USING TOPOGRAPHIC LIDAR DATA TO DELINEATE THE NORTH CAROLINA SHORELINE
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Abstract: In North Carolina, shoreline change rates are an important component of the state’s coastal management program. To enhance methods of measuring shoreline change, the NC Division of Coastal Management (DCM) is considering using mean high water (MHW) shorelines extracted from lidar data together with traditional wet/dry shorelines digitized from aerial photography. To test their compatibility, a wet/dry line and MHW shoreline derived from a concurrent 2004 oceanfront photography and lidar dataset were compared along a distance of 244 km. Results show that the MHW shoreline was seaward of the wet/dry shoreline by 2.82 m on average, and that this offset biased shoreline change rates by an average of 0.05 m/yr. The offset was greatest on low-sloping beaches experiencing higher water levels at the time of photography, but overall was small enough to suggest that the MHW shoreline can be a reliable substitute for the wet/dry shoreline.

INTRODUCTION

Coastal policy and shoreline change rates in North Carolina

Every five to six years, the North Carolina Division of Coastal Management (DCM) updates the state’s shoreline change rates, which have been required for the establishment of oceanfront building setbacks since 1979 under the North Carolina Coastal Area Management Act (CAMA). CAMA rules require that any new
oceanfront structure must meet a specified setback distance measured landward from the first line of stable, natural vegetation surveyed on the beach. In general, the setback distance is a multiplier of the long-term (42 to 71 years) average annual erosion rate. With few exceptions, oceanfront development intended for single-family use must meet a setback distance of 30 times the average annual erosion rate or a minimum of 60 feet (~18 m). Commercial and multi-family development greater than or equal to 5,000 ft² (465 m²) must meet more stringent setbacks, often based on a 60-year multiplier. It follows that the accuracy of shoreline change rates must be high so that setbacks ultimately reflect actual conditions and coastal development can be sited at reduced risk.

In 1999, the North Carolina Coastal Resources Commission’s (CRC) Science Panel on Coastal Hazards, a technical committee primarily composed of geologists and engineers that provides scientific and technical guidance to the CRC, recommended that DCM: 1) begin moving towards using linear regression-based erosion rates instead of end-point rates for calculating oceanfront setbacks and 2) explore the use of short-term erosion rates as a complement to long-term rates. However, switching to linear regression rates would necessitate the use of several statewide shoreline positions, and calculating short-term shoreline change rates (<10 years) may require a shoreline indicator of higher accuracy than what DCM traditionally has used (the wet/dry line, see next section). DCM is currently performing a statewide erosion rate update using a concurrent 2004 aerial photo and lidar dataset, and multiple shoreline indicators are being considered for inclusion. A better knowledge of how these different shoreline types compare and contrast to each another (and why) will not only create a better, more accurate understanding of North Carolina’s dynamic coastal processes, but will also increase the effectiveness of many coastal management and coastal policies that rely upon shoreline analysis.

The wet/dry line
Traditionally, the wet/dry line interpreted from aerial photography (e.g. Dolan et al. 1980; Martin 1997; Overton et al. 1999; Overton and Fisher 2003) has been used to delineate the shoreline and to calculate shoreline change rates in North Carolina. Acting as a visual proxy for shoreline position, the wet/dry line is defined simply as the boundary observed on the beach between wet and dry sand (Figure 1) and is affected by factors such as tides, wave run-up, sediment characteristics (e.g. grain size and porosity), and groundwater levels (Martin 1997).

Although the wet/dry line can sometimes be considered a surrogate for the high water line (HWL; Boak and Turner 2005), it is important to note the differences between them. The HWL has received thorough consideration (e.g. Shalowitz 1964; Stafford 1971; Pajak and Leatherman 2002; Ruggiero et al. 2003; Moore et al. 2006), and is interpreted as the landward extent of the previous high tide (Shalowitz 1964). Even though it was at one time a wet/dry boundary, it is not necessarily a clearly saturated boundary at the time of photography. Rather than actively migrating seaward and landward during a tidal cycle similar to the wet/dry line (Dolan et al. 1980), the HWL is a more static boundary that can be identified by other visual cues besides saturation such as sand discoloration or debris left by the last high tide (Shalowitz 1964). For the
purposes of this study, “HWL” will refer to this definition. The HWL as so defined is often located higher on the beach face than the wet/dry line, and has been quantitatively defined as the elevation exceeded by 2% of wave run-up maxima (Ruggiero et al. 2003). The wet/dry line, on the other hand, has been approximated in North Carolina as the elevation exceeded by 33% of wave run-up (Martin 1997).

An assessment of lateral short-term wet/dry line instability due to wave run-up and tides in North Carolina showed that the wet/dry line varied by up to 5.8 m during a single tidal cycle (Dolan et al. 1980) and 10.3 m during a single day (Martin 1997). Similarly, the HWL has been shown to vary on the order of 10 m during a month in North Carolina (Pajak and Leatherman 2002). This potential instability can introduce uncertainty into shoreline change rates, as a given rate may be an expression of short-term water level variability rather than a true indicator of shoreline movement (Ruggiero et al. 2003).

Interpretation of the wet/dry line from aerial photography, as with other visual shoreline proxies such as the HWL, can vary (Daniels et al. 2000; Ruggiero et al. 2003) due to the different skill or knowledge levels of the digitizers. Daniels et al. (2000) found, for instance, that two interpretations of the HWL on the same set of photography differed on average by 12.44 m. This, along with short-term variability and the possible positional inaccuracies of aerial photography (Ruggiero et al. 2003), can introduce uncertainty into shoreline change rates and in turn affect the accuracy oceanfront structure setbacks or other coastal policy decisions.

**Lidar-derived datum-based shorelines**

Recently, topographic lidar surveys have been used to generate shorelines based on the elevation of a tidal datum, such as mean high water (MHW), calculated over an 18.6-year tidal epoch (e.g. Judge et al. 2001; Stockdon et al. 2002; Moore et al. 2006). Such datum-based shoreline positions may offer noteworthy advantages over photo-interpreted shorelines such as the wet/dry line. First, datum-based lidar shorelines can shift only in response to sediment transport, and any short-term variation due to wave run-up and/or tides is eliminated (List et al. 2006). Second, there is no interpretation
necessary and the shoreline extraction procedure is therefore objective and repeatable. MHW is the most common tidal datum used to extract a shoreline from lidar data because its position on a given beach is thought to be analogous to other shoreline indicators such as the HWL and those derived from National Ocean Service T-sheets (Shalowitz 1964).

Before a lidar-derived MHW shoreline can be included in a long-term shoreline change analysis in North Carolina, the degree of consistency between it and the wet/dry line must first be tested so that any bias to shoreline change rates introduced by using two different shoreline indicators can be quantified. Several studies have addressed the relationship between the HWL and MHW, and the HWL has been found to be landward of MHW by approximately 50 m in Washington (Ruggiero et al. 2003), 18.8 m on Assateague Island (Maryland and Virginia; Moore et al. 2006), and 13.4 m in North Carolina (Pajak and Leatherman 2002). Because the wet/dry line falls somewhat lower on the beach than the HWL, we would expect the offset and possible bias to shoreline change rates found in this study to be less than indicated in previous studies.

In August and September of 2004, a concurrent set of orthophotography and lidar was obtained for the entire North Carolina coast that allows for direct comparison between the wet/dry shoreline and the lidar-derived MHW shoreline. Using this dataset, the goals of this study are to assess 1) the degree of interchangeability between the wet/dry and MHW shorelines over a large and morphologically diverse oceanfront shoreline study area (~244 km) and 2) the feasibility of using MHW shorelines to calculate long-term shoreline change rates in North Carolina.

STUDY AREA, DESCRIPTION OF DATASET, AND METHODOLOGY
The Atlantic barrier island coastline of North Carolina (Figure 2) is a wave-dominated, microtidal environment. Mean annual significant wave heights ($H_{\text{sig}}$) are 0.7 – 1.6 m (NOAA 2006), and semidiurnal tides range, on average, from ~1 m along the northern coast to ~1.5 m near the South Carolina border (NOAA 2006). Because “hard” shoreline stabilization structures such as seawalls and groynes have been banned since 1985, the North Carolina coast is largely unaffected by engineered structures.

Between 27 August and 3 September 2004, MD Atlantic Technologies (Huntsville, AL), co-contracted by the US Army Corps of Engineers (USACE) and DCM, collected a dataset of concurrent lidar and aerial photography covering the entire 516 km-long ocean coastline of North Carolina. Figure 3 shows the dates and times of the surveys, as well as the tidal stage and approximate $H_{\text{sig}}$ values. Lidar was collected with an Optech ALTM 3100 sensor mounted on a Cessna 206. Vertical accuracy is generally expected to be ±0.15 m (Sallenger et al. 2003), which includes all known sources of error. Digital elevation models (DEMs) gridded from the lidar returns were tested and found to be within this range (MD Atlantic 2005). However, subsequent comparisons between the returns of two lidar passes separated by about an hour over the same 40 km-long area showed a significantly greater amount of vertical error – about 0.3 m – which caused MHW shorelines generated from each pass to be offset
by, on average, 2.45 m. This error is likely due to the potential for the GPS data to drift vertically over time (Sallenger et al. 2003). The GPS error is not well understood, so it is difficult to estimate the appropriate error for each data point within a data set. Although the level of vertical drift error present in some of this lidar data might be much higher than what is normally expected, with only limited data demonstrating this we cannot determine a general increased error term to apply to all the data; therefore, we used the standard vertical error estimate of ±0.15 m.

Figure 2. North Carolina location map showing study areas and MHW zones.

Figure 3. Tidal stage (top) and $H_{\text{sig}}$ (bottom) during the 2004 aerial survey dates. Tidal data are from the USACE Field Research Facility (FRF) at Duck, NC; $H_{\text{sig}}$ values are from the FRF waverider buoy at Duck and NOAA buoy FPSN7 near Cape Fear.

A method similar to that presented by Stockdon et al. (2002) was used to extract a MHW shoreline from the North Carolina lidar data. Every 20 m alongshore, beach profiles of scattered lidar data were extracted and a linear regression through a selected set of foreshore data points was used to locate the intercept of a MHW elevation with the beach profile. Operational MHW elevation zones as mapped by...
Weber et al. (2005) were used to determine the elevation of MHW. Three such zones exist in North Carolina (Figure 2; relative to NAVD88): Virginia to Cape Lookout (0.26 m), Cape Lookout to Cape Fear (0.36 m), and Cape Fear to South Carolina (0.51 m). Given a vertical accuracy of ±0.15 m for all data points and using beach slopes measured at each cross-shore transect, the vertical error was converted into a horizontal error. This term was added in quadrature, i.e. the square root of the sum of the squares, to the 95% confidence interval of the MHW intercept on the regression line and resulted in a composite horizontal error estimate for each MHW data point. There were many areas for which a MHW shoreline position could not be produced due to problems encountered in the lidar data, and as a result, the MHW shoreline contains recurrent data gaps.

Digital aerial photography was collected simultaneously with the lidar survey. Using lidar-generated DEMs, the photography was orthorectified and subsequently tested to have a total root mean square (RMS) error of ±1 m (MD Atlantic 2005). The resulting orthophotos have a ground cell resolution of 0.15 m and are at scale of 1:2400. The wet/dry line was digitized from the orthophotography for use in comparing to the MHW shoreline, and three DCM staff members inspected the shoreline to ensure that the wet/dry interpretation was as consistent as possible.

Eleven study areas totaling a distance of 244 km were chosen in which to compare the wet/dry shoreline with the MHW shoreline (Figure 2). We excluded areas where the photos and lidar were asynchronous, large data gaps existed in the MHW shoreline, and consistent wet/dry interpretation was problematic. Comparisons were made using ArcGIS 9 equipped with the Digital Shoreline Analysis System (DSAS; Thieler et al. 2005) at transects spaced every 20 m alongshore.

**MHW AND WET/DRY LINE INTERCHANGEABILITY**

**Observed proxy-datum offsets**

To test the interchangeability of the MHW and wet/dry shorelines, we measured horizontal and vertical offsets between them (i.e. proxy-datum offsets) for all study areas. Vertical proxy-datum offset is defined as the elevation difference between the wet/dry line and MHW, and the elevation of the wet/dry line was measured by intersecting it with the lidar data. The elevation of the wet/dry is assumed to be a relative indicator of water level (i.e. tidal stage and wave run-up) on the beach profile, although other physical variables such as groundwater seepage and sediment permeability can control wet/dry line location (Martin 1997). Figure 4 and Table 1 summarize all observed offsets as well as other results that will be discussed in subsequent sections. On average, the wet/dry line was landward of the MHW shoreline by 2.82 m (σ = 5.31) and higher on the beach profile by 0.18 m (σ = 0.29). The position of the wet/dry line varied horizontally from 35.87 m landward to 12.30 m seaward of the MHW shoreline, and vertically from −0.73 m to 2.4 m. Table 1 shows the mean horizontal proxy-datum offsets for each study area, which range from 0.05 m (Oak Island) to 15.61 m (Ocracoke Island). Positive numbers indicate that the wet/dry line is landward of the MHW shoreline.
Figure 4. Results of the wet/dry line and MHW shoreline comparison for all study areas. Positive numbers on plots A and B indicate that wet/dry line is landward and higher in elevation than MHW, respectively. Positive rate shift values on plot D indicate an erosion rate decrease. The gray line represents per-transect values, and the black line is a smoothed 340-m average.

Table 1. Shoreline position and comparison data for all study areas

<table>
<thead>
<tr>
<th>Study Area</th>
<th>ID</th>
<th>Length (km)</th>
<th>Mean Offset (m)</th>
<th>σ Offset</th>
<th>Mean Rate Shift (m/yr)</th>
<th>σ Rate Shift</th>
<th>2004 Survey Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nags Head</td>
<td>1</td>
<td>81</td>
<td>0.65</td>
<td>2.57</td>
<td>0.01</td>
<td>0.05</td>
<td>08/27</td>
</tr>
<tr>
<td>Cape Hatteras</td>
<td>2</td>
<td>59</td>
<td>0.87</td>
<td>2.66</td>
<td>0.02</td>
<td>0.05</td>
<td>08/27</td>
</tr>
<tr>
<td>Ocracoke</td>
<td>3</td>
<td>19</td>
<td>15.61</td>
<td>8.49</td>
<td>0.27</td>
<td>0.15</td>
<td>09/03</td>
</tr>
<tr>
<td>Bogue Banks</td>
<td>4</td>
<td>35</td>
<td>3.68</td>
<td>3.51</td>
<td>0.27</td>
<td>0.15</td>
<td>08/30</td>
</tr>
<tr>
<td>Bear Island</td>
<td>5</td>
<td>4</td>
<td>5.75</td>
<td>4.17</td>
<td>0.10</td>
<td>0.08</td>
<td>08/30</td>
</tr>
<tr>
<td>Brown’s Island</td>
<td>6</td>
<td>3</td>
<td>7.34</td>
<td>2.65</td>
<td>0.13</td>
<td>0.05</td>
<td>08/30</td>
</tr>
<tr>
<td>Onslow Beach</td>
<td>7</td>
<td>5</td>
<td>6.19</td>
<td>3.43</td>
<td>0.12</td>
<td>0.07</td>
<td>08/30</td>
</tr>
<tr>
<td>Wrightsville Beach</td>
<td>8</td>
<td>5</td>
<td>4.97</td>
<td>3.28</td>
<td>0.07</td>
<td>0.05</td>
<td>09/02</td>
</tr>
<tr>
<td>Masonboro Island</td>
<td>9</td>
<td>10</td>
<td>7.94</td>
<td>2.99</td>
<td>0.11</td>
<td>0.04</td>
<td>09/02</td>
</tr>
<tr>
<td>Oak Island</td>
<td>10</td>
<td>16</td>
<td>0.05</td>
<td>2.70</td>
<td>0.00</td>
<td>0.05</td>
<td>08/31</td>
</tr>
<tr>
<td>Ocean Isle Beach</td>
<td>11</td>
<td>7</td>
<td>3.68</td>
<td>2.70</td>
<td>0.06</td>
<td>0.04</td>
<td>08/31</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>244</td>
<td>2.82</td>
<td>5.31</td>
<td>0.05</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Previous studies have shown the HWL interpreted from aerial photography to be landward of the elevation of MHW by approximately 50 m (Ruggiero et al. 2003), 18.8 m (Moore et al. 2006), and 13.4 m (Pajak and Leatherman 2002). As expected, because the wet/dry line falls consistently lower on the beach face than the HWL, the horizontal proxy-datum offsets measured here are comparatively small. This suggests that a lidar-derived MHW shoreline can be used as a reliable substitute for the
wet/dry line and that bias to shoreline change rates will be minimal, especially over the long-term (>50 years).

Causes of observed proxy-datum offsets
Causes of the trends and magnitudes in offset between the shorelines can depend on variables such as beach slope, short-term variability of the wet/dry line due to water level changes, and consistency of wet/dry line interpretation. Ruggiero et al. (2003) and Moore et al. (2006) found that horizontal proxy-datum offsets are larger on low-sloping, high-energy beaches, and that beach slope may be a good general predictor of offset magnitude. Figure 4A shows horizontal proxy-datum offsets aligned with beach slope measurements alongshore, and many regional and local trends in shoreline offset are inversely proportional to beach slope. For example, the increase in horizontal offset beyond ~140 km alongshore (study areas 3-11, Figure 2) is accompanied by a flattening of the foreshore beach profile, and the small shoreline differences in study areas 1 and 2 are accompanied by the steepest overall slopes in North Carolina. It is interesting to compare the variation of vertical proxy-datum offsets (Figure 4B) with horizontal offsets, as they are linked together by beach slope (Figure 4C). Between roughly 100 and 125 km in study area 2 (Figure 4), for example, the vertical offset approaches 1 m, but due to a steep beach the horizontal offsets are minimal (<5 m). Conversely, on Ocracoke Island (study area 3), vertical offset approaches 1 m, but there a low-sloping beach produces horizontal offsets over 30 m.

The position of the wet/dry line can be variable depending on tidal stage and wave run-up (Martin 1997). All photography used in this study was taken during or near low tide (Figure 3); however tidal stage still varied from a maximum of approximately –0.1 m (9/3, Ocracoke Island) to a minimum of –0.7 m (8/31, Oak Island and Ocean Isle). $H_{sig}$, measured at the USACE FRF waverider buoy near Duck, NC and at NOAA buoy FPSN7 offshore of Cape Fear (NOAA 2006; Figure 3), also potentially varied between surveys. Both buoys indicate that $H_{sig}$ was generally lowest during the surveys on 8/27 and 8/31, higher on 8/30 and 9/2 (although data points are sparse), and highest on 9/3. Consequently, the wet/dry line should not be at a consistent elevation on the beach profile for each survey. Mean horizontal and vertical offsets were lowest on 8/27 and 8/31, higher on 8/30 and 9/2, and highest on 9/3. This suggests, as proposed by Ruggiero et al. (2003), that higher wave energy pushes the wet/dry line higher on the beach profile and increases the horizontal offset at a magnitude inversely proportional to beach slope, while lesser wave energy allows the wet/dry line to be lower on the beach profile and decreases horizontal offsets. On 9/3, in addition to the high $H_{sig}$, the tidal stage was also the highest observed, and that in combination with a low-sloping beach produced the large mean 15.61 m horizontal offset measured on Ocracoke Island. The majority of the total study area, however, was surveyed on 8/27 and 8/31 when $H_{sig}$ was moderate (0.6-1.3 m). In North Carolina, mean annual $H_{sig}$ is 0.7–1.6 m, and so these dates can be taken as representing average, fair-weather conditions. Horizontal offset between the wet/dry and MHW shorelines on 8/27 and 8/31 averaged 0.80 m, indicating that during low tide and fair-weather wave conditions, the shorelines are nearly equivalent. It is
important to note that for study areas at a large distance from both wave buoys (e.g. Bogue Banks, Onslow Beach), $H_{\text{sig}}$ values should be taken as approximations only.

Assuming a relatively constant water level, beach slope alone could theoretically be a good general predictor of horizontal proxy-datum offsets. As discussed above, tides and $H_{\text{sig}}$ varied between survey dates, and wave run-up (and therefore the elevation of the wet/dry line and vertical proxy-datum offsets) should be expected to vary alongshore within study areas as a function of beach slope (Holman 1986; Stockdon 2006). The magnitude of horizontal offsets throughout all study areas is therefore dependent on both beach slope and water level and we can test this relationship using a simple equation:

$$X_0 = \frac{H_{\text{proxy}} - H_{\text{datum}}}{m}$$

(1)

where $X_0$ is the horizontal proxy-datum offset (Moore et al. 2006); $H_{\text{proxy}}$ and $H_{\text{datum}}$ are the heights of the wet/dry line and MHW, respectively; and $m$ is beach slope (note that the numerator is the vertical proxy-datum offset shown in Figure 4B). Figure 5 (left) shows the correlation between horizontal proxy-datum offset ($X_0$) and beach slope along 857 cross-shore transects chosen at random throughout all study areas. Even though the trend is significant at the 95% confidence level, the overall relationship is indistinct. A conspicuous subset of points with high values of $X_0$ from Ocracoke Island is labeled on the graph where the beach is relatively flat but $X_0$ was exaggerated as a result of the high water levels observed on that particular survey date (9/3). Along the same 857 transects, the elevation of the wet/dry line, assumed to be a relative indicator of water level, was measured and equation (1) was applied to predict $X_0$. Results were compared with the observed $X_0$ and are shown in Figure 5 (right). The correlation is very strong and illustrates that $X_0$ will be larger on low-sloping and/or higher energy beaches. This relationship can explain the mean $X_0$ magnitudes for all study areas and survey dates, including the high $X_0$ measured on Ocracoke Island on 9/3 and the low $X_0$ measured in study areas 1 and 2 on 8/27 wherein the beach profile was relatively steep and $H_{\text{sig}}$ was moderate. Plugging the mean beach slope (0.08) and mean vertical proxy-datum offset (0.18 m) for all study areas into equation (1) yields a predicted mean $X_0$ of 2.25 m, which is close to the observed total mean of 2.82 m. In some cases, the assumption of a linear beach slope between the wet/dry line and MHW shoreline may not hold true, and fluctuations in vertical proxy-datum offset may reflect inconsistencies in digitizing the wet/dry line rather than actual water level changes. These factors can account for the discrepancies between observed and predicted offset values.

**Rate shifts**

If the horizontal offset between the wet/dry line and MHW shoreline is large enough, (i.e. if water level is high and/or beach slope is low) it may begin to bias, or shift, change rates when one shoreline indicator is used as a substitute for the other. If the proxy-datum offset and the time elapsed between shoreline positions is known,
however, this rate shift is predictable when using end-point rates and can be determined as follows (Moore et al. 2006): 

\[ R_{Sc} = \frac{X_0}{t} \]  

(2)

where \( R_{Sc} \) is the end-point rate shift; \( X_0 \) is the measured horizontal offset between the wet/dry and MHW shorelines (also defined in equation 1 as \( H_{proxy} - H_{datum}/m \)); and \( t \) is the temporal span between the recent and historic shorelines used to calculate the shoreline change rate. The effects of the horizontal proxy-datum offset, \( X_0 \), will thus be greater at short time intervals (Moore et al. 2006).

Figure 5. Left plot shows the correlation between beach slope and observed horizontal proxy-datum offset. Right plot shows the correlation between observed horizontal offsets and horizontal offsets predicted using equation (1).

DCM uses a composite statewide historical shoreline for calculating long-term end-point shoreline change rates that dates between 1933 and 1962; with the 2004 shoreline, \( t \) in equation (2) varies from 42 to 71 years. Figure 4D shows the per-transect rate shifts that are possible if the 2004 MHW shoreline is used instead of the 2004 wet/dry line to calculate change rates with the historical baseline shoreline, and Table 1 lists the mean rate shifts for each study area. The total mean rate shift is 0.05 m/yr (positive number indicates erosion rate will be reduced and accretion rate will be increased) for all study areas and ranges for individual study areas between 0 (Oak Island, \( t = 60 \) years) and 0.27 m/yr (Ocracoke Island, \( t = 58 \) years). If the rate of shoreline change is rapid or the temporal span between shoreline positions is sufficiently long, the rate shift will only be a small fraction of the total change rate and may be small enough to completely disregard (Moore et al., 2006). Since horizontal proxy-datum offsets are relatively small in North Carolina and the time spans used are typically \( >50 \) years, much of the offset will produce negligible rate shifts. On the other hand, if the rate of change is slow and/or the proxy-datum offset is large, the rate shift may be a much greater fraction of the total rate. In this case, equation (2) can be used to correct for the shift if the mean horizontal offset is known or approximated.
Relative shoreline uncertainties
Some horizontal differences between the MHW and wet/dry shorelines may not be significantly different than zero due to the inherent positional uncertainties of the shorelines. To understand this, we must first assemble an approximate uncertainty budget for the wet/dry shoreline. As discussed above, there are three main sources of wet/dry line uncertainty: interpretation, short-term variability due to water level changes, and source error (Daniels et al. 2000; Ruggiero et al. 2003). Source error of the orthophotos used in this study was determined to be ±1 m (MD Atlantic 2005) after comparing locations on the photos with ground control points. To assess the uncertainty associated with interpretation, two wet/dry lines digitized by DCM staff were compared over a distance of 85 km. The first shoreline was checked for accuracy and consistency by DCM staff to act as a baseline for comparison, and specific visual cues were defined so that shoreline identification would remain consistent for the second iteration. Comparisons of the two shorelines revealed that the second shoreline was seaward of the original by 0.6 m with a total root mean square (RMS) uncertainty of ±2.6 m.

It was not possible to determine the short-term variability of the wet/dry due to water level changes because we lack the necessary frequent observations. In areas where 2004 photography from two different dates was available, the wet/dry line was seen to migrate landward approximately 10 m over a 12-hour period (Ocracoke Island), seaward 20 m over 3 days (Bogue Banks), and around 20 m landward over a month (near Cape Hatteras). Pajak and Leatherman (2002) assessed the variability of the HWL in North Carolina during July, August, and September from 1994-1996 over hourly, daily, and monthly time periods. Excluding storm events, they established a generalized estimate on the order of ±10 m. In addition, field measurements of the wet/dry line in North Carolina by Martin (1997) indicated a variability of ±10.3 m during a single day. These measurements agree with our cursory observations and provide a useful estimate of wet/dry variability in North Carolina, acknowledging that further work needs to be completed to assess its true variability.

Summing the source error (±1 m), interpretation uncertainty (±2.6 m), and potential short-term variability (±10 m) in quadrature yields a total wet/dry line uncertainty of ±10.4 m. Other similar uncertainty budgets for HWL shorelines total ±20 m (straight sum of ±3 source error, ±2 interpretation, ±15 short-term variability; Daniels et al. 2000) and 51-150 m (quadrature sum of ±4 source error, ±11 interpretation, ±50-150 m short-term variability; Ruggiero et al. 2003). Mean uncertainty of the MHW shoreline for all study areas is ±2.22 m (σ = 0.92). Taking the total uncertainty estimate for both shorelines into account, only 6% (694 out of 11,159) of measured horizontal proxy-datum offsets are significant, most of which are located on Ocracoke Island. This suggests a high degree of interchangeability between shorelines.

DISCUSSION
Lidar-derived, datum-based shorelines can offer an increase in accuracy over the wet/dry line for use in end-point rates and can also be used as a supplement to existing wet/dry lines in linear regression models. Short-term change rates (<10 years) that may be difficult to resolve using wet/dry lines are possible using MHW
shorelines, and DCM is considering using them for areas where long-term change rates are heavily biased by beach fill projects (e.g., Wrightsville Beach, Bogue Banks, Oak Island) so that the change rate can be more accurately measured between beach fill episodes. Results presented here suggest that a lidar-derived MHW shoreline is interchangeable with DCM’s traditional shoreline proxy, the wet/dry line, given a steep sloping beach and/or low water levels at the time of photography. Under these circumstances, a MHW shoreline will introduce minimal bias to long-term end-point shoreline change rates in North Carolina. However, during times of high water level and on low-sloping beaches, as demonstrated at Ocracoke Island, the proxy-datum offset is much greater and the interchangeability between the wet/dry line and MHW shoreline is decreased. Here, rate shifts will be a larger fraction of the total change rate, and it is therefore difficult to determine categorically that the shoreline indicators are equivalent because it depends on the conditions at the time of photography as well as beach morphology. On average, though, the observed rate shifts and proxy-datum offsets were small enough that the shorelines can be considered compatible. In future studies, the height of the wet/dry line can potentially be estimated using numerical wave run-up models as discussed in Martin (1997). This could allow proxy-datum offsets and rate shifts to be estimated without a rigorous proxy-datum comparison as described herein, and could also facilitate an assessment of the short-term variability of the wet/dry line.

Horizontal and vertical proxy-datum offsets, based on beach slope and the elevation of the wet/dry line, and the effect of resultant rate shifts on shoreline change rates can be connected through a simple equation using variables from equations (1) and (2) (after Moore et al. 2006):

$$R_A = \left( \frac{H_{proxy} - H_{datum}}{m} \right) \frac{t}{R_0} + R_0$$  \hspace{1cm} (3)

where $R_0$ is the original shoreline change rate and $R_A$ is the adjusted shoreline change rate after the incorporation of the rate shift. $H_{proxy} - H_{datum}$ is the vertical proxy-datum offset, the vertical proxy-datum offset divided by slope ($m$) is the horizontal proxy-datum offset (or $X_0$), and the horizontal proxy-datum offset divided by time span ($t$) is the rate shift. Because horizontal and vertical offsets are relatively small in North Carolina and shoreline change rates are calculated over sufficiently long time spans, the $R_0$ and $R_A$ values should be very similar and the wet/dry line and MHW shoreline can be considered generally interchangeable. The overall mean difference between $R_0$ and $R_A$ values for our study was 0.05 m/yr.

CONCLUSIONS

The 2004 photo-derived wet/dry shoreline presented here, measured over a distance of 244 km in North Carolina, is on average 2.82 m ($\sigma = 5.31$) landward of the 2004 lidar-derived MHW shoreline (Figure 4A) and 0.18 m ($\sigma = 0.29$) higher on the beach profile (Figure 4B). The magnitude of mean horizontal proxy-datum offset varies by
study area and ranges from 0.05 to 15.61 m (Table 1). Considering the uncertainty of the wet/dry line and MHW shoreline, 6% of measured offsets were significantly different than zero. Given a low tide and fair-weather wave conditions at the time of photography and/or a steep-sloping beach, these results suggest that the MHW shoreline can be used as a reliable substitute for the wet/dry line in regional shoreline change analyses. Rate shifts caused by using the MHW shoreline instead of the wet/dry line average 0.05 m/yr for all study areas (Figure 4D) and vary between zero and 0.27 m/yr for individual study areas (Table 1). Rate shifts either a) are a small percentage of the overall change rate and can potentially be disregarded or b) can be corrected using equation (2) providing that the mean proxy-datum offset is known or approximated through equation (1).

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