m there. However, it did show that the flood would cross from the soundside to the oceanside between 2 homes nearly 325 m south of the ditch, where the foredunes were lower than 2 m. The ADCIRC forecast predicted that this developed area would not get flooded because the homes would act as a barrier, while the spread model predicted that the water could spread between the homes. The ADCIRC model did predict that the Rodanthe site would be inundated around the breach, but did not show much detail about where the most vulnerable areas were.

Although the ADCIRC forecast did not show the flooding extent reconstructed by the wrack line elevation, running ADCIRC and spread inundation models together would be beneficial for understanding storm surge flooding. The ADCIRC model is necessary to make
storm surge predictions, and the spread model is important for highlighting vulnerable locations. The high-resolution topography can better illustrate how an area will flood. Further comparisons should be performed between ADCIRC forecast outputs and GRASS inundation models over larger areas to capture more variations in storm surges to better understand how these models can be coupled. Also, future analyses should try to incorporate time in the spread model, so flooding extent is less likely to be overestimated.

2.7 Conclusion

Storm surge levels are usually measured from tide gauges. There are only three tide stations along the North Carolina Outer Banks, and these are inadequate for understanding storm surge damage in areas where there are no gauges. Therefore, a wrack line analysis using remote sensing was utilized as an alternative for reconstructing maximum surge elevations, using Hurricane Irene as a case study. This method was applied at Pea Island and Rodanthe, along Hatteras Island. This provided a faster way of collecting wrack line elevations and a clearer understanding of surge levels, where there were no gauges, and their impacts on smaller areas, rather than focusing on regional surge levels. When extracting wrack line elevations from remotely sensed data, it is important to understand the error associated with the data, and to make sure that the LiDAR points were collected recently enough to compare to the orthoimagery.

It is also important to be able to predict storm surge levels prior to storm impact, to improve coastal community emergency preparedness. Two models were used: the complex ADCIRC model and a simple spread inundation model, to elucidate what areas are
vulnerable to flooding. The ADCIRC model can perform water level predictions, but has a low-resolution grid. While the spread model does not take into account storm dynamics, water levels can be applied to a high-resolution grid, in order to see how a landscape will flood. Coupling these models is beneficial for visualizing potential flooding extent from storm surges. The average maximum wrack line elevations can be applied as the surge elevation in a simple spread inundation model, and these results reveal what areas are vulnerable to flooding, allowing coastal managers to use their resources to reinforce low-lying foredunes. The coupling of the ADCIRC numerical model and simple spread inundation model only compared surges over small areas, but it could eventually be used to forecast potential inundation depths over larger areas.
CHAPTER 3: Space-Time Cube Visualization of Coastal Terrain

3.1 Introduction

The inundation models from the previous chapter do not consider change in topography during a storm. Other coastal processes and human activity continuously change the North Carolina (NC) Outer Banks as well, which act on different spatial and temporal scales. Recent advancements in remote sensing technology, along with frequent collections of light detection and ranging (LiDAR) data, have provided multi-temporal data at high spatial resolutions across the NC Outer Banks, thus presenting an opportunity to analyze topographic change through both space and time.

Traditional terrain analyses performed in a geographic information system (GIS) focus on the spatial distribution of surface elevation and its parameters, but the methods and tools for analysis of multi-temporal data have been rather limited (Tateosian et al. 2013; Andrienko et al. 2011; Andrienko et al. 2010; Andrienko et al. 2003). Various methods have been explored to visualize spatiotemporal evolution of elevation. Small multiples, which are a series of static images taken at discrete intervals in time, are a common way for viewing spatial change through time (Tufte 1990). This method requires the user to place the images in the correct chronological order and use spatial deduction, which can be the difference in shapes and colors, to see how something changed through time. However, as the number of images increases this method can become time consuming and less effective. Also, this method can be difficult when making location-based comparisons between images. The use of animations is another method that has been used to view change in topography through
time. The images are put in the correct temporal order and looped through, so the user can use memory deduction to see the difference between these images as time progresses (Tateosian et al. 2013; Santiago 2008). Recent studies in terrain analyses have shown spatiotemporal change by differencing DEMs to determine the elevation change between two snapshots in time. Other methods quantify volume change over an area (White and Wang 2003), or are focused on the evolution of a feature, such as a shoreline or channel, to determine how it has migrated over time (Burroughs and Tebbens 2008). Mitasova et al. (2010; 2009) proposed a more comprehensive time series analysis, where per cell statistical analyses were performed on a series of DEMs, such as minimum elevation in each cell (core) or maximum elevation in each cell (envelope), recorded over the series time period. However, these images usually need to be paired with other maps, such as time of maximum elevation and time of minimum elevation to understand when these elevations occurred temporally. While each of these methods can provide some insight into what is happening to a surface over time, they do not capture the full spatial complexity of elevation surface dynamics (Tateosian et al. 2013; Andrienko et al. 2011).

A space-time cube (STC) integrates spatial and temporal dimensions to show how a variable, such as elevation, changes in both dimensions. This approach can be used to provide a summary answer to the following question: what is the spatial pattern of this parameters distribution. In a STC, the horizontal base of the cube represents spatial location, which is given as x- and y-coordinates, while time is shown on the vertical axis (z) (Krisstensson et al. 2009). When a temporal dimension is added to perform geospatial analysis, the data must be displayed in chronological order, so the oldest data is at the bottom
of the cube, and the newest data is at the top of the cube, since time can only move in one
direction (Kyriakidis and Journel 1999; Starek et al. 2011).

One of the first STC discussions was documented in the late 1960s in a study of
movement of individuals (Hägerstrand 1970). Since then, several disciplines have adopted a
STC model to better understand different phenomena: Kraak and Mudzudo in 2007 used
STCs to study epidemiology during the Black Plague epidemic in the 14th century;
Turdukulov et al. (2007) studied the extent and duration of precipitating clouds; Nakaya and
Yano (2010) mapped the geographic extent and duration of crime clusters in Kyoto, Japan;
Fang and Lu modeled ambient ozone (O₃) pollution in Houston, Texas (2011); Gismondi and
Huisman observed how areas with different population densities responded to an earthquake
in Japan to improve disaster management (2012); and Song and Miller (2012) modified the
traditional STC study to look at traffic flow patterns at different locations throughout the day.

Although there are several applications where a STC is a useful method for viewing
multi-temporal data, there is limited research on its use to model elevation change through
time (Tateosian et al. 2013). Modeling topography in a STC is fundamentally different than
displaying other four dimensional (4D) data. LiDAR technology has evolved rapidly over
the past 15 years, and the multiple datasets that have been collected have different vertical
and horizontal accuracies, scanning patterns, and point densities (Mitasova et al. 2009).
Also, the various LiDAR survey objectives, such as post-storm reconnaissance and flood
mapping projects, have caused these datasets to cover different spatial areas and to be
collected over irregular time intervals. Therefore, it is nontrivial to integrate these different
datasets into a STC because the data requires preprocessing to assess spatiotemporal
topographic change.

The purpose of this study is to use a STC to visually summarize how coastal terrain at
selected locations on the Outer Banks varies spatially and temporally due to natural events,
such as storms and aeolian transport, and anthropogenic modifications, such as development
and foredune reconstruction. Similar to the previous STC studies, the change of the
parameter being studied, elevation, is observed through space (x- and y-axes) and time (z-axis).
The focus of this study is to use STC visualization to identify variation in coastal
topography, using methods developed by Mitasova et al. (2009); (2011); Starek et al. (2011);
and (2013). By combining the spatial and temporal data in a single image, relationships
between the topography and coastal processes are more visible. The objective of this study is
to explore if a STC analysis can provide additional insight about how coastal topography
evolved over time, and identify landscape trends that other methods could not.

The overall goal for using a STC to understand coastal terrain evolution is to view
spatial and temporal change simultaneously to enhance understanding of coastal processes,
and to create awareness of the dynamic nature of coastal areas. However, the purpose for
using STC models is not to replace existing methods for understanding shoreline and beach
migration, but to summarize spatial and temporal changes in a single image, and to take
advantage of the interactive nature of GRASS GIS interface for exploring spatiotemporal
change.
3.2 Study Sites

For this study, three dynamic sites along the NC Outer Banks were chosen to analyze changes in topography: Jockey’s Ridge, Rodanthe, and Cape Hatteras. Each site is subject to many different coastal processes; however, the dominant coastal processes vary at each location.

3.2.1 Jockey’s Ridge

Jockey’s Ridge is a 170-hectare state park and part of a back barrier dune field located in the town of Nags Head, which is bordered by the Albemarle Sound in the west and the Atlantic Ocean in the east (Weaver 2011, Mitasova et al. 2005b). According to Runyan and Dolan (2001), this back barrier dune system began to develop approximately 1,250 years ago, when storms pushed a large supply of offshore sand inland. Since its origin, Jockey’s Ridge has alternated between active, unvegetated crescendic dunes and inactive, vegetated dunes; these various states determine the extent and height of the dune system. Mitasova et al. (2005b) observed that Jockey’s Ridge increased from 20 m to 42 m between 1915 and 1953, but has since decreased back to nearly 20 m, as a result of an increase in interdune vegetation. Dense vegetation was able to grow when a linear foredune on North Carolina Beaches was constructed in the 1930s, though there is evidence that climate change has contributed to dune evolution (Kunkel et al. 2013; Pelletier et al 2009; Havholm et al. 2004; Birkemeier et al. 1984). Over the past 10 years, Jockey’s Ridge has become more stabilized with vegetation, causing dune transformation from coalescent crescendic dunes to parabolic
dunes with 5 ridges, although there continue to be large areas of active dunes that are shaped by aeolian processes.

3.2.2 Rodanthe

The Rodanthe study site, with the Rodanthe breach, described in Chapter 2 was used in this analysis as well, where the main processes that dominate coastal change are waves, storm surge, and anthropogenic activities (Tateosian et al. 2013).

3.2.3 Cape Hatteras

Nearly 40 km south of Rodanthe is Cape Hatteras, whose morphology is greatly influenced by shoal dynamics. Cape Hatteras is a cuspate landform shaped through various shoal processes. A shoal system, Diamond Shoals, extends into the Atlantic Ocean, terminating approximately 20 km southeast of Cape Hatteras. These shoals cause wave refraction, which influences the direction of littoral drift. Cape Hatteras divides two littoral cells, Hatteras (north) and Ocracoke (southwest), which determine sediment transport between sources and sinks (Inman and Dolan 1989). Diamond Shoals is a sediment sink for both the Hatteras and the Ocracoke cells and does not allow much exchange between the two cells. There has been erosion northeast of Cape Hatteras and this sediment has been deposited on the southwestern shore due to the southerly longshore drift; there is also northeasterly longshore drift in the northeastern part of the Ocracoke cell, depositing sediment on Diamond Shoals. The sediment dynamics at Diamond Shoals are also influenced by the convergence between the Gulf Stream current and the cold Labrador
current at Cape Hatteras, creating a strong pressure gradient, which is conducive to storm formation. Other processes such as sea level rise and barrier island migration strongly affect the shape and sediment transport of these cape systems (McNinch and Wells 1999; Inman and Dolan 1989).

3.3 Data

Elevation data acquired by photogrammetric and LiDAR surveys were used to capture the topography at specific points in time. These datasets were collected by multiple agencies for different purposes and were procured from the National Oceanic and Atmospheric Administration (NOAA) online distribution site, Digital Coast (NOAAa 2013):

- NOAA, the National Aeronautics and Space Administration (NASA), and United States Geological Survey (USGS) collected airborne LiDAR Assessment of Coastal Erosion (ALACE) between 1996 and 1999.
- The North Carolina Department of Environmental and Natural Resources (NCDENR)/North Carolina Flood Mapping Program (NCFMP) collected data in 2001.
- NASA/USGS Experimental Advanced Airborne Research LiDAR (EAARL) obtained data to monitor topographic change due to Hurricane Isabel in 2003, Nor’Ida in 2009, and Hurricane Sandy in 2012.
- The United States Army Corps of Engineers (USACE) and Joint Airborne LiDAR Bathymetry Technical Center of Expertise (JALBTCX) Topo/Bathy mapping project gathered data in 2004, 2005, and August 2009.

All Rodanthe LiDAR data and Jockey’s Ridge 2012 data were obtained from Digital Coast; the Jockey’s Ridge LiDAR data from 1974 to 2009 were from Weaver (2011) and Mitasova et al. (2005); and all Cape Hatteras data was from Hardin (2013).

The LiDAR data were converted into Digital Elevation Models (DEMs) using the Geographic Resource and Analysis Support System Geographical Information System (GRASS GIS). Before LiDAR surveys were collected in the mid-1990s along the NC Outer Banks, photogrammetric surveys were used to generate bare earth DEMs (Mitasova et al. 2005b). All other LiDAR data obtained from Digital Coast were multiple-return, which produce digital surface models (DSM) that include vegetation and homes. All DEMs were projected in the North Carolina State Plane coordinate system, units (m), and referenced to the North American Datum 1983 (NAD83) and North American Vertical Datum 1988 (NAVD88), horizontally and vertically, respectively. The elevation data used to complete the STC analyses along the different study sites on the Outer Banks are listed in Tables 3.1 and 3.2.
Table 3.1 Jockey’s Ridge Elevation Data (Table Derived from Weaver 2011)

<table>
<thead>
<tr>
<th>Year</th>
<th>Agency or Purpose</th>
<th>Collection Information</th>
<th>Accuracy (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1974</td>
<td>Park Design Map</td>
<td>Digitized from 1.5m contours from park map derived from photogrammetric survey BE DEM</td>
<td>Vertical: 0.7, 0.15 for spot elevations</td>
</tr>
<tr>
<td></td>
<td>NCDENR</td>
<td></td>
<td>Horizontal: 0.4</td>
</tr>
<tr>
<td>1995</td>
<td>Dune Assessment Map</td>
<td>Contours, breaklines, and spot elevations derived from photogrammetric survey BE DEM</td>
<td>Vertical: 0.76 for contours, 0.03 for</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>spot elevations</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Horizontal: 0.4</td>
</tr>
<tr>
<td>1998</td>
<td>N/A</td>
<td>Spot elevations and breakline points derived from 1:7200 scale aerial photography</td>
<td>Vertical: 0.06</td>
</tr>
<tr>
<td>(June)</td>
<td></td>
<td>BE DEM</td>
<td>Horizontal: 0.3</td>
</tr>
<tr>
<td>1999</td>
<td>USGS/NASA/NOAA</td>
<td>LiDAR collected using Airborne Topographic Mapper II DSM</td>
<td>Vertical: 0.15 in bare areas</td>
</tr>
<tr>
<td>(Sept 9-10)</td>
<td></td>
<td></td>
<td>Horizontal: 0.8</td>
</tr>
<tr>
<td>2001</td>
<td>North Carolina Floodplain mapping program</td>
<td>LiDAR collected using Leica Geosystems Aeroscan DSM</td>
<td>Vertical: 0.2 in open areas</td>
</tr>
<tr>
<td>(Feb 1)</td>
<td></td>
<td></td>
<td>Horizontal: 2</td>
</tr>
<tr>
<td>2007</td>
<td>NSF, National Center for Airborne Laser Mapping</td>
<td>LiDAR collected using OPTECH Gemini system DSM</td>
<td>Vertical: &lt;0.1 on flat surface</td>
</tr>
<tr>
<td>(July 8)</td>
<td>(NCALM)</td>
<td></td>
<td>Horizontal: 0.15-0.30</td>
</tr>
<tr>
<td>2008</td>
<td>NOAA Integrated Ocean and Coastal Mapping</td>
<td>LiDAR collected using OPTECH ALTM system DSM</td>
<td>Vertical: 0.15</td>
</tr>
<tr>
<td>(Mar 27)</td>
<td></td>
<td></td>
<td>Horizontal: &lt;0.2</td>
</tr>
<tr>
<td>2009</td>
<td>USACE, JALBTCX</td>
<td>LiDAR collected using Compact Hydrographic Airborne Rapid Total Survey (CHARTS) DSM</td>
<td>Vertical: 0.2</td>
</tr>
<tr>
<td>(Aug 24)</td>
<td></td>
<td></td>
<td>Horizontal: 0.75</td>
</tr>
<tr>
<td>2012</td>
<td>USGS</td>
<td>LiDAR collected using OPTECH Gemini LiDAR System DSM</td>
<td>Vertical: 0.15</td>
</tr>
<tr>
<td>(Nov 10)</td>
<td></td>
<td></td>
<td>Horizontal: 0.2</td>
</tr>
<tr>
<td>Date</td>
<td>Agency</td>
<td>Collection Information</td>
<td>Accuracy (m)</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------------------</td>
<td>-----------------------------------------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>10/12/1996*‡</td>
<td>NOAA/NASA</td>
<td>Airborne Topographic Mapper II</td>
<td>Vertical: 0.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Horizontal: 2</td>
</tr>
<tr>
<td>09/27/1997*‡</td>
<td>NOAA/NASA/USGS</td>
<td>Airborne Topographic Mapper II</td>
<td>Vertical: 0.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Horizontal: 2</td>
</tr>
<tr>
<td>09/07/1998*‡</td>
<td>NOAA/NASA/USGS</td>
<td>Airborne Topographic Mapper II</td>
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</tr>
<tr>
<td>Post-Bonnie</td>
<td></td>
<td></td>
<td>Horizontal: 2</td>
</tr>
<tr>
<td>10/06/1999*‡</td>
<td>NOAA/NASA/USGS</td>
<td>Airborne Topographic Mapper II</td>
<td>Vertical: 0.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Horizontal: 2</td>
</tr>
<tr>
<td>02/01/2001*‡</td>
<td>NCDENR/FEMA/ NCFMP</td>
<td>Leica Geosystems Aeroscan</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Horizontal: 2</td>
</tr>
<tr>
<td>09/16/2003*</td>
<td>NASA/USGS</td>
<td>Experimental Advanced Airborne Research LiDAR (EAARL)</td>
<td>Vertical: 0.15</td>
</tr>
<tr>
<td>Pre-Isabel</td>
<td></td>
<td></td>
<td>Horizontal: 2</td>
</tr>
<tr>
<td>09/21/2003*‡</td>
<td>NASA/USGS</td>
<td>Experimental Advanced Airborne Research LiDAR (EAARL)</td>
<td>Vertical: 0.15</td>
</tr>
<tr>
<td>Post-Isabel</td>
<td></td>
<td></td>
<td>Horizontal: 2</td>
</tr>
<tr>
<td>07/16/2004*‡</td>
<td>USACE/JALBTCX</td>
<td>Compact Hydrographic Airborne Rapid Total Survey (CHARTS)</td>
<td>Vertical: &lt;0.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Horizontal: &lt;1.4</td>
</tr>
<tr>
<td>11/26/2005*‡</td>
<td>USACE/JALBTCX</td>
<td>Compact Hydrographic Airborne Rapid Total Survey (CHARTS)</td>
<td>Vertical: 0.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Horizontal: &lt;1.4</td>
</tr>
<tr>
<td>03/27/2008*‡</td>
<td>NOAA</td>
<td>OPTECH ALTM system</td>
<td>Vertical: 0.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Horizontal: &lt;0.2</td>
</tr>
<tr>
<td>08/24/2009*</td>
<td>USACE/JALBTCX</td>
<td>Compact Hydrographic Airborne Rapid Total Survey (CHARTS)</td>
<td>Vertical: 0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Horizontal: 0.75</td>
</tr>
<tr>
<td>12/01/2009*‡</td>
<td>NPS/USGS/NASA</td>
<td>Experimental Advanced Airborne Research LiDAR (EAARL)</td>
<td>Vertical: 0.2</td>
</tr>
<tr>
<td>Post-Ida</td>
<td></td>
<td></td>
<td>Horizontal: 0.75</td>
</tr>
<tr>
<td>08/29/2011*‡</td>
<td>NOAA</td>
<td>Riegl Q680i-D system for Emergency Response Program</td>
<td>Vertical: &lt;0.30</td>
</tr>
<tr>
<td>Post-Irene</td>
<td></td>
<td></td>
<td>Horizontal: &lt;1.0</td>
</tr>
<tr>
<td>11/10/2012*</td>
<td>USGS</td>
<td>OPTECH Gemini LiDAR</td>
<td>Vertical: 0.15</td>
</tr>
<tr>
<td>Post-Sandy</td>
<td></td>
<td></td>
<td>Horizontal: 0.2</td>
</tr>
</tbody>
</table>
As shown in the tables, the LiDAR data were collected by various agencies for different purposes, which makes data accuracy and consistency assessment an imperative task. The systematic errors were identified and corrected for all the data downloaded from the Digital Coast Data Server, the Rodanthe data and 2012 Jockey’s Ridge data, using NCDOT Benchmarks and the methods described in Chapter 2 (Mitasova et al. 2009). However, both the Jockey’s Ridge and Rodanthe study sites have few NCDOT benchmarks. Therefore, points were queried along the NC Highway 12 centerline at both study sites at regular intervals to correct the systematic error. This task was not trivial because the highway had been paved in the early 2000s. The road elevations were compared in groups to baseline DEMs: 2001, 2005, 2008, and 2012. The groups were from 1996-2001, 2003-2005, and 2008-2009, and 2011-2012. The Rodanthe study site contained a 1.1 km segment of NC Highway 12. The most northern point in this section of NC Highway 12 was assigned the position of 0 m and the southern point was assigned 1100 m. Points were skipped between 200 and 400 m in 1998 and between 800 and 900 m in 2003 because no LiDAR data were collected along these portions of NC Highway 12 during these years. Also, the points between 400 and 500 m were skipped in 2011 because this was along the breach. The spatial extent of the Rodanthe LiDAR data varied from 1996 to 2012; the 1996, 1997, 1998, 1999, pre-Isabel 2003, and post-Isabel 2003 did not cover the full extent of the study area. Therefore, this data needed to be patched with other DEMs to show the full study area. The 1996-1999 LiDAR data was patched with the 2001 DEM and the 2003 data was patched with the 2004 DEM.
3.4 Methods

The STC visualization methods were described in the paper *Visualizations of Coastal Terrain Time Series* (Tateosian, L., Mitasova, H., Thakur, S., Hardin, E., Russ, E., and Blundell, B. 2013). These methods were updated and independently applied for the Jockey’s Ridge, Rodanthe, and Cape Hatteras study sites. A STC model was created as a voxel (volumetric pixel) model, where elevation was represented by a function of spatial and temporal dimensions:

\[ z = f(x, y, z) \] (3.1)

To visualize this model in a GIS, it must be able to support volume data. GRASS GIS is a system that can support volume data as a regular 3D grid in a voxel model (Neteler 2001).
3.4.1 Creating the Voxel Model

The general workflow that was followed to perform the 3D analysis included the following steps:

- Acquire LiDAR point cloud data.
- Interpolate the data into 2D raster-based DEMs.
- Assess and correct the systematic errors using NCDOT Benchmarks or other points on the NC Highway 12 centerline.
- Patch the datasets that did not have full LiDAR coverage.
- Generate a mask to display DEMs over a common area.
- Calculate additional layers that represent years that were not present in the time series between consecutive DEMs using linear interpolation in order to have a consistent time step.
- Stack all DEMs and interpolated layers in chronological order to create a continuous volume model of elevation, and display the 3D raster map in the 3D interactive viewer.

There are two methods that can be used to create voxel models in GRASS. The first method is based on 2D raster DEMs that were interpolated from LiDAR data using the bivariate regularized spline with tension interpolation method (Mitasova et al. 2005a):

\[
  z = a + \sum_{j=1}^{N} \lambda_j \left[ -E_i \left( \frac{qr}{2} \right)^2 + 2 \ln \left( \frac{qr}{2} \right) + C_E \right] \tag{3.2}
\]
where \( a \) is a constant and \( \lambda_j \) are coefficients obtained by solving a system of linear equations (Starek et al. 2011; Neteler and Mitasova 2008). \( E \left( \frac{q_r}{2} \right)^2 \) is the exponential integral function, \( \varphi \) is the tension parameter, \( r \) is the distance between grid points \((x, y)\) and the given points \((x_j, y_j)\), and \( C_E \) is the Euler constant. The interpolated, corrected, and masked DEMs are then stacked into a voxel model. This was the method used in this analysis and is discussed in more detail in the following paragraphs.

Before creating this voxel model in GRASS, the 3D area was set and the spatial and temporal resolutions were defined. After experimenting with different DEM resolutions, a 1 m spatial resolution was determined to be the highest resolution at which voxel models could be displayed.

This method of converting a series of DEMs into a volume model assumes an equal time interval between each consecutive DEM, but the time interval between LiDAR surveys is usually irregular. The temporal resolution was set at 0.5-year intervals for the Rodanthe and Cape Hatteras data, and 1-year for the Jockey’s Ridge data. Since surveys were not collected at these frequencies regularly, additional layers, created using linear interpolation to estimate topography at times not present in the time series, were calculated (Tateosian et al. 2013).

The second method for creating a voxel model interpolates a series of LiDAR point clouds directly into a voxel model using a continuous trivariate function. According to Mitasova et al. 2012 and Starek et al. 2013, the trivariate function is created from a series of \( m \) point clouds, which contain coordinates \( \{(x_i, y_i, z_i), i = 1, \ldots, n_k\} \) taken at time \( t_k \), where \( k \)
\( k \) is the point cloud and \( n_k \) is the number of points in the \( k^{th} \) point cloud. The data from all of the point clouds are then organized into a single point cloud with coordinates \( \{(x_i, y_i, t_i, z_i)\}, i = 1, \ldots, \sum_{k=1}^{m} n_k \}. \) This large point cloud is converted into a voxel model using regularized spline with tension trivariate interpolation method:

\[
z = a + \sum_{j=1}^{N} \lambda_j \left[ \frac{\sqrt{\pi}}{qr} 2 \text{erf} \left( \frac{qr}{2} \right) - 2 \right] \quad (3.3)
\]

where \( a \) is a constant, \( \lambda_j \) are coefficients solved through a system of linear equations, \( q \) is the tension parameter, \( r \) is the distance between the voxel grid points \((x, y, t)\) and \((x_j, y_j, t_j)\) with anisotropy \( \theta \) in the time dimension \( r = \sqrt{(x-x_j)^2 + (y-y_j)^2 + \theta(t-t_j)^2} \), and \( \text{erf} \) is the error function (Starek et al. 2013; Neteler and Mitasova 2008; Mitasova et al. 2005a). This approach handles inconsistent time intervals better, since the \( t \)-values are explicitly defined in the point cloud, but requires considerably more processing power.

### 3.4.2 Color Table Design

Two color schemes were developed for this analysis: one to indicate the epoch, time period, throughout the 3D raster, and one to show the rate of change in elevation between surveys. To generate a STC color table for time, one constant surface was created for each layer in the elevation voxel model. The value of each constant is arbitrary, but each surface has to be a different value. Then, the constant surfaces were stacked into a separate voxel model, in chronological order, and each value was assigned a color. The colors for the years were chosen using the Commission Internationale de l’éclairage (1976) \((L^*, u^*, v^*)\) (CIE
LUV) model, where L describes luminance and together u and v describe chromaticity. Healey (1996) explored how this CIE LUV can be used to effectively visualize data. This model allows the user to choose colors on a perceptually balanced color table. The difference in colors is dependent on the Euclidean distance between colors on a model, linear separation between colors, and the color category. The total time between the first and last surveys were compressed from 0 to 1, and the DEMs were assigned values based on where they fall in the time series. If one of the DEMs was exactly halfway between the first and last survey, it was given a value of 0.5. This color model produces a range of colors that reflect the difference in time. The colors were then applied to show time epochs using a bracketing approach. To do this, one color was selected to represent the time from halfway between the previous survey and current survey to halfway between the current survey and next survey. Because of this, only half of the first and last survey epochs were shown. This consistent coloring scheme was designed to make it easier to distinguish between time epochs, and easier to see the length of time that passed between each survey.

Another color table was developed to show the rate of change in elevation between the different surveys. Consecutive surveys were subtracted from each other, more recent minus less recent, and normalized by the amount of time, in years, between the surveys. When differentiating all consecutive DEMs, there was one fewer layer than the original number of surveys. This was handled in the voxel model by stacking the first derivative surface twice, followed by the rest of the surface derivatives because there was no baseline to which the first survey could be compared. A diverging color table from red to blue, erosion to deposition, was chosen to show the rate of change in elevation.
3.4.3 Voxel Model Visualization

Data represented by STC voxel models were visualized using the interactive 3D viewer in GRASS GIS. Topographic change was visualized through space and time by extracting elevation isosurfaces (surfaces of constant elevation). Isosurfaces represent the evolution of a contour through the entire time series. To better interpret these isosurfaces, supportive data, such as reference DEMs and contour lines, were displayed with the isosurface, and manipulated so they were in the correct temporal position. The different color tables were applied through the interactive viewer. Another important component in visualizing an isosurface is to adjust the lighting so subtle features in the isosurface can be identified. Animation options were explored to better explain the isosurfaces. Cutting planes can be utilized to animate the isosurface, so it appears to grow through time. A cutting plane perpendicular to the z-axis was used, and the height adjusted to create an animation of a growing isosurface. Also, multiple isosurfaces of different elevation values can be looped through to highlight the evolution of different coastal features, such as shoreline, upper beach and foredunes, and dune ridges in the same study area.

3.5 Results

An elevation contour line close to shorelines were extracted from the series of DEMs, 0.5 m contours at Rodanthe, Figure 3.2, and 0.2 m contours at Cape Hatteras, Figure 3.3. These elevations were chosen to capture the complex shape and dynamics of the shoreline. While it is evident that there was significant change in the shoreline position over the past 16 years at Rodanthe, and over the 15 year period at Cape Hatteras, the overlapping 2D lines
limit the user’s ability to fully grasp how the shorelines changed spatially and temporally even though a perceptually balanced color table was used to distinguish between the different times. Therefore, the 3D isosurface, colored by epoch, with the shoreline contours placed on the z-axis, approximately where they occur in time, provided a more accessible view for how the shoreline changed through space and time (Figures 3.4 and 3.5). The shoreline isosurfaces are continuous, without any gaps in the surface, but it is clear that the shoreline was highly migratory with several periods of retreat towards land as well as seaward advance. Overall the shoreline migrated west towards land at Rodanthe, while the Cape Hatteras shoreline isosurface showed both cape retreat and growth over the years. The shoreline contours placed at the correct temporal location along the isosurface provided context to the user so that they could visualize where these shorelines occurred in the time period.
Figure 3.2 2D representation of ocean-facing 0.5m contours from 1996 to 2012 for the Rodanthe study site.

Figure 3.3 2D representation of 0.2m contours from 1997 to 2011 draped over the 2011 DEM for the Cape Hatteras study site.
Figure 3.4 0.5m isosurface from 1996 to 2012 colored by year for the Rodanthe study site.

Figure 3.5 0.2m isosurface from 1997 to 2011 colored by year for the Cape Hatteras study site.
Figure 3.6 demonstrates how a rate of change color table could be applied to an isosurface. In Figure 3.6A, the 2 m isosurface, which is the elevation of the upper beach or lower foredune, has been stable and continuous throughout the time series, with slight landward retreat of the dune. There were distinct periods of erosion, evidenced through the dark red sections, which correspond to storm events. The red/orange section in the bottom quarter of the isosurface corresponded to post-Dennis and Floyd in 1999, the dark red section nearly halfway through the isosurface was a result of Hurricane Isabel in 2003, the red band in the upper quarter section of the isosurface was due to Nor’Ida in 2009, and the disappearance of the isosurface in the northern section at the top of the isosurface was because of Hurricane Irene in 2011. The 3 m isosurface is not as stable as the 2 m isosurface, as illustrated through the ‘holes’, where the isosurface was discontinuous. These areas represent where the dunes were flattened below 3 m due to storm overwash after Hurricanes Dennis and Floyd (1999), Isabel (2003), and Nor’Ida (2009). However, the blue color above the holes indicates that the dunes were rebuilt.
The isosurface with reference elevation surfaces is another approach for visualizing coastal evolution by including DEMs at their relative position in time, along the z-axis, with the isosurface. Figures 3.7 at Rodanthe and 3.8 at Cape Hatteras took advantage of this approach by bounding the isosurface by the first and last DEMs in the time series. Similar to including the shoreline contours, this method provided context for where the isosurface elevations occur in space, relative to the DEMs, and how they migrated over the entire time period. Figures 3.7A and 3.8 show lower level elevations, corresponding to upper beach or lower foredune levels, and are mostly continuous. However, the 2.5 m isosurface at Cape Hatteras does have a few holes in the isosurface, especially around the cape feature. Figure
3.7B is of the 4 m isosurface, which is representative of the higher dune ridges in the area. This isosurface includes homes that were built at, or below 4 m, in the southern section of the Rodanthe study site, as evidenced by the column-shaped features. The dune is discontinuous in the northern section, suggesting that there were brief periods where the dunes were above 4 m. This approach is not limited to using the first and last DEMs, but any pairs can be added, as long as they are placed in the correct location relative to time. Figure 3.9 at Cape Hatteras uses the first DEM from 1997 and the DEM from 2008 with the 4.5 m isosurface. Although the 4.5 m isosurface is more discontinuous than the lower dune elevation, it is clear that the dune ridges reached up to 4.5 m on the eastern side between 1997 and 2008, and remained through 2011.
Figure 3.7 A) 2m isosurface and B) 4m isosurface, colored by year, between 1996 and 2012 DEMs for the Rodanthe study site.
Figure 3.8 2.5m isosurface, colored by year, between 1997 and 2011 DEMs, for the Cape Hatteras study site.

Figure 3.9 4.5m isosurface, colored by year, between 1997 and 2008 DEMs for the Cape Hatteras study site.
The Rodanthe study site is greatly impacted by anthropogenic activity, which can be monitored using the space-time cube model as well. In Figure 3.10, the 6 m isosurface was extracted at the Rodanthe study site to view the change in buildings and homes near the shore over the time series. Each column represents a home. The open features at the top end of some of these columns illustrates that these homes were present through the last survey, while features that are closed (rounded at the top) were no longer there as of the last survey. Also, not all homes were present in the first survey, in 1996, as indicated by the features that are not connected to the base surface. Some homes appear to have holes in the middle, which could indicate that homes were destroyed and subsequently rebuilt. However, upon further investigation this pattern was due to a lack of LiDAR data in the area. There are also several small, open features, behind NC Highway 12, that only occur in the last epoch, which are power lines.
The STC modeling approach was also applied at Jockey’s Ridge, an area that is dominated by aeolian sand transport, over a 38 year time period, since the overlapping contours were difficult to interpret (Figure 3.11). Four isosurface elevations were extracted and displayed in Figure 3.12 to show how Jockey’s Ridge dune field evolved over time. Figure 3.12A, the 17 m isosurface, indicates that the main dune never dropped below 17 m, but the complex geometry of the isosurface shows that it evolved from a single ridge into 3 distinct ridges after 1995. The eastern dune dropped below 17 m after 1995, but increased in
elevation by 1999. The 20 m and 21 m isosurfaces depicted in Figures 3.12B and 3.12C show that the center ridge reached these elevations in 2012, as evidenced by the open shape, while the other peaks did not reach this high, since the isosurfaces are shown as closed features. The 25 m isosurface is only present through 1999. It is evident from these narrowing isosurfaces that the area of dunes greater than 17 m decreased between 1974 and 2012. Figures 3.13 and 3.14 support this observation, where the volume of the sand greater than 18 m decreased over time, concomitant with an increase in sand volume between 6 m and 18 m during the same period (Table 3.3).

Figure 3.11 2D representation of 17 m contours (left) and 20 m contours (right) for the Jockey’s Ridge study site.
Figure 3.12 A) 17m, B) 20m, C) 21m, D) 25m isosurfaces, colored by year, between 1974 and 2012.

Figure 3.13 6-18 m elevations at Jockey’s Ridge in 1974 (left), 1999 (middle), and 2009 (right).
Table 3.3 Volume Comparison at Jockey’s Ridge

<table>
<thead>
<tr>
<th>Year</th>
<th>Volume of Sand 6-18m (m$^3$)</th>
<th>Volume of Sand &gt;18m (m$^3$)</th>
<th>Total Volume (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1974</td>
<td>3,467,343</td>
<td>1,624,498</td>
<td>5,143,796</td>
</tr>
<tr>
<td>1999</td>
<td>4,350,095</td>
<td>793,701</td>
<td>5,091,841</td>
</tr>
<tr>
<td>2009</td>
<td>4,476,432</td>
<td>389,544</td>
<td>4,865,976</td>
</tr>
</tbody>
</table>

3.6 Discussion

The space-time cube was designed so the user could easily visualize coastal change throughout space and time. One of the challenges was ensuring that the user could observe the irregular time steps between data. Ideally, the temporal resolution would be the shortest length of time between consecutive LiDAR surveys (Tateosian et al. 2013). However, this was 5 days at Rodanthe, and the entire time series was nearly 6000 days, which would have resulted in over 1000 time steps. Therefore, the time interval was set to 0.5-years for simplicity. Also, the color table was an important element for depicting the amount of time that has passed between surveys. The interactive 3D viewer was used to enhance the design of the voxel models and to give the user flexibility over what they wanted to display. Not only could this viewer incorporate contour lines or DEMs with an isosurface, there were
other options that allow the user to create an animation of the voxel model ‘growing’ throughout time. This further helps users conceptualize how topography is changing, and reinforces the dynamic nature of coastal landscapes. However, there are limitations involved with the interactive viewer, such as illuminating the elevation isosurfaces completely. There was no way to make all of the colors of the isosurface show up with the lighting that is available in the GRASS GIS 3D viewer. Each of these isosurfaces had shadowed areas, where the color was not obvious. This could be improved by having two light sources that illuminate the isosurface.

This STC analysis of the NC Outer Banks sites can aid in the visualization of coastal evolution. Trends in the landscape can be identified, and linked to known coastal processes. Unlike previous approaches to capture topographic change, the isosurfaces extracted from the voxel model in Figures 3.2 – 3.12 were designed to capture the evolution of various coastal features: shoreline, upper beach, and dune ridges throughout time in a single image. These visualizations can help guide coastal analyses in order to determine where distinct topographic change occurred, and tie these changes with a specific time (Tateosian et al. 2013).

Both the Rodanthe and Cape Hatteras study sites were affected by large storms that ultimately led to significant topographic change. These changes were obvious in the isosurfaces, which captured shoreline retreat, landward migration of dunes, and a decrease in dune ridge elevation following storm impacts. Being able to visualize the amount of change an area sustained following a storm can highlight how much damage a particular storm caused, as well as point out the more vulnerable areas. When an area is repeatedly damaged,
coastal managers can focus more attention on repairs to prevent or ameliorate the effects of future storm impacts.

Unfortunately not all coastal change through time can be shown in an isosurface, and linear interpolation does not necessarily reflect the topography at times there was no LiDAR data. Since many LiDAR surveys were taken following storm events, these changes are better connected to the isosurface than the changes that occur from natural coastal processes that happen on a more regular time scale, such as wind and wave transport. While these smaller scale processes may not show the drastic surface changes that result from storms, knowing when large storm systems made landfall on the Outer Banks and when there was a calm period can help distinguish between change associated with storm and other natural processes. Overall landscape trends, those that are not a result of storm impacts, can be seen in the different isosurfaces, such as landward shoreline and foredune migration, and shoal processes dictating the change along Cape Hatteras. Visualizing these changes as a continuous surface throughout time underscores the dynamic nature of coastal areas.

Jockey’s Ridge has also undergone morphological changes over the years. Notable changes include the increase in dune elevation from 20 to 40 m between 1915 and 1953 and subsequently, the decrease back to 20 m between 1953 through the present. The decrease in dune elevation is visible in Figure 3.12 from 1974 to 2012. This is consistent with the findings of Pelletier et al. (2009) and Mitasova et al. (2005) that the dune field has become more stabilized since the 1930s due to interdune vegetation, which has led to dune deflation. The increase in vegetation could be related to the increase in the precipitation that has been observed in the southeast (Kunkel et al. 2013). Observing the evolution of dune elevations
over time using isosurfaces helped facilitate volume analysis that could be used to understand the processes affecting dune morphology. It is clear in the images that the Jockey’s Ridge isosurfaces have narrowed through time. However, there had not been much total volume change in the park, which suggests that the sand had been redistributed to lower elevations instead of lost (Mitasova et al. 2005b). The increase in volume of sand between 6 m and 18 m and the decrease in volume of sand greater than 18 m indicates that the dunes were becoming more deflated over the time series (Table 3.3). Isosurface topology at Jockey’s Ridge is highly complex, and significant change has occurred over a relatively recent time period. These visualizations help identify where large changes are occurring, and when these happened in time.

This approach can also be used to track anthropogenic activity. Through this analysis, homes were extracted and inspected to see if these were able to withstand storm impacts, or if they were lost. Also, it enabled the user to see clearly when, in time, these homes were built. Other changes that would have a human influence may not be as obvious as the building of large homes, such as the rebuilding of a foredune system after a storm impact, can be examined using the STC. For example, it is clear that the dunes were rebuilt after storm events at Rodanthe, where there were periods of deposition. However, in order to pinpoint these less obvious changes, some knowledge of the maintenance of the area needs to be known.

As indicated in Starek et al. (2013), this approach is not restricted to only viewing elevation though time, but it can be applied to understand the change in any topographic parameter, such as the change in elevation over time. This is most useful for identifying
abrupt changes in topography due to storm impacts or human interference. Future work should be directed at creating STCs of elevation derivations, such as change in elevation, slopes, and curvatures, to better understand the coastal landscape evolution.

Being able to visualize these changes is an important part of understanding coastal dynamics, and can be an additional step for performing coastal analyses. This type of visualization highlights that there is strong spatial and temporal variability in coastal landscapes. Although this analysis is geared towards coastal scientists, these visualizations can be a powerful tool for identifying areas that need attention from coastal managers and civil engineers as well.

3.7 Conclusion

The availability of multi-temporal LiDAR data over the North Carolina Outer Banks at high spatial resolutions has facilitated the need to develop spatiotemporal GIS methods. Visualizing topographic change through space and time in a 3D space-time cube (STC) model provides a unique approach to understanding coastal change since it incorporates both spatial and temporal dimensions simultaneously. In this analysis, voxel models were developed along three locations on the NC Outer Banks: Jockey’s Ridge, Rodanthe, and Cape Hatteras to understand surface trends over time.

Designing effective visualizations was an important component for preparing the isosurfaces. The interactive 3D viewer in GRASS gives the user control over what they want to display. A unique color table can be applied to emphasize changes in topography. These visualizations serve an important purpose for coastal analyses, since the user can determine
what types of analyses should be applied to an area to better understand how an area is changing. Through these isosurfaces, landscape changes due to different processes, such as storm impacts, development, and aeolian transport were visible. Then, coastal scientists can view this information to help determine what further analyses are needed, or coastal managers and civil engineers could use these visualizations to recognize and reinforce vulnerable areas in the terrain.
CHAPTER 4: Vector Field Analysis

4.1 Introduction

Vector fields are commonly used to understand physical processes because they display graphics of features that represent the magnitude of change and direction of movement of some phenomena in a spatial domain. Force fields that include electric, magnetic, and gravitation fields are often illustrated using vectors, where the vector magnitude represents the field strength (Galbris and Maestre 2012). Vector fields are also commonly applied to symbolize velocity, such as those that occur with ocean currents (Ocean Surface Currents 2013) and wind maps. These applications have been expanded upon to show both continuous ocean current and wind maps using comet trails to represent vectors (NASA 2013; Viegas and Wattenberg 2013; Fowler and Ware 1989).

A special type of vector field known as the gradient describes the direction and magnitude of maximum change over a surface. In vector calculus, the gradient is defined as a vector of a scalar surface that points upslope in the direction of maximum change, and has a magnitude (the length of the vector) that represents the rate of increase (Galbris and Maestre 2012). Mathematics, physics, and chemistry are among the many disciplines that use gradient vectors to model flow. There are multiple applications in physical sciences that use gradient vectors, such as showing how heat, pressure, or contaminants vary spatially. Gradient vector analyses also extend into biological sciences, as evidenced by Webb (2012) in a study of source/sink population dynamics.
Gradient analyses are also applied in geographic information systems (GIS) in order to better understand topographic surface change over digital elevation models (DEMs). In topographic analyses the gradient is typically expressed as slope, the steepness of relief, and aspect, the direction of maximum steepness over a surface. In addition to these topographic parameters describing the change over a surface, they also serve as inputs for other analyses. Wang and Pullar (2005), Mitasova and Mitas (1998), and Desmet and Govers (1995) described the necessity for calculating slope and aspect to understand water flow and accumulation across a landscape. This is a crucial step for running sediment transport models. Slope and aspect are equally important for performing solar radiation analyses, especially over mountainous terrain (Corripio 2003).

As described in the previous chapter, numerous coastal processes can alter the Outer Banks at different spatial and temporal scales. The increase in available data along the coast of North Carolina recently has motivated coastal scientists to analyze these dynamic surfaces through space and time and investigate the processes shaping them. Dune field evolution has been well documented at Jockey’s Ridge, the largest active sand dune on the east coast, through several photogrammetric and light detection and ranging (LiDAR) surveys. Many terrain analyses that extract dune features and measure their movement have been applied to Jockey’s Ridge to interpret dune migration and how it is being deformed (Mitasova et al. 2005b). Previous investigations to understand how Jockey’s Ridge evolved observed the change in elevation between DEMs using map algebra techniques. Also, methods to follow directional change were performed by tracking the dune peak, crest, or slip face position through time (Weaver 2011; Mitasova et al. 2005b). However, these methods track only
select features in the dune field, and give an incomplete look at how the entire spatial area evolved. Therefore, numerical models have been utilized to conceptualize how the dune field evolved over time, but these do not replicate the exact change in morphology the dune experienced (Pelletier et al. 2009). The space-time cube (STC) method was applied to observe the morphological changes of Jockey’s Ridge between 1974 and 2012 (Tateosian et al. 2013). This approach extracted specific elevations, which can be used as a proxy for a feature, such as dune ridges, throughout the time series. This investigation was able to show visible changes in the dune elevations over time, but it can be hard to interpret the processes leading to dune deformation. Instead of generalizing the movement of the dune based on the migration of dune peaks and slip faces, or trying to track a single elevation through time, an exploratory vector field method was developed, which utilized the change between gradient vectors over two DEMs, to depict the direction and magnitude of movement through each cell between two times, and illustrate the deformation of the geometry of the dune to help characterize evolution.

The purpose of this chapter is to create a map of landform evolution in terms of change of shape, position, and elevation by looking at horizontal and vertical migration at any point in space and time. These vector field visualizations will provide visible patterns that can show how a coastal landform is changing. The analyses in this chapter are an extension of the STC analyses described in Chapter 3 because the vector fields are utilized to enhance visualization of coastal processes impacting a landscape through space and time.
4.2 Study Sites

For this analysis, Jockey’s Ridge, one of the same study sites from Chapter 3, was chosen to observe changes in topography using vector fields. This site was selected because of the high dune ridges and the distinct slip faces, as well as the recent change in morphology due to interdune vegetation (Weaver 2011; Pelletier et al. 2009; Mitasova et al. 2005). Jockey’s Ridge is a field of five coalesced dune peaks: west, main, which is made up of two peaks, east, and south. The east and main dunes were observed in this analysis. Refer back to Chapter 3 for a more detailed description of the Jockey’s Ridge site and the processes impacting it.

Figure 4.1 2009 Jockey’s Ridge DEM with main and east dunes identified.
4.3 Methods

4.3.1 Elevation Surface Gradient Vectors

In this chapter, a methodology using gradient vectors to show spatiotemporal change between two DEMs is described. When performing topographic analyses, elevation is represented as a function of spatial location taken at a specific time:

$$z_t = f(x,y) \quad (4.1)$$

Then, the gradient is calculated from the first order partial derivatives of a scalar surface function $f(x,y)$:

$$\nabla f = \frac{\partial f}{\partial x} \hat{i} + \frac{\partial f}{\partial y} \hat{j} = (f_x, f_y) \quad (4.2)$$

where $\nabla$ is the differential vector operator, $\frac{\partial f}{\partial x} \hat{i} + \frac{\partial f}{\partial y} \hat{j}$ is the sum of the partial derivative vectors in the x- and y-directions.

The elevation surface can be discretized into a regular grid, or DEM:

$$z(i,j) = f(x_i, y_j) \quad (4.3)$$

where $i, j$, is the row, column index.

The standard method used by GIS software for approximating partial derivatives is a third order finite difference method, applied to a central point in a 3x3 neighborhood grid, introduced by Horn (1981). This approach uses weighted averages, where cells sharing an edge with the central point are given more weight than the cells that share a vertex (diagonal), to calculate the partial derivatives over the 3x3 grid of z-values. The weighting value is based on the reciprocal of squared distances. The figure below of the 3x3 gridded cells was adapted from Horn (1981) and Neteler and Mitasova (2008):
The surface gradient vector was represented by a line made up of two coordinates:

The origin, or the center point of a grid cell in the 3x3 window:

\[ x_0 = x_i \quad (4.4) \]
\[ y_0 = y_j \quad (4.5) \]

And the end point,

\[ x_1 = x_0 + f_x \quad (4.6) \]
\[ y_1 = y_0 + f_y \quad (4.7) \]

which was calculated by adding the origin and partial derivatives of the elevation surface.

The partial derivatives of elevation with respect to the x- and y-directions were approximated using Horn’s (1981) algorithm of weighted averages:

\[ f_x = \left( \frac{z_{i+1,j+1} - z_{i-1,j+1} + 2(z_{i+1,j} - z_{i-1,j}) + (z_{i+1,j-1} - z_{i-1,j-1})}{8 \Delta x} \right) \quad (4.8) \]
\[ f_y = \left( \frac{z_{i+1,j+1} - z_{i+1,j-1} + 2(z_{i,j+1} - z_{i,j-1}) + (z_{i+1,j+1} - z_{i-1,j+1})}{8 \Delta y} \right) \quad (4.9) \]

Then, the surface gradient vectors was drawn as:

\[ \vec{v} = P_0P_1, P_0 = (x_0, y_0), P_1 = (x_1, y_1) \quad (4.10) \]
A python script was developed to output 2D vector fields of the surface gradient vector through approximating partial derivatives over a DEM, and adding them to the origin. The script, which required a DEM input, called built-in python modules, user defined modules, the numpy module, and GRASS GIS commands to output the gradient vector over a regular grid (Appendix D).

The partial derivatives also could have been solved from slope and aspect values. Slope is a function of gradient magnitude, and is defined as the steepest angle, or maximum rate of change in elevation over a surface:

$$
\gamma = \arctan \left( \sqrt{f_x^2 + f_y^2} \right) \quad (4.11)
$$

$$
\gamma[\%] = 100 \cdot \sqrt{f_x^2 + f_y^2} \quad (4.12)
$$

While slope is a function of gradient magnitude, aspect is a function of gradient direction and it reflects the downslope direction of the steepest slope angle, and is calculated using trigonometry:

$$
\alpha = \arctan \left( \frac{f_y}{f_x} \right) \quad (4.13)
$$

### 4.3.2 Change in Gradient Vectors

Gradient vectors can also be calculated in three dimensions (3D). A surface can be expressed as function of x, y, and t, where t is time. Then the gradient of this function is defined as:

$$
\nabla f = \frac{\partial f}{\partial x} \hat{i} + \frac{\partial f}{\partial y} \hat{j} + \frac{\partial f}{\partial t} \hat{k} = \left( f_x, f_y, f_t \right) \quad (4.14)
$$
where \( \frac{\partial f}{\partial x} \hat{i} + \frac{\partial f}{\partial y} \hat{j} + \frac{\partial f}{\partial t} \hat{k} \) is the sum of the partial derivative in the x-, y-, and t-directions.

Using this concept of 3D gradient vectors a method to output a 3D vector field to represent spatiotemporal change between two surfaces was developed. This showed the change in surface gradients and elevation between the two surfaces. There are two ways this was performed.

The first method approximated the partial derivatives, using Horn’s (1981) algorithm, of two surfaces that represent the same spatial area at different times, so there were two \( f_x \) and \( f_y \):

\[
f_{x(t=1)} = \frac{\left(z_{t=1}(i+1,j+1) - z_{t=1}(i-1,j+1)\right) + 2\left(z_{t=1}(i+1,j) - z_{t=1}(i-1,j)\right) + \left(z_{t=1}(i+1,j,1) - z_{t=1}(i-1,j,1)\right)}{8\Delta x} \tag{4.15}
\]

\[
f_{x(t=2)} = \frac{\left(z_{t=2}(i+1,j+1) - z_{t=2}(i-1,j+1)\right) + 2\left(z_{t=2}(i+1,j) - z_{t=2}(i-1,j)\right) + \left(z_{t=2}(i+1,j,1) - z_{t=2}(i-1,j,1)\right)}{8\Delta x} \tag{4.16}
\]

\[
f_{y(t=1)} = \frac{\left(z_{t=1}(i+1,j+1) - z_{t=1}(i+1,j-1)\right) + 2\left(z_{t=1}(i+1,j) - z_{t=1}(i+1,j)\right) + \left(z_{t=1}(i+1,j,1) - z_{t=1}(i+1,j,1)\right)}{8\Delta y} \tag{4.17}
\]

\[
f_{y(t=2)} = \frac{\left(z_{t=2}(i+1,j+1) - z_{t=2}(i+1,j-1)\right) + 2\left(z_{t=2}(i+1,j) - z_{t=2}(i+1,j)\right) + \left(z_{t=2}(i+1,j,1) - z_{t=2}(i+1,j,1)\right)}{8\Delta y} \tag{4.18}
\]

Then, the \( f_x \) were differenced to calculate the total change in the x-direction, more recent minus less recent, and the \( f_y \) were also differenced to calculate the total change in the y-direction between the two times. The total change in the x-direction is represented using \( f_{xx} \) and the total change in y-direction is represented using \( f_{yy} \). These are not to be confused with
second order partial derivatives, but were given these symbols to differentiate between partial derivatives and change in partial derivatives:

\[ f_{xx} = f_{x(t=2)} - f_{x(t=1)} \] (4.19)

\[ f_{yy} = f_{y(t=2)} - f_{y(t=1)} \] (4.20)

The difference in elevation between the two surfaces represents the change in elevation with respect to time, for a given grid cell:

\[ f_t \approx \Delta z = z_{t=2} - z_{t=1} \] (4.21)

Since only two surfaces were differenced, the elevation at time one was taken as the initial elevation, \( z_0 \), at each grid cell, and \( f_t \) was added to calculate the elevation at time two:

\[ t_1 = z_0 + f_t \] (4.22)

In the second method, the surfaces were differenced first, to output the change in elevation with respect to time, \( f_t \). Then, the partial derivatives were approximated over the temporal derivative surface, \( f_t \):

\[ f_{xx} = \left( \frac{\Delta z_{(i+1,j+1)} - \Delta z_{(i-1,j+1)}}{8 \Delta x} + 2 \left( \frac{\Delta z_{(i+1,j)} - \Delta z_{(i-1,j)}}{\Delta x} \right) + \left( \frac{\Delta z_{(i+1,j-1)} - \Delta z_{(i-1,j-1)}}{\Delta x} \right) \right) \] (4.23)

\[ f_{yy} = \left( \frac{\Delta z_{(i+1,j+1)} - \Delta z_{(i+1,j-1)}}{8 \Delta y} + 2 \left( \frac{\Delta z_{(i,j+1)} - \Delta z_{(i,j-1)}}{\Delta y} \right) + \left( \frac{\Delta z_{(i-1,j+1)} - \Delta z_{(i-1,j-1)}}{\Delta y} \right) \right) \] (4.24)

Both methods output the same results. Again, the origins were connected to the end points, this time with three dimensions, to draw the 3D change in gradient vectors:

\[ \vec{v} = P_0P_1, P_0 = (x_0, y_0, t_0), P_1 = (x_1, y_1, t_1) \] (4.25)
The 3D vectors were computed using a similar python script that was written for the 2D vector analysis, which called built-in python modules, user defined modules, the numpy model, and GRASS GIS commands, but expanded upon the 2D vector concept to create spatiotemporal vectors. Two DEMs at different times were required as input arguments (Appendix D).

The grid spacing in the Jockey’s Ridge DEMs was very close, 1 m, and it was not necessary to output a vector at every grid cell. Therefore, an optional argument was included in the 2D and 3D scripts that displayed a vector at every nth grid cell. Also, a constant scale factor was another optional argument that could scale the length of the vectors.

The partial derivatives were calculated using an existing tool in GRASS GIS. This tool uses the same equations as listed above, but instead of producing gradients that point in the upslope direction, they point downslope. Therefore, all of the gradients in this analysis point in the direction of maximum decrease in elevation.

4.4 Results

4.4.1 Elevation Surface Gradient Comparison

Figures 4.2 through 4.7 show a DEM draped with contour lines paired with a slope map that has the gradient vector field overlaid to depict the change in slope and aspect (or gradient) that has occurred on Jockey’s Ridge main dune from 1974 to 2012. These figures indicate that the main dune has migrated southeast since 1974, and has also undergone significant changes in shape. The main dune began to develop two peaks in 1995. Figures 4.8 through 4.13 show the evolution of Jockey’s Ridge east dune from 1974 to 2012. The
slope map provides a reference to where the dune slip faces are, and the gradient vectors illustrate both the direction and magnitude of spatial elevation change. Similar to the main dune, the change in location of the slip faces on the eastern dune show that it has migrated south since 1974, and has experienced morphological changes. For example, the eastern dune had begun to split into two separate features.

Starting in 1999, Figure 4.4 for the main dune and Figure 4.10 for the east dune, the contour lines begin to take on a much more complex shape than in the 1974 and 1995 DEMs, especially along the southern slip faces of these dunes. This is because the DEMs starting in 1999 were created from multiple-return LiDAR data, which included vegetation on the surface. The presence of this vegetation led to more complex slope maps and gradient vector fields than the bare earth DEMs created for 1974 and 1995. There was more variation in the gradient vector magnitude and direction over the vegetation.

Figure 4.2 1974 Main Dune DEM draped with contour lines (left), and the slope map overlaid with gradient vectors (right).
Figure 4.3 1995 Main Dune DEM draped with contour lines (left), and the slope map overlaid with gradient vectors (right).

Figure 4.4 1999 Main Dune DEM draped with contour lines (left), and the slope map overlaid with gradient vectors (right).
Figure 4.5 2001 Main Dune DEM draped with contour lines (left), and the slope map overlaid with gradient vectors (right).

Figure 4.6 2008 Main Dune DEM draped with contour lines (left), and the slope map overlaid with gradient vectors (right).
Figure 4.7 2012 Main Dune DEM draped with contour lines (left), and the slope map overlaid with gradient vectors (right).

Figure 4.8 1974 East Dune DEM draped with contour lines (left), and the slope map overlaid with gradient vectors (right).
Figure 4.9 1995 East Dune DEM draped with contour lines (left), and the slope map overlaid with gradient vectors (right).

Figure 4.10 1999 East Dune DEM draped with contour lines (left), and the slope map overlaid with gradient vectors (right).
Figure 4.11 2001 East Dune DEM draped with contour lines (left), and the slope map overlaid with gradient vectors (right).

Figure 4.12 2008 East Dune DEM draped with contour lines (left), and the slope map overlaid with gradient vectors (right).
4.4.2 2D Change in Gradient Vectors

Figures 4.14 through 4.18 are the 2D representation of the change in surface gradients between two years over the main dune, while Figures 4.19 through 4.23 represent the east dune. These vectors show the change in direction of the steepest slope, downhill, at each grid cell. Only vectors where there were greater than ±0.30 m elevation differences were drawn in order to eliminate areas where the elevation difference was less the vertical accuracy of the LiDAR data. Draping a difference in elevation color map over the study sites indicates the change in elevation, where red colors represent where elevation was lost and blue colors represent where elevation was gained between the two times. There are several areas where there are small vector magnitudes, which suggests that there was not much change in the direction of steepest slope between the two years. The grid cells with larger vector magnitudes are of more interest, because these areas would have undergone more distinct directional change.

Figure 4.13 2012 East Dune DEM draped with contour lines (left), and the slope map overlaid with gradient vectors (right).
Figures 4.14 and 4.19 show the change in gradient over a large gap in time, from 1974 to 1995. The eastern slip face on the main dune migrated nearly 50 m east and the southern slip face migrated nearly 50 m south (Figure 4.14). The distribution of the blue and red colors over this dune further indicates that the dune has migrated. Also, the eastern dune migrated south by nearly 50 m over this time (Figure 4.19). This is supported by the presence of blue colors in the southeastern section of the eastern dune, where the dune migrated to by 1995, and red colors in the north central position, where the dune was in 1974. The biggest directional changes occurred where the dune slip faces were, surrounding areas where there were large changes in dune elevation, on the eastern and southern sides of both the main and east dunes.

The change in gradient between 1995 and 1999 is shown in Figure 4.15 on the main dune and Figure 4.20 on the east dune. The main dune shows that there was a loss in elevation on the northern section of the dune, but a gain in the south. This further shows southerly migration of the dune. There were small directional changes along the eastern and southern slip faces. On the east dune, there continued to be a loss in elevation in the north, but there was some gain on the southern leading edge. The directional changes were not as widespread, but contained along the southern slip face. However, the appearance of vegetation in 1999 affected the change in gradient in the southern section of both dunes.

Similarly, there was not much significant change between 1999 and 2001, on either the main dune (Figure 4.16) or east dune (Figure 4.21), and the slip faces occupied nearly the same spatial location over the two-year time period. The main change that is visible at these dunes was a change in elevation. Again, in the southeastern section of the dunes, the
vegetation caused variation in the direction of change in gradient. Both elevation loss and gain occurred over this area.

Between 2001 and 2008, the presence of large magnitude vectors on the main dune (Figure 4.17) indicates that the eastern and southern slip faces migrated, south and east, respectively. Figure 4.22 illustrates that the eastern dune was beginning to develop two ridges between 2001 and 2008.

The largest changes in gradient between 2008 and 2012 over the main dune (Figure 4.18) were concentrated over the eastern slip face since the dune had migrated east. Also, the red colors over the dune ridges show that the dune was losing elevation. The eastern dune had developed into two peaks by 2008 (Figure 4.23). The distribution of vectors with large magnitudes further show this change, where the vectors between the two peaks show a diverging pattern. Also, the presence of red colors over the dune ridges suggests that the eastern dune began to decrease in elevation. However, the blue colors on the southern and southeastern portion of the dune are consistent with the dune migrating southeast. The loss of elevation between the two dune peaks shows that the eastern dune had begun to take on a parabolic dune form.
Figure 4.14 Change in gradient over the main dune between 1974 and 1995 displayed over the 1974 DEM.

Figure 4.15 Change in gradient over the main dune between 1995 and 1999 displayed over the 1995 DEM.
Figure 4.16 Change in gradient over the main dune between 1999 and 2001 displayed over the 1999 DEM.

Figure 4.17 Change in gradient over the main dune between 2001 and 2008 displayed over the 2001 DEM.
Figure 4.18 Change in gradient over the main dune between 2008 and 2012 displayed over the 2008 DEM.

Figure 4.19 Change in gradient over the east dune between 1974 and 1995 displayed over the 1974 DEM.
Figure 4.20 Change in gradient over the east dune between 1995 and 1999 displayed over the 1995 DEM.

Figure 4.21 Change in gradient over the east dune between 1999 and 2001 displayed over the 1999 DEM.
Figure 4.22 Change in gradient over the east dune between 2001 and 2008 displayed over the 2001 DEM.

Figure 4.23 Change in gradient over the east dune between 2008 and 2012 displayed over the 2008 DEM.
4.4.3 3D Change in Gradient and Elevation Vectors

Figures 4.24 through 4.28 display the 3D vectors over the main dune DEMs and Figures 4.29 through 4.33 show this change over the eastern dune DEMs in order to show the change in the gradient and elevation between two years. Although all vectors are oriented in the positive z-direction, the color indicates whether elevation was lost (red) or gained (blue). The angles at which the vectors are pointing indicate the change in direction of the gradients, or steepest slope, in specific grid cells from the first year to the second year. If the vector is oriented (nearly) perpendicular to the surface, the main difference between years in this grid cell was dune elevation change. However, if this angle was closer to parallel, the main difference was change in direction of steepest slope.

The 3D vectors displayed over the main dune between 1974 and 1995 in Figure 4.24 show that the dune migrated south and east. The vectors show a diverging pattern between the 1974 slip face position and the 1995 slip face. This shows that the direction of steepest slope changed because the slip face migrated. In Figure 4.29, the 3D vectors showing the change between 1974 and 1995 over the east dune depict that there was significant elevation loss in the northern section of the dune and gain in the southern section, which is consistent with the other results that indicate the dune was migrating southward.

The change over the main dune between 1995 and 1999 was not as distinct as the change between 1974 and 1995 because not as much time had passed (Figure 4.25). However, the elevation loss on the northern section of the dune and gain to the south indicate that the dune had migrated. Also, the directional changes are concentrated along the slip faces. The 3D vectors displayed over the eastern dune between 1995 and 1999 in Figure 4.30
show a southerly migration. Also, the main directional changes on the east dune were along the southern slip face.

There was not much change over the main dune between 1999 and 2001 as shown in Figure 4.26. Between 1999 and 2001, the east dune continued to migrate south as evidenced by the loss in elevation in the north and gain in the south (Figure 4.31). Vegetation was present in the southeast area, which explains the complex topography, and greatly affected the vector directions and magnitudes.

The vectors show a diverging pattern between where the eastern and southern slip face were in 2001 and where they were in 2008 along the main dune in Figure 4.27. Also, this divergence is visible between the two dune peaks, which suggest that the dune is changing shape. The distribution of elevation loss and gain vectors supports that the dune is migrating south and east. The east dune also shows divergent vectors between the two peaks in Figure 4.32, which means that the shape is changing.

The 3D vectors over the main dune between 2008 and 2012 show the divergence between the two peaks in Figure 4.28. The eastern slip face also shows this divergence, which means the slip face migrated. The eastern dune continued to migrate southeast between 2008 and 2012 as indicated by the loss in elevation in the north and gain in the southeast (Figure 4.33). However, it is important to note that there is a section of loss in the southern portion of the dune, between the two dune ridges, and these vectors show an area of divergence. This further supports that the east dune is splitting into two parabolic dunes.
Figure 4.24 3D change in gradient and elevation between 1974 and 1995 displayed over the 1974 main dune DEM.

Figure 4.25 3D change in gradient and elevation between 1995 and 1999 displayed over the 1995 main dune DEM.
Figure 4.26 3D change in gradient and elevation between 1999 and 2001 displayed over the 1999 main dune DEM.

Figure 4.27 3D change in gradient and elevation between 2001 and 2008 displayed over the 2001 main dune DEM.
Figure 4.28 3D change in gradient and elevation between 2008 and 2012 displayed over the 2012 main dune DEM.

Figure 4.29 3D change in gradient and elevation between 1974 and 1995 displayed over the 1974 east dune DEM.
Figure 4.30 3D change in gradient and elevation between 1995 and 1999 displayed over the 1995 east dune DEM.

Figure 4.31 3D change in gradient and elevation between 1999 and 2001 displayed over the 1999 east dune DEM.
Figure 4.32 3D change in gradient and elevation between 2001 and 2008 displayed over the 2001 east dune DEM.

Figure 4.33 3D change in gradient and elevation between 2008 and 2012 displayed over the 2008 east dune DEM.
4.5 Discussion

The design for effectively presenting these vector analyses was an important component of this investigation. Spatially, many vectors had small magnitudes, and only the vectors with large magnitudes could be seen clearly. Therefore, all vectors over the surface were multiplied by a constant scale factor. Also, a constant thickness was applied to the vector field, so all vectors had the same width, to determine if this would improve the visualization. However, increasing the constant thickness on vectors with small magnitudes could create the effect that these vectors were pointing perpendicular to their real direction, if the width was greater than the length of the vector. To prevent this, vectors could be selected, based on a specific attribute, like vector magnitude in the x- and y-directions. However, in this analysis, vectors were displayed in cells that had greater than 0.30 m elevation change.

The DEMs, contour lines, and slope maps were all used to support the vector field visualizations. Although the 2D change in gradient was displayed over a change in elevation map with contours (Figures 4.13-4.22), other options were explored. This design was chosen to highlight the change in gradients on the slip faces, where the contours are closely spaced. However, the interactive nature of the GRASS interface provides multiple design possibilities.

Another challenge included finding an appropriate symbol to represent the vector field features, while preserving the angle they were pointing. The stick features were appropriate since the user can see the direction and magnitude of change in the vector field. Also, endpoint symbols (circles) were included with the 2D change in vector field, so the
direction of change is clearer. Other potential designs could use glyphs, such as those described in Tateosian et al. 2013, to show the magnitude of elevation change, but it would be difficult to show the direction of change in the gradient.

One of the main challenges with this analysis was determining an appropriate design that can help visualize the change in topography in 3D. Initially, the vectors were displayed over a constant surface, with an elevation of 0, so each vector started at the same elevation. This led to a cluttered view of the vector field, since some were pointing in the positive z-direction and others were pointing in the negative z-direction. If the view angle was lowered to capture both gain and loss in elevation, the field of view was severely limited. To resolve this issue, the absolute value of the change in elevation was shown as the end z-coordinate of the vector, and colors were used to indicate whether loss or gain in elevation was occurring. This simplified vector field was applied so that the user would not have to alternate between a top view and bottom view of the 3D surface in order to see where loss and gain were occurring, but rather they were able to view both simultaneously from the same view angle. Another challenge was using a constant plane to visualize these spatiotemporal vector fields, which limited the understanding of how the vector field was related to topography. Therefore, the script was modified so the initial elevation was the same as the elevation during the first input DEM. This provided better spatial context to the user, and allowed the vector field to be displayed over the DEM.

When the change in gradient vectors were displayed in 2D, there are several areas where there was minimal directional change. However, when the change in gradient and elevation vectors were displayed in 3D, it was revealed that many of these areas that showed
minimal directional change had undergone significant elevation change. When the changes in elevation are more prominent than the changes in direction, the dune shape is more stable, and the main process that is occurring is primarily dune migration. In areas where there are distinct changes in direction, it is clear that some process is causing change in the shape of the dune. For example, as the sand supply is restricted, possibly due to increased vegetation, dunes transform from crescentic to parabolic shape (Pelletier et al. 2009). The vector method of calculating the change in gradient can be a useful first step in determining where these directional changes are taking place, and what could potentially be causing this change.

This was an exploratory approach for visualizing vector field migration and deformation, and the results for this preliminary study are inconclusive for understanding how the dune geometry evolved and the processes that led to the change. The elevation change was more easily understood than the change in direction of downhill slope. The long-term change of the dune between 1974 and 1995 shows areas of distinct change in the direction of steepest slope that were associated with the slip faces. The short-term comparisons were noisier, and the vegetated areas were associated with the most directional change. There was not much change in the dune position in the DEM pairs that were compared over shorter time periods: 1995-1999, 1999-2001, 2001-2008, and 2008-2012. There were changes in the gradient direction on the slip faces in the more recent data, and this could be a clue to how the dune shape has begun to fall apart. However, this change is difficult to interpret using the results produced for this analysis.

There are studies that have explored using satellite and aerial imagery to determine how sand dunes have migrated over time. The Co-registration of Optically Sensed Images
and Correlations (COSI-Corr) methods have been used to monitor migration rates of both slow and fast moving dunes (Necsoiu et al. 2009; Vermeesch and Drake 2008; Leprince et al. 2007). Using COSI-Corr software, pairs of images are compared to measure the north-south and east-west displacement fields. Another study by Guth (2013) compared two DEMs to create a vector field that showed how White Sand Dunes in New Mexico evolved. A search window was applied to the DEMs to determine how the dunes were correlated and the direction the dunes were migrating. These analyses were applied to active dune fields that were migrating, but had not undergone significant morphological change.

As described in the previous chapter, Jockey’s Ridge has undergone significant morphological changes over the past century. The overall change that has been documented includes a decrease in dune elevation, southern migration, and an increase in dune field area since the 1950s (Mitasova et al. 2005b). One of the reasons this occurs is the establishment of vegetation within the dune field, which increases the surface roughness, allowing the vegetation to absorb wind energy. Vegetation is able to grow in areas where there is minimal erosion, and then is able to capture sand, causing a shift in the shape of the dune. Models have been developed to show the morphological changes a dune would undergo in the presence of vegetation (Pelletier et al. 2009, Duran and Herrmann 2006). Pelletier et al. (2009) applied a dune evolution model at Jockey’s Ridge to compare how dunes evolve with and without interdune vegetation. Although this model did not replicate the exact evolution of Jockey’s Ridge, it did help conceptualize and quantify the amount of change a dune experiences. The goal of this study is to use the vector field analysis to gain a better understanding of how a dune is changing shape, which is omitted in the dune evolution
models. This analysis could aid in the design and updating of these numerical models, by allowing users to see what directional changes are occurring. Although there is still work that needs to be done, these vector fields could one day help extract areas where large changes in dune shape are occurring, which would be useful for calibrating future numerical models.

4.6 Conclusion

Vector fields are informative visuals that can be used to see how topography has changed spatially and temporally. Gradient vectors are important for topographic analyses that use slope and aspect to understand how a surface changes spatially. As multi-temporal elevation data has become available, understanding how these surfaces change through time can provide insights on how surface processes affect coastal morphology. The change in gradient vector fields couple both spatial and temporal components to show how a surface changed between two years, which can underscore how large surface features, such as dunes are changing through time. A new methodology that calculates the change between gradient vectors in a pair of DEMs and the elevation change between the two DEMs was explored in this analysis at Jockey’s Ridge. However, the results were not linked to specific natural processes, and future work should focus on how to interpret these results. Ultimately, this analysis can be useful for updating dune morphology numerical models.
CHAPTER 5: Conclusion

The North Carolina Outer Banks are highly dynamic and are altered by a variety of different coastal and anthropogenic processes. Our ability to understand coastal geomorphology through space and time has improved from using geographic information systems (GIS) to perform analyses on light detection and ranging (LiDAR) data. In this work, three geospatial techniques were presented to assimilate storm impacts and topographic change on the Outer Banks.

A storm surge analysis was performed to assess maximum flooding extent during Hurricane Irene by identifying wrack lines in post-storm orthoimagery. The wrack line was compared to Hurricane Irene ADCIRC storm surge forecasts in order to evaluate the model’s accuracy. Although the results indicated that ADCIRC underestimated maximum water levels during Hurricane Irene, coupling it with a wave model could improve these predictions. This information is invaluable in order to make informed coastal emergency decisions. While the ADCIRC model does incorporate storm dynamics into the prediction, the inundation forecast is restricted by the low grid resolution. Therefore, a simple spread inundation applied over a high-resolution DEM can supplement the ADCIRC forecast by showing how water can flood over a more detailed surface. Using the ADCIRC prediction, this spread model was able to highlight areas that were vulnerable to flooding, such as low foredunes. Future work should be directed towards incorporating a temporal component in the spread model in order to reduce overestimation of flooding extent. Then, the updated
spread model outputs should be compared with ADCIRC predictions over larger spatial areas to better understand how these models can be coupled.

One of the limitations to the inundation models is that they do not show how topography changes due to storm impacts or other coastal processes. To better visualize how coastal landscapes change through space and time, a space-time cube (STC) approach was applied at three study sites along the Outer Banks. This approach integrates both spatial and temporal dimensions in order to visually summarize topographic evolution in a single image. This change was analyzed by extracting isosurfaces. Landscape trends were visible in the isosurfaces, such as storm impacts, human development, and complex dune evolution due to aeolian processes and vegetation distribution. In future studies, the evolution of other parameters, such as slope and change in elevation, should be explored using isosurfaces to see if the topology can be linked with coastal and anthropogenic processes.

Although these landscape patterns can be associated with processes, other analyses are needed to comprehend how these processes change coastal terrain. An exploratory vector field analysis was used to better understand the spatial and temporal migration of dune fields. This analysis required the gradient vectors of a DEM to be calculated. Then, the change in gradient between DEMs pairs was found. Also, these vector fields incorporated change in elevation. These vectors displayed the change in elevation and direction of steepest slope in each grid cell. The main changes that were observed were elevation and directional changes on the dune slip faces due to dune migration. All results presented in this analysis were preliminary, and future work should be directed in this area to improve these methods in order to understand how dunes are transforming and migrating through time. This
information could then be used to calibrate numerical dune evolution models. Each of these geospatial analyses present a new way for investigating the effects of coastal processes. The storm surge impact analysis employs methods that are more efficient than traditional techniques for assessing and predicting storm surge flooding. The STC approach builds upon previous methods for analyzing spatiotemporal change by displaying all data concurrently. Although the vector field analysis is still in an exploratory stage, the results can eventually be used to gain information on how coastal landforms change. Further research should be directed to expand upon each of these geospatial methods to advance our understanding of coastal geomorphology.
REFERENCES


## Appendix A

### Table A.1 Wrack Line elevation along Pea Island transects

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### Table A.3 ADCIRC and GRASS Inundation Comparison at Pea Island

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Appendix B

# Purpose: Storm Surge Impact analysis GRASS commands and python scripts
# Prepared by Emily Russ
# Edited November 9, 2013

Pea Island
# set geographic region
g.region n=220800 s=218490 e=928560 w=926650 res=0.5

# Import 2009 data
v.surf.rst -z input=PI_20091201@PI_wrackline_2013 layer=0 elev=PI_20091201_05rst tension=40.
smooth=0.8 segmax=40 npmin=120 dmin=0.5 dmax=1.250000 zmult=1.0

# No systematic error correction needed
# Apply inundation model r.lake to 2009 DEM through python
python
import os
for level in range(26):
    os.system("r.lake elevation=PI_20091201_05rst xy=927359.752294,219890.834862 wl="+str(level/10.)+" lake=PI_20091201_05rst_"+str(level))
for level in range(26):
    os.system("d.rast PI_20091201_05rst")
    os.system("d.rast -o PI_20091201_05rst_"+str(level))
    os.system("d.out.file output=PI_20091201_05rst_"+str(level))
    os.system("d.erase")

# Import 2011 data
v.surf.rst -z input=PI_20110829@PI_wrackline_2013 layer=0 elev=PI_20110829_05rst tension=40.
smooth=0.8 segmax=40 npmin=120 dmin=0.5 dmax=1.250000 zmult=1.0

# Systematic Error Correction
# NC Highway 12 coordinates 2009
point = [(927729.763,220741.384), (927753.747,220644.2897), (927762.24,220594.9889),
(927770.1115,220492.8658), (927770.1115,220441.0792), (927952.0658,219765.141),
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(928235.8413,218701.7205), (928246.3405,218653.0046),
(928254.7398,218603.4488)]

# Query Elevation of DEM with baseline (2009) points
python
import os
for point in NC12:
    coords=str(point[0]+','+str(point[1])
    os.system(r.input=PI_20110829_rst coordinates=""+coords)

# Remove median error for each DEM
# Difference benchmark elevation and DEM elevation to get median error (trendline)
r.mapcalc '2011_trendError = (220800 - y()) * -0.0001046308 + 0.15559172'
r.mapcalc 'PI_20110829_rstc = PI_20110829_rstc - 2011_trendError'

# Wrack line elevation comparison
Wrack line coordinates:
wrack =
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import os
for w in wrack:
    coords=str(w[0])+','+str(w[1])
o.s.system("r.what input=PI_20091201_05rst coordinates="+coords)

for w in wrack:
    coords=str(w[0])+','+str(w[1])
o.s.system("r.what input=PI_20110829_05rstc coordinates="+coords)

# Spread Model and ADCIRC Comparison
# Generate random points
r.random input=Ro_20091201_05rst n=30 cover=Ro_20091201 raster_output=Ro_randpoints
vector_output=Ro_randpoints
v.out.ascii input=Ro_randpoints layer=1 format=point fs=, output=Ro_randpoints.txt

import os
dir = os.getcwd()
f = open(dir+/'Ro_randpoints.txt', 'r')
g = open(dir+/'Ro_randpoints_xy.txt', 'w')
for line in f:
    a = line.split(',')
    b = '{0},{1}
n'.format(str(a[0]),str(a[1]))
g.write(b)
f.close()
g.close()

DEM = DEM Name string
g = open(dir+/'Ro_randpoints_xy.txt', 'r')
for line in g:
    os.system(r.what="+DEM+:" coordinates=line)
g.close()

# Compare with ADCIRC output

Rodanthe
g.region n=212061 s=211023 e=930000 w=929149 res=0.5

# Import 2009 data
v.surf.rst -z input=Ro_20091201_Rodanthe_Summer2013 layer=0 elev=Ro_20091201_05rst tension=40.
smooth=0.8 segmax=40 npmin=120 dmin=0.5 dmax=1.250000 zmult=1.0

# No systematic error correction needed
# Apply inundation model r.lake to 2009 DEM through python
python
import os
for level in range(26):
    os.system(f"r.lake elevation=Ro_20091201_05rst xy=929231.674312,211740.077064 wl="+str(level/10.)+" lake=Ro_20091201_05rst_"+str(level))
for level in range(26):
    os.system(f"d.rast Ro_20091201_05rst")
    os.system(f"d.rast -o Ro_20091201_05rst_"+str(level))
    os.system(f"d.out.file output=Ro_20091201_05rst_"+str(level))
    os.system(f"d.erase")

# Import 2011 data
v.surf.rst -z input=PI_20110829@PI_wrackline_2013 layer=0 elev=Ro_20110829_05rst tension=40. smooth=0.8 segmax=40 npmin=120 dmin=0.5 dmax=1.250000 zmult=1.0

# Systematic Error Correction
# NC Highway 12 coordinates 2009 DEM
point = [(929699.9983,211986.8082), (929702.9332,211976.5358), (929706.2875,211965.2152),
(929478.6174,212741.4108), (929466.8775,212900.109), (929467.7161,212868.3484),
(929471.0703,212828.5166), (929472.3282,212809.6489), (929474.0053,212787.5318),
(929475.2632,212767.8256)]

# Query Elevation of DEM with baseline (2009) points
import os
for point in NC12:
    coords=str(point[0]+','+str(point[1])
    os.system(r.what input=Ro_20110829_rst coordinates=+coords)

# Remove median error for each DEM
Ro_20110829_rstw@Rodanthe_Summer2013 - 0.7460116

# Wrack line elevation comparison
Wrack line coordinates:
wrack = [(929547.3,212054.5), (929534.4,212036.6), (929476.5,212026),
(929577.5,211980), (929519.1,211898), (929321.7,211811.4),(929425.1,211778.4), (929497.3,211817),
(929565.2,211772.2), (929684.2,211719.9), (929709.7,211624.6), (929479.4,211583.7),(929558.4,211343.6),
(929625.6,211372), (929603.3,211161.7),(929611.5,211140.6), (929723.5,211136.4), (929781.1,211109.4)]

import os
for w in wrack:
    coords=str(w[0]+','+str(w[1])
    os.system(r.what input=Ro_20091201_05rst coordinates=+coords)

# Spread Model and ADCIRC Comparison
# Generate random points
r.random input=Ro_20091201_05rst n=30 cover=Ro_20091201 raster_output=Ro_randpoints
vector_output=Ro_randpoints
v.out.ascii input=Ro_randpoints layer=1 format=point fs=, output=Ro_randpoints.txt
python
import os
dir = os.getcwd()
f = open(dir+'/Ro_randpoints.txt', 'r')
g = open(dir+'/Ro_randpoints_xy.txt', 'w')
for line in f:
    a = line.split(',
    b = '{0},{1}
        format(str(a[0]),str(a[1]))
    g.write(b)

f.close()
g.close()
DEM = DEM Name string
g = open(dir+'/Ro_randpoints_xy.txt', 'r')
for line in g:
    os.system(r.what="+DEM+" coordinates=line)

g.close()

# Compare with ADCIRC output
Appendix C

# Purpose: Space-time cubes analysis GRASS commands and python scripts
# Prepared by Emily Russ
# Edited November 9, 2013

Rodanthe
g.region n=212061 s=211023 e=930000 w=929149 res=1 res3=2 tbres=8 t=264 b=0

# Interpolate Point Clouds into 1m resolution DEMs
v.surf.rst -z input=Rodanthe_19961012@Rodanthe_Summer2013 layer=0 elev=Ro_19961012_rst smooth=0.8 npmin=120 --o
v.surf.rst -z input=Rodanthe_19970927@Rodanthe_Summer2013 layer=0 elev=Ro_19970927_rst smooth=0.8 npmin=120 --o
v.surf.rst -z input=Rodanthe_19980907@Rodanthe_Summer2013 layer=0 elev=Ro_19980907_rst smooth=0.8 npmin=120 --o
v.surf.rst -z input=Rodanthe_19991006@Rodanthe_Summer2013 layer=0 elev=Ro_19991006_rst smooth=0.8 npmin=120 --o
v.surf.rst -z input=Rodanthe_20010201@Rodanthe_Summer2013 layer=0 elev=Ro_20010201_rst smooth=0.8 npmin=120 --o
v.surf.rst -z input=Rodanthe_20030916@Rodanthe_Summer2013 layer=0 elev=Ro_20030916_rst smooth=0.8 npmin=120 --o
v.surf.rst -z input=Rodanthe_20030921@Rodanthe_Summer2013 layer=0 elev=Ro_20030921_rst smooth=0.8 npmin=120 --o
v.surf.rst -z input=Rodanthe_20040716@Rodanthe_Summer2013 layer=0 elev=Ro_20040716_rst smooth=0.8 npmin=120 --o
v.surf.rst -z input=Rodanthe_20051126@Rodanthe_Summer2013 layer=0 elev=Ro_20051126_rst smooth=0.8 npmin=120 --o
v.surf.rst -z input=Rodanthe_20080327@Rodanthe_Summer2013 layer=0 elev=Ro_20080327_rst smooth=0.8 npmin=120 --o
v.surf.rst -z input=Rodanthe_20090824@Rodanthe_Summer2013 layer=0 elev=Ro_20090824_rst smooth=0.8 npmin=120 --o
v.surf.rst -z input=Rodanthe_20091201@Rodanthe_Summer2013 layer=0 elev=Ro_20091201_rst smooth=0.8 npmin=120 --o
v.surf.rst -z input=Rodanthe_20110829@Rodanthe_Summer2013 layer=0 elev=Ro_20110829_rst smooth=0.8 npmin=120 --o
v.surf.rst -z input=Rodanthe_20121110@Rodanthe_Summer2013 layer=0 elev=Ro_20121110_rst smooth=0.8 npmin=120 --o

# Correct systematic errors
NC Highway 12 Benchmark coordinates
import os
for point in NC12:
    coords=str(point[0])+';'+str(point[1])
    os.system("r.what input=Ro_19961012_rst@Rodanthe_Summer2013,Ro_19970927_rst@Rodanthe_Summer2013,Ro_19980907_rst@Rodanthe_Summer2013,Ro_19991006_rst@Rodanthe_Summer2013,Ro_20010201_rst@Rodanthe_Summer2013,Ro_20030916_rst@Rodanthe_Summer2013,Ro_20030921_rst@Rodanthe_Summer2013,Ro_20040716_rst@Rodanthe_Summer2013")
# Remove median error for each DEM

# Clean up DEMs with manually digitized masks
r.mapcalc --o 'Ro_19961012_rstc=Ro_19961012_rst*mask_96'
r.mapcalc --o 'Ro_19970927_rstc=Ro_19970927_rst*mask_97'
r.mapcalc --o 'Ro_19980907_rstc=Ro_19980907_rst*mask_98'
r.mapcalc --o 'Ro_19991006_rstc=Ro_19991006_rst*mask_99'
r.mapcalc --o 'Ro_20000916_rstc=Ro_20000916_rst*mask_03'
r.mapcalc --o 'Ro_20030921_rstc=Ro_20030921_rst*mask_031'
r.mapcalc --o 'Ro_20040716_rstc=Ro_20040716_rst*mask_04'
r.mapcalc --o 'Ro_20051126_rstc=Ro_20051126_rst*mask_05'
r.mapcalc --o 'Ro_20051126_rstc=if(isnull(Ro_20051126_rstc),0.0, Ro_20051126_rstc)'
r.mapcalc --o 'Ro_20051126_rstc=float(Ro_20051126_rstc)'
r.mapcalc --o 'Ro_20090824_rstc=Ro_20090824_rst*mask_09'
r.mapcalc --o 'Ro_20090824_rstc=if(isnull(Ro_20090824_rstc),0.0, Ro_20090824_rstc)'
r.mapcalc --o 'Ro_20090824_rstc=float(Ro_20090824_rstc)'
r.mapcalc --o 'Ro_20091201_rstc=Ro_20091201_rst*mask_091'
r.mapcalc --o 'Ro_20091201_rstc=if(isnull(Ro_20091201_rstc),0.0, Ro_20091201_rstc)'
r.mapcalc --o 'Ro_20091201_rstc=float(Ro_20091201_rstc)'

# Patch incomplete datasets
r.patch --o input=Ro_19961012_rstc,Ro_20010201_rst output=Ro_19961012_rstcp
r.patch --o input=Ro_19970927_rstc,Ro_20010201_rst output=Ro_19970927_rstcp
r.patch --o input=Ro_19980907_rstc,Ro_20010201_rst output=Ro_19980907_rstcp
r.patch --o input=Ro_19991006_rstc,Ro_20010201_rst output=Ro_19991006_rstcp
r.patch --o input=Ro_20030916_rstc,Ro_20040716_rst output=Ro_20030916_rstcp
r.patch --o input=Ro_20030921_rstc,Ro_20040716_rst output=Ro_20030921_rstcp

# Mask to common area

# Extract 0.5m (shoreline) contour from DEMs
r.contour input=Ro_19970413_rstc@Rodanthe_Summer2013 output=Ro_19970413_05 levels=0.5 cut=100
r.contour input=Ro_19991006_rstc@Rodanthe_Summer2013 output=Ro_19991006_05 levels=0.5 cut=100
r.contour input=Ro_20010201_rstc@Rodanthe_Summer2013 output=Ro_20010201_05 levels=0.5 cut=100
r.contour input=Ro_20030916_rstc@Rodanthe_Summer2013 output=Ro_20030916_05 levels=0.5 cut=100
r.contour input=Ro_20030921_rstc@Rodanthe_Summer2013 output=Ro_20030921_05 levels=0.5 cut=100

# Calculate ~0.5 year rasters using map algebra
r.mapcalc 'Ro_19970413=Ro_19961012_rstcp+ ((Ro_19970927_rstcp-Ro_19961012_rstcp)/350)*183' --o
r.mapcalc 'Ro_19980413=Ro_19970927_rstcp+ ((Ro_19980907_rstcp-Ro_19970927_rstcp)/345)*199' --o
r.mapcalc 'Ro_19990415=Ro_19980907_rstcp+ ((Ro_19991006_rstcp-Ro_19980907_rstcp)/394)*220' --o
r.mapcalc 'Ro_20001015=Ro_19991006_rstcp+ ((Ro_20010201_rst-Ro_19991006_rstcp)/484)*375' --o
r.mapcalc 'Ro_20011016=Ro_20010201_rst+ ((Ro_20030916_rst-Ro_20010201_rst)/957)*257' --o
r.mapcalc 'Ro_20020417=Ro_20010201_rst+ ((Ro_20030916_rst-Ro_20010201_rst)/957)*440' --o
r.mapcalc 'Ro_20021017=Ro_20010201_rst+ ((Ro_20030916_rst-Ro_20010201_rst)/957)*623' --o
r.mapcalc 'Ro_20040417=Ro_20030921_rstcp+ ((Ro_20040716_rst-Ro_20030921_rstcp)/299)*209' --o
r.mapcalc 'Ro_20050419=Ro_20040716_rstcp+ ((Ro_20051126_rst-Ro_20040716_rstcp)/498)*277' --o
r.mapcalc 'Ro_20060420=Ro_20051126_rstcp+ ((Ro_20061020_rst-Ro_20051126_rstcp)/852)*145' --o
r.mapcalc 'Ro_20061020=Ro_20051126_rstcp+ ((Ro_20061020_rst-Ro_20051126_rstcp)/852)*328' --o
r.mapcalc 'Ro_20070421=Ro_20061020_rstcp+ ((Ro_20070421_rst-Ro_20061020_rstcp)/852)*511' --o
r.mapcalc 'Ro_20070421=Ro_20061020_rstcp+ ((Ro_20070421_rst-Ro_20061020_rstcp)/852)*694' --o
r.mapcalc 'Ro_20081021=Ro_20070421_rstcp+ ((Ro_20081021_rst-Ro_20070421_rstcp)/515)*208' --o
r.mapcalc 'Ro_20081021=Ro_20070421_rstcp+ ((Ro_20081021_rst-Ro_20070421_rstcp)/515)*362' --o
r.mapcalc 'Ro_20081021=Ro_20070421_rstcp+ ((Ro_20081021_rst-Ro_20070421_rstcp)/515)*511' --o
r.mapcalc 'Ro_20081021=Ro_20070421_rstcp+ ((Ro_20081021_rst-Ro_20070421_rstcp)/515)*694' --o
r.mapcalc 'Ro_20090824_rstcp=Ro_20080327_rst+ ((Ro_20090824_rst-Ro_20080327_rst)/515)*208' --o
r.mapcalc 'Ro_20090824_rstcp=Ro_20080327_rst+ ((Ro_20090824_rst-Ro_20080327_rst)/515)*362' --o
r.mapcalc 'Ro_20090824_rstcp=Ro_20080327_rst+ ((Ro_20090824_rst-Ro_20080327_rst)/515)*511' --o
r.mapcalc 'Ro_20090824_rstcp=Ro_20080327_rst+ ((Ro_20090824_rst-Ro_20080327_rst)/515)*694' --o

# Stack rasters into voxel model
r.to.rast3
input='Ro_19961012_rstcp,Ro_19970927_rstcp,Ro_19980413,Ro_19980907_rstcp,Ro_19990415,Ro_19991006_rstcp,Ro_20000415,Ro_20001020_rst,Ro_20010201_rst,Ro_20011016,Ro_20020417,Ro_20021017,Ro_20030916_rstcp,Ro_20030921_rstcp,Ro_20040417,Ro_20040716_rstcp,Ro_20050419,Ro_20051126_rstcp,Ro_20060420,Ro_20061020,Ro_20070421,Ro_20071021,Ro_20080327_rst,Ro_20081021,Ro_20090824_rstcp,Ro_20091201_rstcp,Ro_20100423,Ro_20101023,Ro_20110829_rst,Ro_20110829_rst,Ro_20120423,Ro_20121107_rst,Ro_20120423,Ro_20121107_rst'
output='STC_9612'

# Calculate rasters for time
r.mapcalc --o 'Ro_19961012c=100'
or.mapcalc --o 'Ro_19970927c=200'
or.mapcalc --o 'Ro_19980413c=300'
or.mapcalc --o 'Ro_19980907c=400'
or.mapcalc --o 'Ro_19990415c=500'
or.mapcalc --o 'Ro_19991006c=600'
or.mapcalc --o 'Ro_20000415c=700'
or.mapcalc --o 'Ro_20001020c=800'
or.mapcalc --o 'Ro_20010201c=900'
or.mapcalc --o 'Ro_20011016c=1000'
or.mapcalc --o 'Ro_20020417c=1100'
or.mapcalc --o 'Ro_20021017c=1200'
or.mapcalc --o 'Ro_20030916c=1300'
or.mapcalc --o 'Ro_20030921c=1400'
or.mapcalc --o 'Ro_20030921c=1500'
or.mapcalc --o 'Ro_20040417c=1600'
or.mapcalc --o 'Ro_20040716c=1700'
or.mapcalc --o 'Ro_20050419c=1800'
or.mapcalc --o 'Ro_20051126c=1900'
or.mapcalc --o 'Ro_20060420c=2000'
or.mapcalc --o 'Ro_20061020c=2100'
or.mapcalc --o 'Ro_20070421c=2200'
or.mapcalc --o 'Ro_20071021c=2300'
or.mapcalc --o 'Ro_20080327c=2400'

# Stack rasters into voxel model
r.to.rast3
input='Ro_19961012_rstcp,Ro_19970927_rstcp,Ro_19980413,Ro_19980907_rstcp,Ro_19990415,Ro_19991006_rstcp,Ro_20000415,Ro_20001020_rst,Ro_20010201_rst,Ro_20011016,Ro_20020417,Ro_20021017,Ro_20030916_rstcp,Ro_20030921_rstcp,Ro_20040417,Ro_20040716_rstcp,Ro_20050419,Ro_20051126_rstcp,Ro_20060420,Ro_20061020,Ro_20070421,Ro_20071021,Ro_20080327_rstcp,Ro_20081021,Ro_20090824_rstcp,Ro_20091201_rstcp,Ro_20100423,Ro_20101023,Ro_20110829_rstcp,Ro_20120423,Ro_20121107_rstcp'
output='STC_9612'
r.mapcalc --o 'Ro_20081021c=2500'
r.mapcalc --o 'Ro_20090824c=2600'
r.mapcalc --o 'Ro_20091201c=2700'
r.mapcalc --o 'Ro_20100423c=2800'
r.mapcalc --o 'Ro_20101023c=2900'
r.mapcalc --o 'Ro_20110829c=3000'
r.mapcalc --o 'Ro_20120423c=3100'
r.mapcalc --o 'Ro_20121107c=3200'

# Stack year rasters into voxel model to create color table
r.to.rast3 --o
input=Ro_19961012c,Ro_19970413c,Ro_19970927c,Ro_19980413c,Ro_19980907c,Ro_19990415c,Ro_19991006c,Ro_20000415c,Ro_20001015c,Ro_20010201c,Ro_20011016c,Ro_20020417c,Ro_20021017c,Ro_20030916c,Ro_20030921c,Ro_20040417c,Ro_20040716c,Ro_20050419c,Ro_20051126c,Ro_20060420c,Ro_20061020c,Ro_20070421c,Ro_20071021c,Ro_20080327c,Ro_20081021c,Ro_20090824c,Ro_20091201c,Ro_20100423c,Ro_20101023c,Ro_20110829c,Ro_20120423c,Ro_20121107c output=STC_time_32

# Difference rasters to find volume change
r.mapcalc --o 'Diff_0201=(Ro_19970413c-Ro_19961012c)/(183./365)'
r.mapcalc --o 'Diff_0302=(Ro_19970927c-Ro_19970413c)/(167./365)'
r.mapcalc --o 'Diff_0403=(Ro_19980413c-Ro_19970927c)/(199./365)'
r.mapcalc --o 'Diff_0504=(Ro_19980907c-Ro_19980413c)/(146./365)'
r.mapcalc --o 'Diff_0605=(Ro_19990415c-Ro_19980907c)/(220./365)'
r.mapcalc --o 'Diff_0706=(Ro_19991006c-Ro_19990415c)/(174./365)'
r.mapcalc --o 'Diff_0807=(Ro_20000415c-Ro_19991006c)/(192./365)'
r.mapcalc --o 'Diff_0908=(Ro_20001015c-Ro_20000415c)/(183./365)'
r.mapcalc --o 'Diff_1009=(Ro_20010201c-Ro_20001015c)/(109./365)'
r.mapcalc --o 'Diff_1110=(Ro_20011016c-Ro_20010201c)/(257./365)'
r.mapcalc --o 'Diff_1211=(Ro_20020417c-Ro_20011016c)/(183./365)'
r.mapcalc --o 'Diff_1312=(Ro_20021017c-Ro_20020417c)/(183./365)'
r.mapcalc --o 'Diff_1413=(Ro_20030916c-Ro_20021017c)/(336./365)'
r.mapcalc --o 'Diff_1514=(Ro_20030921c-Ro_20030916c)/(3./365)'
r.mapcalc --o 'Diff_1615=(Ro_20040417c-Ro_20030921c)/(210./365)'
r.mapcalc --o 'Diff_1716=(Ro_20040716c-Ro_20040417c)/(89./365)'
r.mapcalc --o 'Diff_1817=(Ro_20050419c-Ro_20040716c)/(277./365)'
r.mapcalc --o 'Diff_1918=(Ro_20051126c-Ro_20050419c)/(221./365)'
r.mapcalc --o 'Diff_2019=(Ro_20060420c-Ro_20051126c)/(145./365)'
r.mapcalc --o 'Diff_2120=(Ro_20061020c-Ro_20060420c)/(183./365)'
r.mapcalc --o 'Diff_2221=(Ro_20070421c-Ro_20061020c)/(183./365)'
r.mapcalc --o 'Diff_2322=(Ro_20071021c-Ro_20070421c)/(183./365)'
r.mapcalc --o 'Diff_2423=(Ro_20080327c-Ro_20071021c)/(158./365)'
r.mapcalc --o 'Diff_2524=(Ro_20081021c-Ro_20080327c)/(208./365)'
r.mapcalc --o 'Diff_2625=(Ro_20090824c-Ro_20081021c)/(307./365)'
r.mapcalc --o 'Diff_2726=(Ro_20091201c-Ro_20090824c)/(99./365)'
r.mapcalc --o 'Diff_2827=(Ro_20100423c-Ro_20091201c)/(143./365)'
r.mapcalc --o 'Diff_2928=(Ro_20101023c-Ro_20100423c)/(183./365)'
r.mapcalc --o 'Diff_3029=(Ro_20110829c-Ro_20101023c)/(310./365)'
r.mapcalc --o 'Diff_3130=(Ro_20120423c-Ro_20110829c)/(238./365)'
r.mapcalc --o 'Diff_3231=(Ro_20121107c-Ro_20120423c)/(201./365)'

# Stack difference rasters into voxel model to create color table
Cape Hatteras

g.region n=170076 s=167518 e=925778 w=924134 res=1 res3=2 tbres=3 t=87 b=0

# Calculate ~0.5 year rasters using map algebra
r.mapcalc 'Hat_040398 = (Hat_98_1m - Hat_97_1m) * 0.5 + Hat_97_1m'
r.mapcalc 'Hat_030999 = (Hat_99_1m - Hat_98_1m) * 0.5 + Hat_98_1m'
r.mapcalc 'Hat_031000 = (Hat_01_1m - Hat_99_1m) * 0.35 + Hat_99_1m'
r.mapcalc 'Hat_090900 = (Hat_01_1m - Hat_99_1m) * 0.7 + Hat_99_1m'
r.mapcalc 'Hat_080301 = (Hat_03_1m - Hat_01_1m) * 0.2 + Hat_01_1m'
r.mapcalc 'Hat_020202 = (Hat_03_1m - Hat_01_1m) * 0.4 + Hat_01_1m'
r.mapcalc 'Hat_080202 = (Hat_03_1m - Hat_01_1m) * 0.6 + Hat_01_1m'
r.mapcalc 'Hat_020103 = (Hat_03_1m - Hat_01_1m) * 0.8 + Hat_01_1m'
r.mapcalc 'Hat_032304 = (Hat_04_1m - Hat_03_1m) * 0.6 + Hat_03_1m'
r.mapcalc 'Hat_012505 = (Hat_05_1m - Hat_04_1m) * 0.4 + Hat_04_1m'
r.mapcalc 'Hat_072505 = (Hat_05_1m - Hat_04_1m) * 0.8 + Hat_04_1m'
r.mapcalc 'Hat_052806 = (Hat_08_1m - Hat_05_1m) * 0.2 + Hat_05_1m'
r.mapcalc 'Hat_112706 = (Hat_08_1m - Hat_05_1m) * 0.4 + Hat_05_1m'
r.mapcalc 'Hat_052607 = (Hat_08_1m - Hat_05_1m) * 0.6 + Hat_05_1m'
r.mapcalc 'Hat_112607 = (Hat_08_1m - Hat_05_1m) * 0.8 + Hat_05_1m'
r.mapcalc 'Hat_092608 = (Hat_09_1m - Hat_08_1m) * 0.3 + Hat_08_1m'
r.mapcalc 'Hat_032809 = (Hat_09_1m - Hat_08_1m) * 0.6 + Hat_08_1m'
r.mapcalc 'Hat_060110 = (Hat_11_1m - Hat_09_1m) * 0.3 + Hat_09_1m'
r.mapcalc 'Hat_120210 = (Hat_11_1m - Hat_09_1m) * 0.6 + Hat_09_1m'

# Stack Rasters into voxel model
r.to.rast3
input=Hat_97_1m,Hat_040398,Hat_98_1m,Hat_030999,Hat_99_1m,Hat_031000,Hat_090900,Hat_01_1m,Hat_080301,Hat_020202,Hat_080202,Hat_020103,Hat_03_1m,Hat_032304,Hat_04_1m,Hat_012505,Hat_072505,Hat_05_1m,Hat_052806,Hat_112706,Hat_052607,Hat_112607,Hat_08_1m,Hat_092608,Hat_032809,Hat_060110,Hat_120210,Hat_11_1m output=Hat9711_29stack

# Calculate year rasters
r.mapcalc 'Hat_1_t = 10'
r.mapcalc 'Hat_2_t = 20'
r.mapcalc 'Hat_3_t = 30'
r.mapcalc 'Hat_4_t = 40'
r.mapcalc 'Hat_5_t = 50'
r.mapcalc 'Hat_6_t = 60'
r.mapcalc 'Hat_7_t = 70'
r.mapcalc 'Hat_8_t = 80'
r.mapcalc 'Hat_9_t = 90'
r.mapcalc 'Hat_10_t = 100'
r.mapcalc 'Hat_11_t = 110'
r.mapcalc 'Hat_12_t = 120'
r.mapcalc 'Hat_13_t = 130'
r.mapcalc 'Hat_14_t = 140'
r.mapcalc 'Hat_15_t = 150'
r.mapcalc 'Hat_16_t = 160'
r.mapcalc 'Hat_17_t = 170'
r.mapcalc 'Hat_18_t = 180'
r.mapcalc 'Hat_19_t = 190'
r.mapcalc 'Hat_20_t = 200'
r.mapcalc 'Hat_21_t = 210'
r.mapcalc 'Hat_22_t = 220'
r.mapcalc 'Hat_23_t = 230'
r.mapcalc 'Hat_24_t = 240'
r.mapcalc 'Hat_25_t = 250'
r.mapcalc 'Hat_26_t = 260'
r.mapcalc 'Hat_27_t = 270'
r.mapcalc 'Hat_28_t = 280'
r.mapcalc 'Hat_29_t = 290'

# Stack year rasters into voxel model to create color table
r.to.rast3
input=Hat_1_t,Hat_2_t,Hat_3_t,Hat_4_t,Hat_5_t,Hat_6_t,Hat_7_t,Hat_8_t,Hat_9_t,Hat_10_t,Hat_11_t,Hat_12_t,Hat_13_t,Hat_14_t,Hat_15_t,Hat_16_t,Hat_17_t,Hat_18_t,Hat_19_t,Hat_20_t,Hat_21_t,Hat_22_t,Hat_23_t,Hat_24_t,Hat_25_t,Hat_26_t,Hat_27_t,Hat_28_t,Hat_29_t output=Hat_stack_29t

Jockey's Ridge

g.region n=250905 s=249388 e=914112 w=912693 res=1 res3=2 tbres=3 t=117 b=0

r.mapcalc 'JR_1975 = (JR_1995_1m - JR_1974_1m) * (1/22) + JR_1974_1m'
r.mapcalc 'JR_1976 = (JR_1995_1m - JR_1974_1m) * (2/22) + JR_1974_1m'
r.mapcalc 'JR_1977 = (JR_1995_1m - JR_1974_1m) * (3/22) + JR_1974_1m'
r.mapcalc 'JR_1978 = (JR_1995_1m - JR_1974_1m) * (4/22) + JR_1974_1m'
r.mapcalc 'JR_1979 = (JR_1995_1m - JR_1974_1m) * (5/22) + JR_1974_1m'
r.mapcalc 'JR_1980 = (JR_1995_1m - JR_1974_1m) * (6/22) + JR_1974_1m'
r.mapcalc 'JR_1981 = (JR_1995_1m - JR_1974_1m) * (7/22) + JR_1974_1m'
r.mapcalc 'JR_1982 = (JR_1995_1m - JR_1974_1m) * (8/22) + JR_1974_1m'
r.mapcalc 'JR_1983 = (JR_1995_1m - JR_1974_1m) * (9/22) + JR_1974_1m'
r.mapcalc 'JR_1984 = (JR_1995_1m - JR_1974_1m) * (10/22) + JR_1974_1m'
r.mapcalc 'JR_1985 = (JR_1995_1m - JR_1974_1m) * (11/22) + JR_1974_1m'
r.mapcalc 'JR_1986 = (JR_1995_1m - JR_1974_1m) * (12/22) + JR_1974_1m'
r.mapcalc 'JR_1987 = (JR_1995_1m - JR_1974_1m) * (13/22) + JR_1974_1m'
r.mapcalc 'JR_1988 = (JR_1995_1m - JR_1974_1m) * (14/22) + JR_1974_1m'
r.mapcalc 'JR_1989 = (JR_1995_1m - JR_1974_1m) * (15/22) + JR_1974_1m'
r.mapcalc 'JR_1990 = (JR_1995_1m - JR_1974_1m) * (16/22) + JR_1974_1m'
r.mapcalc 'JR_1991 = (JR_1995_1m - JR_1974_1m) * (17/22) + JR_1974_1m'
r.mapcalc 'JR_1992 = (JR_1995_1m - JR_1974_1m) * (18/22) + JR_1974_1m'
r.mapcalc 'JR_1993 = (JR_1995_1m - JR_1974_1m) * (19/22) + JR_1974_1m'
r.mapcalc 'JR_1994 = (JR_1995_1m - JR_1974_1m) * (20/22) + JR_1974_1m'
r.mapcalc 'JR_1995 = (JR_1995_1m - JR_1998_1m - JR_1974_1m) * (1/3) + JR_1995_1m'
r.mapcalc 'JR_1996 = (JR_1998_1m - JR_1995_1m) * (1/3) + JR_1995_1m'
r.mapcalc 'JR_1997 = (JR_1998_1m - JR_1995_1m) * (2/3) + JR_1995_1m'
r.mapcalc 'JR_2000 = (JR_NH_2001_JanMarch_1m - JR_NH_19991104_1m) * (1/2) + JR_NH_19991104_1m'
r.mapcalc 'JR_2002 = (JR_NH_20070708_1m_float - JR_NH_2001_JanMarch_1m) * (1/6) + JR_NH_2001_JanMarch_1m
r.mapcalc 'JR_2003 = (JR_NH_20070708_1m_float - JR_NH_2001_JanMarch_1m) * (2/6) + JR_NH_2001_JanMarch_1m
r.mapcalc 'JR_2004 = (JR_NH_20070708_1m_float - JR_NH_2001_JanMarch_1m) * (3/6) + JR_NH_2001_JanMarch_1m
r.mapcalc 'JR_2005 = (JR_NH_20070708_1m_float - JR_NH_2001_JanMarch_1m) * (4/6) + JR_NH_2001_JanMarch_1m
r.mapcalc 'JR_2006 = (JR_NH_20070708_1m_float - JR_NH_2001_JanMarch_1m) * (5/6) + JR_NH_2001_JanMarch_1m
r.mapcalc 'JR_2010 = (JR_2012_1mrstc_f - JR_2009_mr_1m) * (1/3) + JR_2009_mr_1m
r.mapcalc 'JR_2011 = (JR_2012_1mrstc_f - JR_2009_mr_1m) * (2/3) + JR_2009_mr_1m

# Stack Rasters into Voxel model
r.to.rast3 --o

# Calculate year rasters
r.mapcalc 'JR_1_t = 10'

r.mapcalc 'JR_2_t = 20'

r.mapcalc 'JR_3_t = 30'

r.mapcalc 'JR_4_t = 40'

r.mapcalc 'JR_5_t = 50'

r.mapcalc 'JR_6_t = 60'

r.mapcalc 'JR_7_t = 70'

r.mapcalc 'JR_8_t = 80'

r.mapcalc 'JR_9_t = 90'

r.mapcalc 'JR_10_t = 100'

r.mapcalc 'JR_11_t = 110'

r.mapcalc 'JR_12_t = 120'

r.mapcalc 'JR_13_t = 130'

r.mapcalc 'JR_14_t = 140'

r.mapcalc 'JR_15_t = 150'

r.mapcalc 'JR_16_t = 160'

r.mapcalc 'JR_17_t = 170'

r.mapcalc 'JR_18_t = 180'

r.mapcalc 'JR_19_t = 190'

r.mapcalc 'JR_20_t = 200'

r.mapcalc 'JR_21_t = 210'

r.mapcalc 'JR_22_t = 220'

r.mapcalc 'JR_23_t = 230'

r.mapcalc 'JR_24_t = 240'

r.mapcalc 'JR_25_t = 250'

r.mapcalc 'JR_26_t = 260'

r.mapcalc 'JR_27_t = 270'

r.mapcalc 'JR_28_t = 280'

r.mapcalc 'JR_29_t = 290'

r.mapcalc 'JR_30_t = 300'

r.mapcalc 'JR_31_t = 310'

r.mapcalc 'JR_32_t = 320'
r.mapcalc 'JR_33_t = 330'
r.mapcalc 'JR_34_t = 340'
r.mapcalc 'JR_35_t = 350'
r.mapcalc 'JR_36_t = 360'
r.mapcalc 'JR_37_t = 370'
r.mapcalc 'JR_38_t = 380'
r.mapcalc 'JR_39_t = 390'

# Stack year rasters into voxel model to create color table
r.to.rast3
input=JR_1_t,JR_2_t,JR_3_t,JR_4_t,JR_5_t,JR_6_t,JR_7_t,JR_8_t,JR_9_t,JR_10_t,JR_11_t,JR_12_t,JR_13_t,
JR_14_t,JR_15_t,JR_16_t,JR_17_t,JR_18_t,JR_19_t,JR_20_t,JR_21_t,JR_22_t,JR_23_t,JR_24_t,JR_25_t,JR_26_t,
JR_27_t,JR_28_t,JR_29_t,JR_30_t,JR_31_t,JR_32_t,JR_33_t,JR_34_t,JR_35_t,JR_36_t,JR_37_t,JR_38_t,
JR_39_t
output=JR_colors
# VectProcedures.py
# Emily Russ
# Set of procedures to be run to output 2D and 3D vector fields
import sys, os, numpy

def removeNull(file):
    """removes null values""
    f = open(file, 'r')
    lines = f.readlines()
    f.close()
    newFile = os.path.splitext(file)[0]+"_clean.txt"
    g = open(newFile, 'w')
    for line in lines:
        if not line:
            g.write(line)
    g.close()
    return newFile

def makeArrayFull(file):
    """creates an array from text files""
    array = numpy.loadtxt(file)
    return array

def makeArrayLast(file):
    """creates an array from txt files""
    array = numpy.loadtxt(file, usecols=(2,))
    return array

def regionDict(file):
    """Reads information file about region and outputs dictionary of information""
    f = open(file,'r')
    lines = f.readlines()
    f.close()
    dict = {}  
    for line in lines:
        newKey = line.split(':')[0]
        newStrip = newKey[1].rstrip('\n')
        dict[newKey[0]]=newStrip
    return dict

# arrayMath.py
# Purpose: Perform math on array fuctions
# Script prepared by Emily Russ for GIS 540 Project
import numpy

def removeOutside(Array, rows, cols):
    """removes cells on the outside of arrays"""
    i = range(0, rows)
    j = range(0, cols)
    for value in i:
        for num in j:
            # Rows and columns on outside of array were not included in partial calculation
            # Therefore, for array addition, the arrays need to be same size
            if value == 0 or value == len(i) - 1 or num == 0 or num == len(j) - 1:
                Array[(value, num)] = 0
    Array = Array[Array.nonzero()]
    Array = Array.reshape((rows - 2, cols - 2), order='C')
    return Array

def displayNthPoint(array, rows, cols, skipN):
    """displays every nth point in the array over each row and column"""
    i = range(0, rows, skipN)
    j = range(0, cols, skipN)
    nList = []
    for value in i:
        for num in j:
            if value < rows and num < cols:
                # Only print every nth value
                nValue = array[value, num]
                nList.append(nValue)
    nArray = numpy.array(nList, dtype=float)
    nArray = nArray.reshape(len(i), len(j), order='C')
    return nArray

def addPartial(origArray, partialVal):
    """Adds original array values and partial derivative values in grid"""
    newArray = numpy.add(origArray, partialVal)
    return newArray

# VectorField2D.py
# Emily Russ
# Purpose: Output 2D vector fields every nth points over a regular grid using GRASS GIS commands
# 2 arguments: Elevation Raster and number of points to skip
import os, sys, numpy
scriptDir = os.path.dirname(sys.argv[0])
sys.path.append(scriptDir)
import arrayMath, VectProcedures
file = sys.argv[1]
nPoints = int(sys.argv[2])
scale = int(sys.argv[3])
outdx = file + "_dx" # output dx file
outdy = file + "_dy" # output dy file
dxFile = outdx + ".txt" # output dx text file
dyFile = outdy + ".txt" # output dy text file
infoFile = file + "_info.txt" # output file with region information
os.system("r.slope.aspect --o elevation="+file+" dx="+outdx+" dy="+outdy) # generate dx and dy maps
os.system("r.stats -1 -g --o input="+outdx+" output="+dxFile) # write x,y,dx to file
os.system("r.stats -1 -g --o input="+outdy+" output="+dyFile) # write x,y,dy to file
os.system("g.region -p > "+infoFile) # write information to file

# Edit files to remove lines with no data (outside coordinates)
dxFileC = VectProcedures.removeNull(dxFile)
dyFileC = VectProcedures.removeNull(dyFile)

# Get x, y, dx, and dy arrays using numpy module
array1 = numpy.loadtxt(dxFileC)
array2 = numpy.loadtxt(dyFileC, usecols=(2,))
xArray = array1.T[0]
yArray = array1.T[1]
dxArray = array1.T[2]
dyArray = array2
dxArray = numpy.multiply(dxArray, scale)
dyArray = numpy.multiply(dyArray, scale)
endX = numpy.add(xArray, dxArray)
endY = numpy.add(yArray, dyArray)

# Get region information from infoFile and write into dictionary
myDict = VectProcedures.regionDict(infoFile)
rows = int(myDict['rows'])-2
cols = int(myDict['cols'])-2

# Reshape arrays so they can be sampled every nth point and display evenly
xArray = xArray.reshape(rows, cols)
yArray = yArray.reshape(rows, cols)
endX = endX.reshape(rows, cols)
endY = endY.reshape(rows, cols)

cmath.displayNthPoint(xArray, rows, cols, nPoints)
cmath.displayNthPoint(yArray, rows, cols, nPoints)
cmath.displayNthPoint(endX, rows, cols, nPoints)
cmath.displayNthPoint(endY, rows, cols, nPoints)

# Reshape arrays back into a single column
startX = startX.reshape((startX.size, 1), order='C')
startY = startY.reshape((startY.size, 1), order='C')
endX = endX.reshape((endX.size, 1), order='C')
endY = endY.reshape((endY.size, 1), order='C')

vectArray = numpy.hstack((startX, startY, endX, endY))
outFile = file + "_out.txt"
numpy.savetxt(outFile, vectArray, delimiter=',')

h = open(outFile, 'r')
asciiFile = file + "_vectors.txt"
m = open(asciiFile, 'w')

vectors = h.readlines()
h.close()
for v in vectors:
    k = v.split(',')
    l = "L 2 \n{0} \n{1} \n{2} \n{3}".format(k[0],k[1],k[2],k[3])
m.write(l)

m.close()
vectFile = file+"_vect"
os.system("v.in.ascii --o -n input="+asciiFile+" output="+vectFile+" format=standard")

# VectField3D_1.py
# Emily Russ
# Another method for finding spatio-temporal vector fields
# 4 arguments
# 2 input rasters, every nth point, scale
import os, sys, numpy

scriptDir = os.path.dirname(sys.argv[0])
sys.path.append(scriptDir)
import arrayMath, VectProcedures

rast1 = sys.argv[1]
rast2 = sys.argv[2]
nPoints = int(sys.argv[3])
scale = int(sys.argv[4])

diffRast = rast1 + "_rast2" + "_diff"
outdx = diffRast + ".dx"
outdy = diffRast + ".dy"
dxFile = outdx + ".txt"
dyFile = outdy + ".txt"
infoFile = rast1 + ".info.txt"
outDiff = diffRast + ".txt"
zFile = rast1 + ".txt"

os.system("r.mapcalc '+diffRast+' = '+rast2+" -'+rast1+" --o")
os.system("r.slope.aspect --o elevation="+diffRast+" dx="+outdx+" dy="+outdy")
os.system("r.stats -l -g --o input="+outdx+" output="+dxFile")
os.system("r.stats -l -g --o input="+outdy+" output="+dyFile")
os.system("g.region -p >"+infoFile) # write information to file

dxFileC=VectProcedures.removeNull(dxFile)
dyFileC=VectProcedures.removeNull(dyFile)
arrayX = VectProcedures.makeArrayFull(dxFileC)
xArray = arrayX.T[0]
yArray = arrayX.T[1]
dxArray = arrayX.T[2]
dyArray = VectProcedures.makeArrayLast(dyFileC)
dxArray = numpy.multiply(dxArray, scale)
dyArray = numpy.multiply(dyArray, scale)

endX = numpy.add(xArray, dxArray)
endY = numpy.add(yArray, dyArray)

myDict = VectProcedures.regionDict(infoFile)
rows = int(myDict['rows']) - 2
cols = int(myDict['cols']) - 2

xArray = xArray.reshape(rows, cols)
yArray = yArray.reshape(rows, cols)
endX = endX.reshape(rows, cols)
endY = endY.reshape(rows, cols)

startX = arrayMath.displayNthPoint(xArray, rows, cols, nPoints)
startY = arrayMath.displayNthPoint(yArray, rows, cols, nPoints)
endX = arrayMath.displayNthPoint(endX, rows, cols, nPoints)
endY = arrayMath.displayNthPoint(endY, rows, cols, nPoints)

startX = startX.reshape((startX.size, 1), order='C')
startY = startY.reshape((startY.size, 1), order='C')
endX = endX.reshape((endX.size, 1), order='C')
endY = endY.reshape((endY.size, 1), order='C')

os.system("r.mapcalc 'new = ('+outdx+' * 0) + 1' --o")
diffRastN = rast1 + "._diffC"

os.system("r.mapcalc "+diffRastN+" = new * "+diffRast+" --o")
onZ = rast1 + "._N"

os.system("r.mapcalc "+onZ+" = new * "+rast1+" --o")

outzN = rast1 + "_outZ.txt"

zArray = VectProcedures.removeNull(zFile)
zArray = VectProcedures.makeArrayLast(zArray)
endZ = zArray.reshape(rows, cols)
startZ = arrayMath.displayNthPoint(startZ, rows, cols, nPoints)
startZ = startZ.reshape((startZ.size, 1), order='C')
endZ = numpy.add(startZ, endT)

endArray = numpy.hstack((endX, endY, endT))
endOut = rast1 + "._out.txt"
numpy.savetxt(endOut, endArray, delimiter=',')

zArray = VectProcedures.removeNull(zFile)
zArray = VectProcedures.makeArrayLast(zArray)
startZ = zArray.reshape(rows, cols)
startZ = arrayMath.displayNthPoint(startZ, rows, cols, nPoints)
startZ = startZ.reshape((startZ.size, 1), order='C')
endZ = numpy.add(startZ, endT)

endArray = numpy.hstack((endX, endY, endT))
endOut = rast1 + "._out.txt"
numpy.savetxt(endOut, endArray, delimiter=',')
endFile = os.path.splitext(endOut)[0]
os.system("v.in.ascii --o-z -n input="+endOut+" output="+endFile+" fs=, z=3 format=point")
vecArray = numpy.hstack((startX,startY,startZ,endX,endY,endZ))
outFile = rast1 +"_" + rast2 +"_out3D_2.txt"
numpy.savetxt(outFile,vecArray,delimiter=',')

h = open(outFile,'r')
asciiFile = rast1 +"_" + rast2 +"_vectors3d_2.txt"
m = open(asciiFile, 'w')

vectors = h.readlines()
h.close()
for v in vectors:
    k = v.split(',')
    l = "L 2\n{0} {1} {2}\n{3} {4} {5}".format(k[0],k[1],k[2],k[3],k[4],k[5])
m.write(l)
m.close()
vectFile = os.path.splitext(asciiFile)[0]
os.system("v.in.ascii --o-n-z input="+asciiFile+" output="+vectFile+" format=standard")

# Jockey' Ridge Main Dune
g.region n=250457 s=250021 e=913398 w=913055 -pa
python "VectField2D.py" JR_1974_main 15 20
python "VectField2D.py" JR_1995_main 15 20
python "VectField2D.py" JR_1999_main 15 20
python "VectField2D.py" JR_2001_main 15 20
python "VectField2D.py" JR_2008_main 15 20
python "VectField2D.py" JR_2012_main 15 20
python "VectField3D_2.py" JR_1974_main JR_1995_main 15 20
python "VectField3D_2.py" JR_1995_main JR_1999_main 15 20
python "VectField3D_2.py" JR_1999_main JR_2001_main 15 20
python "VectField3D_2.py" JR_2001_main JR_2008_main 15 20
python "VectField3D_2.py" JR_2008_main JR_2012_main 15 20

# Jockey's Ridge East Dune
g.region n=250495.17 s=249968.75 e=913901.07 w=913541.77 -pa
cd Desktop/ThesisWork/Ch4/Ch4_scripts
python "VectField2D.py" JREast_1974_1m 15 20
python "VectField2D.py" JREast_1995_1m 15 20
python "VectField2D.py" JREast_1999_1m 15 20
python "VectField2D.py" JREast_2001_1m 15 20
python "VectField2D.py" JREast_2008_1m 15 20
python "VectField2D.py" JREast_2012_1m 15 20
python "VectField3D_2.py" JREast_1974_1m JREast_1995_1m 15 20
python "VectField3D_2.py" JREast_1995_1m JREast_1999_1m 15 20
python "VectField3D_2.py" JREast_1999_1m JREast_2001_1m 15 20
python "VectField3D_2.py" JREast_2001_1m JREast_2008_1m 15 20
python "VectField3D_2.py" JREast_2008_1m JREast_2012_1m 15 20

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