Shoreline Change on the East Coast: Exploring the Role of Shoreline Curvature

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Executive Summary

The low sloping sandy shoreline of the East Coast of the United States is a dynamic and complicated system that is affected by a series of factors. Previous work that has applied both qualitative and quantitative analyses has enhanced the understanding of shoreline change and has provided suggestions for coastal management. For decades, the United States Geological Survey (USGS) has conducted work to examine the factors that influence the local shoreline change rate. However, because the coastal system is so complex and various types of input information are required, the existing data in the USGS database may not be complete enough to address all the important factors.

This project focuses on the study of shoreline change in a way that differs in scope from existing work. The key variable discussed here is shoreline curvature, which has been mentioned in several examples in the literature as one of the factors influencing shoreline change rate. However, few quantitative research efforts have provided evidence to show the shoreline curvature's effect on the shoreline change rate. Moreover, shoreline curvature has not yet been incorporated into the USGS database as one of the variables for shoreline change.

This project report starts with a general introduction and background information regarding basic concepts, previous research, and the study region (the East Coast of the United States). Then, the report provides scientific explanations regarding the shoreline change process, followed by the data analysis methods, results, and discussion. Using the coastline contour data from the Global Self-consistent, Hierarchical High-resolution Geography (GSHHG) database in the National Geophysical Data Center,¹ I have divided the coastline into several small pieces and constructed each of them into a series of equally

¹ The database can be obtained from the National Oceanic and Atmosphere Administration (NOAA) website at: [http://www.ngdc.noaa.gov/mgg/shorelines/gshhs.html](http://www.ngdc.noaa.gov/mgg/shorelines/gshhs.html)
spaced points (1 m). I then calculated the curvature of each point after applying smoothing processes (on 1-km, 3-km and 5-km spatial scale) on the resultant data to reduce the high-frequency undulation and keep the general trend of the coastline.

The results of the correlation analysis indicate a significant correlation between the shore curvature and the shoreline change rate for some locations.² A previous study (Lazarus & Murray, 2007) has shown that, at one location, using short-term shoreline change rate data, correlations vary according to different time and spatial scales. This study, however, uses longer-term shoreline change rates (measured over recent decades) and has found the existence of significant correlations. The statistical significance of these correlations varies at different locations in Florida and North Carolina. Most of the significant coefficients were either greater than 0.1 or less than -0.1, whereas the less significant coefficients were generally between -0.1 and 0.1. These results are consistent with those from the previous work of Lazarus and Murray (2007) and indicate widespread correlations between the shoreline curvature and shoreline change rate for different spatial scales and at different locations. This report also discusses some other influential factors of the study, including human activities and the complexity of the coastal system, and also puts forward ideas for the direction of future work.

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Introduction

Coastal protection and management are topics that are receiving increased attention in the 21st century with concerns over sea-level rise in the context of global warming. Sea-level rise and its corresponding impacts have drawn public attention because they “have a wide range of effects on coastal environments, human development, and infrastructure in coastal areas” (Gutierrez, Plant, & Thieler, 2011). Increasing efforts have been made to gain a better understanding of the coastal climate and long-term shoreline changes, both of which are of vital importance when considering and applying proper coastal protection strategies.

Although numerous research projects have been undertaken to address coastline-related concerns, great uncertainty remains in predicting the shoreline change rate at different locations because a broad range of complex factors affect coastal systems (Gutierrez, Plant, & Thieler, 2011). Examples found in the literature explain shoreline change in terms of both quantitative and qualitative analytical approaches. The local shoreline change rate and predictions are important parameters because: 1) they provide useful scientific information for understanding the complicated coastal system; 2) they will help the government to distribute funding more effectively by targeting local conditions; and 3) they provide a scientific basis for policy makers when addressing different cases that are specific to local conditions.

The U.S. Geological Survey (USGS) has commenced work to examine local shoreline change rates and the main factors influencing those rates at the local, regional, and global levels over several decades. Focusing on several applied problems in coastal areas (e.g., determining the shoreline response to sea-level rise, predicting the shoreline retreat rates, planning management strategies to
address coastal zone loss, etc.).³ the USGS has developed a number of models that require large amounts of data inputs. However, several key components of coastal vulnerability, including shoreline curvature, notably, are either indeterminate or they may simply not exist (Klein & Nicholls, 1999) in the existing body of literature.

This project aims to measure the shoreline curvature of regions of the East Coast of the United States, expand the current database, and contribute to the development of a new prediction scheme for shoreline change. Thus, with a more complete variable inventory, more precise predictions of coastal change can be made that will provide a more reliable scientific basis for coastal management in the future.

Background Information

1. General information of the study region: the U.S. East Coast

   General geologic setting

   The East Coast of the United States is a passive margin coast along the Atlantic Ocean with little mountain-building or volcanic activity (Gabler, Petersen, Trapasso, & Sack, 2008). The most typical features of this passive margin are the wide continental shelf and low-relief coastal landforms (Inman & Nordstrom, 1971). From Virginia northward, the landform types become highly variable, showing complicated coastline orientation and irregular, crenulated shapes in the plane view. Much of the southern part of the coastline is composed primarily of mainland and barrier beaches (Hapke, Himmelstoss, Kratzmann, List, & Thieler, 2011), with relatively regular shapes and gentle curves.

³ Detailed work about coastal change research can be found from the project page ‘Coastal Vulnerability to Sea-Level Rise: A Preliminary Database for the U.S. Atlantic, Pacific and Gulf of Mexico Coast’ at: http://pubs.usgs.gov/dds/dds68/html/docs/project.html.
The study region for this project covers the east coasts of Florida, Georgia, South Carolina, and the barrier-beaches of North Carolina (Figure 1). In the horizontal plane view, the curvatures range in size from cusps to capes for the coastlines of the Carolinas and Georgia, whereas the Florida coastline is relatively straight.

![Figure 1. Shoreline included in the study region (bold black parts)](image)

**Shoreline change process**

The general trend of shoreline change in the long term is landward erosion, especially in the context of accelerating sea-level rise. However, local shoreline change can vary greatly for different locations. Figure 2 shows the shoreline change rates along the East Coast. Although the sea-level rise accelerates shoreline erosion on a large scale, the local shoreline change rate can be caused by other factors and therefore requires a more specific explanation.
Figure 2. Map of the U.S. Atlantic coast and shoreline change rates

(Gutierrez, Plant, & Thieler, 2011)

Previous studies have explained local shoreline shape changes using the alongshore gradient in the alongshore sediment transport. As waves approach and shoal into shallow water, the sediment on the shoreface is disturbed due to the wave-orbital velocity and breaking-wave turbulence. A subtle alongshore current that is generated by wave breaking whenever the wave crests are not parallel to shore, advects the suspended sediment alongshore. Given that waves usually approach the shore at an angle (Figure 3), the nearshore sediment tends to be transported along the shore at all times. Because the waves that affect the coastal area usually come with different wave heights and from different directions at different times, it is the net sediment transport within a particular period of time that determines the shoreline erosion/accretion. Specifically,
Shoreline accretion relates to the negative net alongshore sediment transport gradient, which means that the shoreline gains more sediment than it loses. Conversely, positive net alongshore sediment transport gradients lead to landward erosion.

Figure 3. Wave angle between the wave crest and coastline

In Figure 4, the arrows indicate both the direction and the volume of alongshore sediment transport. The left-hand illustration indicates the negative net sediment transport gradient and sediment accumulation. Conversely, in the right-hand figure, sediment is lost over time and the shore tends to erode landward.
One way to produce a gradient in the alongshore transport involves the existing coastline shape. A previous study (Ashton & Murray 2006) has shown that the wave-driven alongshore sediment transport can be expressed as a function of the offshore wave angle before nearshore refraction. Figure 5 shows that the alongshore sediment transport ($Q_s$) keeps increasing with the wave angle (relative to the coastline orientation) and reaches its maximum value when the angle is approximately 45 degrees. Thus, in the case of a curved shoreline piece, the gradient of the alongshore sediment transport forms due to the variation of the relative wave angles from one place to another.
Figure 5. Relationship between wave angle and alongshore sediment transport (Ashton & Murray, 2006)

For example, Figure 6 (a) shows the responses of a seaward convex shoreline bump in a 'low-angle wave' scenario, that is, when the relative wave angles are below the value that maximizes the transport. Moving along the shoreline, the wave angle decreases from the updrift side to the inflection point, leading to a decrease in the alongshore sediment transport. Then, the wave angle becomes greater, moving downdrift along the crest of the bump to the other inflection point, thereby leading to an increase in the alongshore sediment transport. Thus, the gradient of the alongshore sediment transport forms, leading to the erosion of the convexity and accretion in the concave sections on both sides of the bump. In other words, this piece of shoreline tends to be smoothed in the long run (Ashton & Murray, 2006). This example shows that shoreline shape can affect shoreline change and sheds light on the possible correlation between these two parameters.

When waves approach from angles relative to the regional coastline orientation, that are above the value that maximizes the alongshore transport, the same
coastline curvatures produce opposite alongshore-transport gradients. Thus, in this 'high-angle' wave scenario, the bump in the coastline becomes exaggerated (Ashton & Murray, 2006). As shown in Figure 6 (b), negative net sediment transport flux occurs on both flanks of the convex shoreline shape, whereas the sediment flux will accrete along the crest. Thus, the high-angle waves will further erode along the flanks and create a bulge, leading to the shoreline having a more sinuous shape (Ashton & Murray, 2006).

(a) Shoreline smoothing in a low-angle wave scenario

(b) Shoreline accretion in a high-angle wave scenario

Figure 6. Alongshore sediment transport under different wave scenarios (Ashton & Murray, 2006)
Whether coastlines tend to become smoother or rougher in any location depends on the relative influences of high-angle waves and low-angle waves. Thus, the sign of the correlation coefficient is expected to show the shoreline response for the particular wave scenario. (An interpretation of the correlation coefficients can be found in the section, “Model and scientific basis: 5. Correlation analysis”.)

In the case of the sandy beaches on the East Coast, the active shoreline shaping processes are significantly related to the gradient in the alongshore sediment transport. As waves obliquely approach the East Coast and generate different amounts of alongshore sediment transport from one place to another, a gradient in the alongshore sediment transport forms and results in shoreline erosion or accretion at different locations (Larson, Rosati, & Kraus, 2002). In reality then, a mix of waves from different directions affects the coastline. Given the dominant type of wave for a specific location, the shoreline change rate would be expected to depend on the coastline curvature at those locations.

2. The concept: curvature

As one of the geometric features of the shoreline, curvature can be used to describe the shoreline shape in the plan view. From the perspective of geometry, curvature is the rate of change of the angle at a point on the curve. In other words, curvature gives information about how fast the curve is turning and in which direction the curve is bending. This variable is useful for describing shoreline shapes and large-scale coastline trends.

The positive value and negative value of the curvature represent whether the curve is turning in a clockwise or counterclockwise direction, respectively, in terms of the reference line. The absolute value of the curvature indicates the degree of bending. Briefly, if the curvature value is zero, then the curve looks like a line near this point. Conversely, if the curvature value is large, then the curve
has a sharp bend. In this project, the reference lines for the shoreline pieces are built parallel to the main direction of each coastline segment on the landside; thus, the positive value relates to the seaward concave shape of the shoreline and the negative value relates to seaward convexity.

Based on the discussion presented in the previous section, different curvatures should result in different gradients of alongshore sediment transport and thus should affect shoreline change. Figure 7 shows that a larger transport gradient is expected for a shoreline with a greater curvature, whereas a smaller transport gradient is expected for a smooth shoreline with a smaller curvature. Therefore, a correlation between curvature and shoreline change rate is expected because the net sediment transport, generated by the gradient, dominates the shoreline change rate, especially for the sandy beaches on the East Coast (Larson, Rosati, & Kraus, 2002). Moreover, because both different shoreline shapes and wave types cause this gradient, I also hypothesize that the strength of this correlation will differ from one place to another. Furthermore, both the sign and magnitude of the curvature should also affect shoreline change.

Figure 7. Gradients of alongshore sediment transport with different shoreline curvatures
Method and scientific basis

1. General introduction of data processing

Figure 8 shows the key steps involved in the data processing for this study. In simple terms, using the coastline contour data from the Global Self-consistent, Hierarchical high-resolution Geography Database (GSHHG) in the National Geophysical Data Center, I divided the eastern coastline into several shoreline pieces according to natural geological and morphological features. Next, I projected these shoreline pieces under the same projection coordinate system in ArcGIS and then used these shoreline pieces to construct a series of equally spaced points (1-m distance between two points) along the shoreline. Then, I generated a straight reference line (which keeps an approximately parallel trend with the shoreline piece) for each piece by connecting the two endpoints. Using the “near” function in ArcGIS, I measured the distance from the points to the line and exported this measurement as a dataset. Next, I used this dataset for the curvature calculations as these data represent the locations of the points in the x-y coordinate system. After averaging the distance data for every 1000, 3000, and 5000 points for the shoreline pieces, which refer to 1-km, 3-km and 5-km scales of smoothing, I calculated the curvature data for the different spatial scales.
In order to explore the correlation between curvature and shoreline change rate, I selected the shoreline change rates with 50-m resolutions between 1967 and 1999 from the USGS database as the response variables. Projected in the same coordinate system, the annual erosion rates for the different shoreline locations could be observed to correspond to the points. Then, I could conduct correlation analysis to determine the curvature and shoreline change rate relationship.

2. Shoreline piece extraction

The coastline from Miami, Florida to the Outer Banks of North Carolina has been divided into pieces based on natural morphological features and general trends. The lengths of the shoreline pieces vary from 0.9 km to 87 km. The short shoreline pieces are mainly small islands with irregular shapes with inconsistent shoreline orientations. Most of these shoreline pieces were extracted from the Georgia to South Carolina coasts where inlets are well developed (Figure 9). The Florida coastline is comparatively straight and continuous, with just an abrupt
bulge at Cape Canaveral (28°27’00.0”N 80°31’44.4”W). The shorelines of the barrier islands along the North Carolina coast tend to maintain a continuous trend and form the large-scaled curve of the Carolina Capes (see Figure 1). In other words, shorelines pieces with lengths of 10 km or longer are distributed mainly in Florida and North Carolina. Long shoreline pieces from these two regions are preferable for correlation analysis (which is discussed later in this report). For details regarding software operations and data sources, see Appendix A: “Shoreline piece extraction using Coastline Extractor”.

Figure 9. Barrier islands and short shoreline pieces extracted from Georgia and South Carolina coasts

3. Curvature calculation

The shoreline pieces were projected in the data frame under the same projected coordinate system, which is the “North America Lambert Conformal Conic System” in this project. Then, a series of equally spaced points was constructed along each shoreline piece, and an approximately parallel reference line was built by connecting the two endpoints. All of these preparations were based on
the assumptions made when calculating the curvatures in this project, which are described further in the following paragraphs.

Mathematical theory defines the second derivative of the curve function as the curvature, which can also be described as the slope change rate of the curve. In Figure 10, A, B, and C are equal-spaced points on the curve, and $\Delta x = 1$. Assuming that the space between the adjacent points is finite and small compared to the total length of the curve, the slopes for points B and C are $\frac{y_2-y_1}{\Delta x}$ and $\frac{y_3-y_2}{\Delta x}$, respectively. Thus, the curvature for point B is the slope change rate that can be represented as $\frac{y_3-y_2}{\Delta x} - \frac{y_2-y_1}{\Delta x} = \frac{y_3-2y_2+y_1}{(\Delta x)^2}$. In short, the curvature of a point on the curve (point B in this case) can be calculated once the vertical coordinate values of the point and two adjacent points are known.

![Figure 10. Explanation of curvature calculations](image)

Applying this concept to the shoreline pieces, an x-y coordinate system was generated by setting the reference line as the x-axis (Figure 10). Because the points have the same distance of 1 m between them on the curve, $\Delta x$ is assumed
also to be approximately equal to 1 m because the reference line is very close to parallel to the shoreline piece. Thus, I could simply calculate the curvature of any location on the shoreline by using the distance data from the reference line, which are the vertical coordinate values in the shoreline x-y coordinate system. Detailed steps for the shoreline projection, point construction, reference line construction, distance measurements, and data export can be found in Appendix B: “Geographic information system (GIS) manipulation”.

![Shoreline x-y coordinate system](image)

**Figure 11. Shoreline x-y coordinate system**

4. **Shoreline smoothing**

The main purpose of shoreline smoothing is to examine the curvature on different alongshore scales. Because the shoreline data points are spaced 1 m apart, “high-frequency undulations in shoreline position” will “swamp more subtle, low-frequency patterns” for such small spacing (Lazarus & Murray, 2007). For example, if shoreline undulation exists on the alongshore scale of 100 meters, the local curvature values will be dominated by those undulations, which will obscure a larger-scale curvature that exists along the shoreline, e.g., the curving
coastline over the scale of kilometers in the bay of the Carolina Capes (Figure 12). Another example is the shoreline segment from Florida (Figure 13), which also shows that the original distance data exported from ArcGIS are sinuous on very small alongshore scales. In this case, however, smoothing the shoreline on different spatial scales reveals different patterns of curvature inherent in the data on larger spatial scales (Figure 13).

![Shoreline smoothed on different scales (P_94)](image)

**Figure 12. Shoreline smoothing case P_94**

The method used for shoreline smoothing is to average the distance data and reallocate the points. In other words, smoothing the shoreline on the 1-km scale means reallocating the point by averaging the distance of 1000 points around this point (i.e., 500 before this point and 500 after the point). The smoothed shoreline piece will be shorter because a number of points on both ends cannot be averaged (e.g. 500 meters on either end of the shoreline segment). Furthermore, smoothing on a large scale means losing more points on the shoreline segment, so smoothing can be conducted effectively only for long shoreline pieces.
5. Correlation analysis

Thus far, I have explained in theoretical terms how the shoreline curvature influences shoreline change. Correlation analysis of the curvature and shoreline change rate relationship may provide more quantitative evidence for the theory. The explanatory variable is the curvature data on different spatial scales. The response variable is the shoreline change rates generated at a 50-m transect spacing between 1967 and 1999. Shoreline change rates in units of meters per year (m/yr) were calculated using the endpoint method by comparing the 1970s data and the most recent shoreline positions.\(^4\) I selected 11 shoreline segments for the correlation analysis: FL_4 to FL_7 from north of Miami, Florida and NC_92 to NC_96 around Cape Hatteras in North Carolina (Figure 13). I chose these pieces because they show continuous shoreline trends and large spatial scale curvature of the coastline. Another reason for selecting these pieces is that they are all long segments that can be smoothed on 1-km, 3-km, and 5-km scales (Table 1). As aforementioned, smoothing on a larger scale means losing more points at both ends of the segment. In order to have enough data after smoothing, pieces that are longer than 5 km are ideal.

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\(^4\) The dataset description can be viewed on the USGS website at: [http://pubs.usgs.gov/of/2005/1326/metadata/Florida/fl_transects_st.htm](http://pubs.usgs.gov/of/2005/1326/metadata/Florida/fl_transects_st.htm)
Figure 13. Locations of shoreline examples used in correlation analysis

Table 1. Selected shoreline pieces used in correlation analysis

<table>
<thead>
<tr>
<th>State</th>
<th>Shoreline Pieces</th>
<th>Length (m)/Number of Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Florida</td>
<td>FL_4</td>
<td>14124</td>
</tr>
<tr>
<td></td>
<td>FL_5</td>
<td>21124</td>
</tr>
<tr>
<td></td>
<td>FL_6</td>
<td>18060</td>
</tr>
<tr>
<td></td>
<td>FL_7</td>
<td>8774</td>
</tr>
<tr>
<td></td>
<td>FL_8</td>
<td>22970</td>
</tr>
<tr>
<td></td>
<td>FL_9</td>
<td>24980</td>
</tr>
<tr>
<td>North Carolina</td>
<td>NC_92</td>
<td>11057</td>
</tr>
<tr>
<td></td>
<td>NC_93</td>
<td>25284</td>
</tr>
<tr>
<td></td>
<td>NC_94</td>
<td>19737</td>
</tr>
<tr>
<td></td>
<td>NC_95</td>
<td>61138</td>
</tr>
<tr>
<td></td>
<td>NC_96</td>
<td>79341</td>
</tr>
</tbody>
</table>
It is important to understand the sign of the variables when interpreting the results of the correlation analysis. The sign of the explanatory variable, which is the shoreline curvature on different scales, depends on the relative location of the reference line. In this project, the reference line was built on the landward side of the shoreline (Figure 11), indicating that the negative value of the curvature refers to the seaward convex shape and the positive value refers to the seaward concave shape of the shoreline. Considering that the absolute value of the curvature indicates the degree of bending, a more seaward convex shape of the shoreline piece indicates a more negative value of the curvature of the piece. Conversely, a more seaward concave shape would be associated with a more positive curvature (Figure 14). For the response variable, which is the shoreline change rate, a positive value represents the accretion and a negative value represents the erosion (Morton & Miller, 2005).

Thus, the correlation coefficients can show how a piece of shoreline with a specific shape will change over a period of time. A positive correlation indicates that a shoreline piece with a more seaward convex shape (i.e., a negative curvature) will experience more erosion or less accretion. Conversely, a negative correlation indicates that a shoreline piece with a more seaward convex shape
(i.e., a negative curvature) will experience more accretion or less erosion. In other words, a positive correlation coefficient indicates shoreline smoothing, whereas a negative coefficient is associated with shoreline roughening.

Results

Significant correlations were found at different locations in this project, and these correlations tended to become stronger on a greater spatial scale. Table 2 lists all the correlation coefficients on all three spatial scales for the selected sections. The significant coefficients, which are the values with a small p-value (p < 0.05), are marked in red, and the less significant coefficients are marked in blue. The R-square value indicates the percentage of the response variable that can be explained by the explanatory variable. For the Florida sections, most of the significant coefficients are positive, indicating that these pieces have a tendency to be smoothed in the long run. A positive correlation also was found for the northern part of the Hatteras Inlet (NC_94) and North Cape Hatteras to the Oregon Inlet (NC_95). The curvature of the southern part of the Hatteras Inlet is negatively correlated with the shoreline change rate, which means that the shoreline is getting rougher. Specifically, the seaward concave parts are eroding and the convex areas are growing.
Table 2. Correlation coefficients of selected pieces

<table>
<thead>
<tr>
<th>Shoreline pieces</th>
<th>1-km scale</th>
<th>3-km scale</th>
<th>5-km scale</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FL_4</strong></td>
<td>0.13</td>
<td>0.39</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>P=0.025</td>
<td>P=0.00</td>
<td>P=0.12</td>
</tr>
<tr>
<td></td>
<td>R square=0.020</td>
<td>R square=0.16</td>
<td>R square=0.013</td>
</tr>
<tr>
<td><strong>FL_5</strong></td>
<td>-0.082</td>
<td>0.035</td>
<td>-0.055</td>
</tr>
<tr>
<td></td>
<td>P=0.10</td>
<td>P=0.50</td>
<td>P=0.33</td>
</tr>
<tr>
<td></td>
<td>R square=0.0067</td>
<td>R square=0.0013</td>
<td>R square=0.0030</td>
</tr>
<tr>
<td><strong>FL_6</strong></td>
<td>0.11</td>
<td>0.040</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>P=0.04</td>
<td>P=0.49</td>
<td>P=0.019</td>
</tr>
<tr>
<td></td>
<td>R square=0.012</td>
<td>R square=0.0016</td>
<td>R square=0.021</td>
</tr>
<tr>
<td><strong>FL_7</strong></td>
<td>0.14</td>
<td>0.22</td>
<td>0.021</td>
</tr>
<tr>
<td></td>
<td>P=0.090</td>
<td>P=0.016</td>
<td>P=0.084</td>
</tr>
<tr>
<td></td>
<td>R square=0.018</td>
<td>R square=0.050</td>
<td>R square=0.041</td>
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<tr>
<td><strong>FL_8</strong></td>
<td>-0.028</td>
<td>0.051</td>
<td>0.051</td>
</tr>
<tr>
<td></td>
<td>P=0.56</td>
<td>P=0.31</td>
<td>P=0.33</td>
</tr>
<tr>
<td></td>
<td>R square=0.0008</td>
<td>R square=0.0026</td>
<td>R square=0.0026</td>
</tr>
<tr>
<td><strong>FL_9</strong></td>
<td>-0.15</td>
<td>0.023</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>P=0.0013</td>
<td>P=0.63</td>
<td>P=0.0004</td>
</tr>
<tr>
<td></td>
<td>R square=0.022</td>
<td>R square=0.0005</td>
<td>R square=0.031</td>
</tr>
<tr>
<td><strong>NC_92</strong></td>
<td>-0.21</td>
<td>-0.16</td>
<td>-0.14</td>
</tr>
<tr>
<td></td>
<td>P=0.0033</td>
<td>P=0.041</td>
<td>P=0.13</td>
</tr>
<tr>
<td></td>
<td>R square=0.044</td>
<td>R square=0.027</td>
<td>R square=0.020</td>
</tr>
<tr>
<td><strong>NC_93</strong></td>
<td>-0.071</td>
<td>-0.16</td>
<td>-0.096</td>
</tr>
<tr>
<td></td>
<td>P=0.12</td>
<td>P=0.0005</td>
<td>P=0.052</td>
</tr>
<tr>
<td></td>
<td>R square=0.0051</td>
<td>R square=0.027</td>
<td>R square=0.0092</td>
</tr>
<tr>
<td><strong>NC_94</strong></td>
<td>0.12</td>
<td>0.21</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>P=0.024</td>
<td>P=0.0001</td>
<td>P=0.0000</td>
</tr>
<tr>
<td></td>
<td>R square=0.014</td>
<td>R square=0.044</td>
<td>R square=0.088</td>
</tr>
<tr>
<td><strong>NC_95</strong></td>
<td>0.067</td>
<td>0.15</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>P=0.019</td>
<td>P=0.0000</td>
<td>P=0.0000</td>
</tr>
<tr>
<td></td>
<td>R square=0.0045</td>
<td>R square=0.022</td>
<td>R square=0.029</td>
</tr>
<tr>
<td><strong>NC_96</strong></td>
<td>0.015</td>
<td>0.0052</td>
<td>0.0066</td>
</tr>
<tr>
<td></td>
<td>P=0.55</td>
<td>P=0.84</td>
<td>P=0.80</td>
</tr>
<tr>
<td></td>
<td>R square=0.0002</td>
<td>R square=0.00</td>
<td>R square=0.00</td>
</tr>
</tbody>
</table>

Figure 15 shows the range of all these coefficients. The significant correlation coefficients (red) mainly spread above 0.1 and below -0.1, whereas the less significant results (blue) are generally between -0.1 and 0.1. Stronger correlations generally are found on the greater spatial scales (3-km scale and some on 5-km scale). The peak value is around 0.4, which occurs on the 3-km scale in Florida.
Figure 15. Correlation coefficient range and spread

Discussion

1. Correlations for different spatial scales and time scales

Lazarus and Murray (2007) have already found a persistent, significant correlation between the curvature and shoreline change positions for the northern North Carolina Outer Banks. However, different from this earlier study that focused on one piece of shoreline, for this project I analyzed the correlation coefficients at several locations and found significant correlations for most of the selected pieces (except FL_5, FL_8, and NC_96). My results also support the hypothesis that the strength of the correlation should differ from one place to another given the various wave climates.

Focusing on one location, Lazarus and Murray (2007) illustrated the variation of the coefficients for both different time scales and alongshore length scales. In
Figure 16, each curve represents the correlations observed in that study for different spatial scales given a specific time period. Small but significant correlation coefficients can be observed at annual scales and peaks at the sub-kilometer scales, whereas large coefficients are shown for the decadal scale (1996-2005) and kilometer scales. These findings reflect the fact that small-scale curves of the shoreline tend to change rapidly, whereas large-scale curves usually respond more slowly because more sediment is required to change the shoreline shape.

Figure 16. Curvature-to-position change correlations for smoothing windows

(Lazarus & Murray, 2007)

Instead of using the shoreline change rate for different time periods, in this project I used one single shoreline change database with a three-decade time
scale, and observed the variation of the curvature on different spatial scales. Because relatively long-term shoreline change rates were considered in this study, greater correlation coefficients were expected on relatively large spatial scales (kilometers). The findings from this project support this expectation. Furthermore, in contrast to the Lazarus and Murray (2007) study, a larger spatial scale (5-km scale) also was also considered in this project. The correlation coefficients tended to reach their maximum values at the 3-km or 5-km smoothing scale (for FL_6, FL_9, NC_94, and NC_95). All these findings point to the importance of considering the spatial scale when interpreting the correlations between shore curvature and shoreline change rate.

Moreover, the maximum correlation coefficient in this study is approximately 0.4 as observed on the 3-km scale, which is close to the greatest absolute value (∼0.5) in the Lazarus and Murray (2007) study. The lower absolute value of the correlation coefficient in this study compared to that found from Lazarus and Murray (2007) study could be due to the use of longer-term shoreline change data, for two reasons. First, with longer-term shoreline change data, the shape of the coastline tends to change more during a measured timespan than it does over shorter durations. This progressive change in shoreline shape makes the curvature measured at one snapshot in time less and less relevant to the shoreline change averaged over longer times. Second, stochastic variations in wave climate can cause the relationship between shoreline change rates and curvature to vary over time, even possibly changing from a positive to a negative correlation (Valvo et al., 2006; Lazarus and Murray. 2011). However, even using shoreline change data that spans decades, a significant correlation nonetheless is evident at several locations. The evidence thus far conveys a strong indication that the interaction between curvature and alongshore sediment transport patterns commonly play a significant role in determining patterns of shoreline change.
2. Human activities

One important factor that may have affected the correlation results in this project is human activity, i.e., coastal protection construction for managing shoreline retreat. Commonly used methods include hard engineering solutions, such as groynes and sea walls, and soft engineering solutions, such as beach nourishment/replenishment and sand dune stabilization (Komar, 1998). These activities will significantly affect the natural shoreline change processes around the construction site.

For instance, beach nourishment/replenishment is one of the most popular ‘soft’ approaches to mitigate shoreline erosion and is accomplished by adding sand to beach and nearshore zones (Figure 17). This strategy is a temporary one and usually needs to be repeated after a few years (usually 1 to 10 years). Because large quantities of sand must be replenished occasionally to combat shoreline retreat, the shoreline, where it is being nourished, basically maintains its original location for a long time. Thus, even if the shoreline curvature is tending to produce erosion locally, the ongoing nourishment prevents any long-term shoreline change, therefore resulting in no observable correlation between the shore curvature and shoreline change rate locally. Beach nourishment has been applied at many locations in Florida and North Carolina, which may have led to an underestimation of the correlation coefficients in this project relative to those that would be observed in the absence of shoreline stabilization.
Some hard engineering approaches may have more complicated effects on both the shoreline change rate and the shoreline shape. The alongshore sediment transport “manifests itself whenever this natural movement is prevented by the structure of jetties, breakwaters and groynes” (Komar, 1998). For the case of groynes (Figure 18), they are used to prevent erosion by slowing down the water flow and trapping the sediment coming from the updrift side. Therefore, groyne usage makes the sediment accumulate on the updrift side of the structure, which may also accelerate downdrift erosion and lead to a concave shape of the shoreline consequentially. The length and height of the groynes and the space between them all contribute to the plan-view shapes, which should be considered carefully when studying construction sites.
Beach replenishment and groyne usage are just two examples among numerous human activities that can affect the natural process of shoreline change and should be noted when interpreting the correlation analysis results in this project. However, examining historical data regarding these engineering approaches was beyond the scope of this project, although such analysis would be a useful direction for future research.

3. Coastal system

*Sediment composition of the shoreface*

Beach sediment at a specific location closely reflects the sources of that sediment and the grain size of the sediment that determines whether the sediment can remain on the beach. Fine-grained (‘muddy’) sediment eroded from the nearshore seabed will not remain in the nearshore system, whereas coarse sand (or gravel) eroded from the nearshore seabed ultimately joins the beach. What range of grain sizes will become part of the nearshore system is determined by the “complex relationship between the energy level of the nearshore waves and
currents, the general offshore slope, and the resulting grain size of the beach deposits” (Komar, 1998).

The material composing the nearshore seabed shows wide variation in its composition and grain sizes from one place to another. Where the shoreline and nearshore seabed experience chronic erosion, this variation contributes to the different responses of the shoreline when waves and nearshore currents are continuously eroding into that underlying material. Where the underlying material is composed of an appreciable fraction of fine material, a given gradient in the alongshore sediment transport will tend to produce more erosion than it would if the underlying material was composed of all coarse grains (Valvo et al., 2006; Lazarus and Murray, 2011). Therefore, the correlation between the curvature and shoreline change rate should vary at different locations that have different underlying materials, which also explains the regional variation of the correlation coefficients observed in this research.

**Wave climate**

As stated earlier, the coastal system is complex and the shoreline change rate is determined by many factors. Thus, the results of the simple linear regression that I applied in the correlation analysis may not exactly reflect that complexity in the coastal system because of the interaction of so many factors. For instance, focusing on the wave-driven sediment transportation and plan-view shoreline shaping processes, this study does not discuss wave climate in depth. Thus, the variation in correlation coefficients obtained in this research, both in terms of sign and value, may also be related to variations in wave climate.

A previous study (Lazarus & Murray, 2007) cited in this report and a wave hind-casting analysis for the northern Outer Banks (Ashton & Murray, 2006) mention the predominantly low-angle incident wave climate, at least locally, over
the last two decades. Ashton and Murray (2006) note that the large-scale capes, including most notably Cape Hatteras in North Carolina, exhibit wave-shadowing and shoreline-orientation effects that create and maintain the low-angle wave climate on both flanks. The shoreline will be smoothed in the low-angle wave scenario, whereas predominant high-angle waves can cause shoreline roughening (Ashton & Murray, 2006). The positive correlation between the curvature and shoreline change rate found at NC_94 (southern flank) and NC_95 (northern flank) in this study dovetails with the results of the previous study (Lazarus & Murray, 2007).

For this project, the correlation coefficients are generally small. However, the significant values are comparatively greater than the less significant ones, indicating the existence of the correlation between curvature and shoreline change rate. The multi-sample tests of the selected shoreline pieces and the consistency with the results from previous work (Lazarus & Murray, 2007) reinforce the validity of the existence of this correlation. Even excluding the effects of any human activity and considering only an over-simplified wave scenario, significant correlations can be observed for many locations. This findings support the importance of taking shoreline curvature into account for better coastal management, especially at locations that exhibit a strong correlation between curvature and shoreline change rate.

4. Future work

Human activity may significantly affect the natural shoreline change processes and should be included in any future study. Moreover, research into different time periods and scales for more locations is necessary to provide additional strong evidence or ideas regarding the impact of regional coastal climates.

Conclusion
The low sloping sandy shoreline of the East Coast is a dynamic and complicated system that is affected by a series of factors. Shoreline curvature has been mentioned in several studies (e.g., Lazarus & Murray; Larson et al.; Dolan et al.) as one of these factors, because it influences the shaping processes of the shoreline by affecting alongshore sediment transport. Using quantitative methods, this research supports the idea that the shoreline curvature affects the long-term shoreline change rate. Using the coastline contour data for the East Coast of the United States, I calculated and smoothed the curvatures on different spatial scales. The results of the correlation analysis of selected shoreline pieces in Florida and North Carolina indicate the widespread existence of a significant correlation between shoreline curvature and shoreline change rate. The results also show the variation in the correlation significance for the different spatial scales as well as different locations. These findings indicate the importance of considering shoreline curvature when planning and implementing local coastal management strategies.
Appendix A. Shoreline piece extraction using Coastline Extractor

The extraction of the shoreline pieces used for analysis in this study was accomplished by following these steps:

1. Download the National Geophysical Data Center Desktop Coastline Extractor from: [http://www.ngdc.noaa.gov/mgg/shorelines/gshhs.html](http://www.ngdc.noaa.gov/mgg/shorelines/gshhs.html) and download both files of the shoreline data (gshhg-shp-2.3.0.zip).

2. Open the GEODAS Coastline Extractor and go to the directory of downloaded coastline data. Select “Coastlines+” then “GSHHS Shorelines, WDB2 Rivers/Political” and direct it to the requested folders.

3. Plot the coastline data.

4. Zoom in on the section of coastline that is desired for making a shoreline piece. Then, save it as type “ESRI ShapeFile Format” for the GIS projection for the next step. For organizational purposes, create a new folder for each shoreline piece and keep the ShapeFile in that folder.
Appendix B. Geographic information system (GIS) manipulation

This appendix includes two sections: the basic steps of data processes for each shoreline piece and the methods used to address the noncontinuous segments.

**Basic steps:**

1. Open ArcGIS and connect the folder with the designated shoreline piece ShapeFile.

2. Download a general background layer for reference, if needed. For this project, the reference layer is “the US States” found on the Esri website.5

3. Create a “new file geodatabase” in the folder that was created earlier for all future files.

4. Select the projected coordinate system for the layer. (Right click on “Layers”→“Coordinate System”→”Projected Coordinate System”.). The projected system used in this project is “North America Lambert Conformal Conic”.

5. Project the desired shoreline in the same projected coordinate system. (”Data Management Tools”→”Projections and Transformations”→”Feature”→”Project.”).

6. Delete the shapes or lines that do not belong to the shoreline piece using “Editor Toolbar”. Save the changes by selecting “Save the Change” or “Stop Editing”.

7. Create a new “Point Feature Class” in the geodatabase. Then, select the projected shoreline and construct points along the shoreline. Remember to choose the distance as 1 meter to keep the space between the adjacent points equal. (”Editor Toolbar”→”Construct Points”.)

8. Delete the points that are not needed for the curvature calculations; these points are located mostly at both ends of the shoreline piece or back of the barrier island.

9. Create the reference line using the endpoints of the shoreline piece. (Create a new feature class file and the type should be “Points”→ copy the endpoints of the  

5 Geographic information system company website at: http://www.esri.com/
shoreline into the new feature class file → construct the reference line with “Points to Line.”) (Arc Toolbox → Data Management → Features → Points to Line.)

10. In order to keep all the shoreline points on one side of the shoreline, the reference line may need to be shifted slightly. (“Editor Toolbar” → “Copy Parallel” → fill the distance and choose the side.) The line may be moved to either the left or right according to the points. If both left and right are chosen, two parallel lines will appear on both sides.

11. Calculate the distance from the points to the reference line. (“Arc Toolbox” → “Analysis Tool” → “Proximity” → “Near”).

12. Export the distance data. (Right-click the layer of the points and choose “Open Attribute Table” to see the distances between the points and the reference line. The table can be exported by clicking the “table options” button on the top left.)

Noncontinuous shorelines

1. If the shoreline pieces are linked with each other (i.e., if they have overlapping parts or the endpoints of each piece are very close), then:
   - Create a new feature class file and the type should be “line”.
   - Copy all the small pieces into that new feature class file.
   - Choose the following tool to make the shoreline pieces into a whole piece: arc toolbox → data management → features → unsplit line.
   - Copy ALL the linked pieces; otherwise ArcGIS will not be able to make one whole line (i.e., ArcGIS might put several closed or linked pieces together).
   - If the output file still contains two pieces or more of shoreline, repeat all the steps in (1) until all the small pieces of shorelines are combined.

2. If the shoreline pieces are not linked with each other (i.e., if the pieces do not intersect each other), then:
   - Construct each small piece into points (see step 8).
   - Create a new feature class file and the type should be “points”.

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- Copy all the points constructed from the small pieces into the new feature class file.

- Choose the following tool to make all the points into a line: arc toolbox → data management → features → points to line.

Then the output should be a continuous line.
References


