Determining depth of closure based on time-series beach profiles and empirical formulas: A case study along the Florida coast

By

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ABSTRACT

Depth of closure (DOC) is defined as the most landward depth seaward of which there is no significant change in bed elevation and no significant net sediment exchange between the nearshore and the offshore over a certain period of time, such as 5 to 20 years. DOC is an essential parameter used in beach and shore protection, sediment management, and many other aspects of coastal studies. Taking advantage of advancements in wave hindcast and bathymetry measurement in the past 20 years (2000-2019), this study determined the DOC at 12 locations along the Florida coast, including three from the northwest Gulf coast, three from the west Gulf coast, and six from the east Atlantic coast. The 12 sites covered a wide range of coastal morphodynamic conditions, with considerable difference in tidal ranges, incident wave heights, as well as nearshore and offshore morphology. Hindcast wave data from WAVEWATCHIII, available since 2005, were analyzed and applied to calculate the closure depth using various empirical formulas.

At all the 12 study sites, time-series profiles demonstrated an apparent convergence point indicating the presences of a DOC. The bed-level change at DOC, as quantified by the standard deviation of elevation variation, ranged from 0.05 m to 0.19 m. Along the studied northwest Florida Gulf coast the DOC ranged from 9.12 m to 9.76 m. The DOC along the studied west Florida Gulf coast ranged from 1.59 m to 4.06 m and is influenced by the shallow flat inner continental shelf. Along the studied east Florida Atlantic coast, the DOC ranged from 4.35 m to 8.20 m, with considerable alongshore variation. The Birkemeier formula yielded the closest predictions to the measured values. A linear relationship between the seaward slope of the outer bar and DOC was identified. Incorporating the seaward slope of the outer bar into the Birkemeier formula improved the accuracy of DOC prediction.

KEYWORDS: Storm impacts, sediment transport, coastal modeling, depth of closure, Florida, beach profiles.

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The depth of closure (DOC) is defined as "the most landward depth seaward of which there is no significant change in bottom elevation and no significant net sediment exchange between the nearshore and the offshore" (Kraus *et al.* 1999). DOC is often used as a boundary separating the active nearshore zone of sediment transport and the less active offshore zone. DOC is dependent on both spatial and temporal scales. The DOC (i.e. knowing the seaward boundary of active bed-level change) is an essential parameter used in many coastal engineering and management projects. For example, DOC is a key parameter in the design of beach nourishment, and also enters in transport and/or morphological models as a separation between the active zone of morphology change and deeper zone of largely negligible sediment deposition and erosion (Larson and Kraus 1994; Marsh *et al.* 1999; Kraus *et al.* 1999; Dean 2002).

As stated in the Kraus *et al.* (1999) definition, the value of DOC is significantly controlled by spatial and temporal scales. DOC can be evaluated through many different timescales from a single energetic event to a decade or longer duration (Nicholls *et al.* 1998; Hinton and Nicholls 1999). As expected, a longer temporal scale results in deeper DOC. As the temporal scale increases, larger variations in the time-series profiles tend to occur (Nicholls *et al.* 1998). Practically, the temporal scale is often controlled by the availability of time-series data. Based on previous time-series beach profile studies, Aragones *et al.* (2019) suggested that it is important to have a minimum of five years of data in order to determine and interpret the DOC accurately. Spatial scale can also have considerable influence on the determination of DOC, because a larger spatial scale would include more spatial variations. For example, if an entire barrier island is included, the areas in close proximity to the tidal inlet may have a different DOC as compared to the rest of the area. Spatial scales can be controlled by the goal of a particular project. As emphasized in Kraus *et al.* (1999), the temporal and spatial scales associated with DOC values should be clearly specified. The influences of temporal and spatial scales on DOC were examined in this study.

Regional geological characteristics can have significant influence on DOC (Wright *et al.* 1986; Wright 1995). Generally, geological influences on DOC can be quite variable and are not well documented. Morphological characteristics of the inner continental shelf, such as slope and its spatial variations, can have significant influence on sediment transport and therefore DOC. Morphological features on the inner continental shelf, like shoals and their subsequent migration near tidal inlets further complicate the DOC estimate, compared to a simpler featureless coastline (Barrineau *et al.* 2021). Sedimentological and geologic characteristics such as outcropping of rocks, which are common along the east and west coasts of Florida, can impose a limit on the DOC, i.e. a maximum value. Transport and deposition of cohesive muddy sediment is different from those of non-cohesive sand-sized sediment. Along coasts with significant mud-sized sediment, sandy beaches often transition seaward to muddy sediments. Transport of mud is strongly influenced by its cohesiveness. Largely nonerodible stiff mud can impose a limit on DOC, similar to a rock outcrop, while soft mud can be easily eroded. Furthermore, muddy inner continental shelf tends to be flat, potentially imposing morphological constraint on DOC.

The concept of DOC also plays a key role in the estimation of rate of shoreline change as driven by sea level rise, i.e. the Bruun Rule (Bruun 1962). The concept and application of Bruun Rule has been improved by many recent studies on modeling long-term coastal changes associated with climate change and sea-level rise. However, DOC (or a seaward converging point) remains a key parameter anchoring the seaward limit of morphology change. Rosati *et al.* (2013) expanded the Bruun Rule by incorporating landward sediment transport due to overwash. Moore and Murray (2018) compiled a series of papers discussing various aspects on the modeling of long-term barrier-island response to sea-level rise (Moore *et al.* 2010; Lorenzo-Trueba and Ashton 2014; Murray and Moore 2018; Cowell and Kinsela 2018; Ashton and Lorenzo-Trueba 2018). All the models adopted the general concepts of an equilibrium shape of shoreface similar to that of equilibrium beach profile (Dean 1991) and a seaward depth limit of morphology change. Improved verification and estimation of DOC are essential to modeling long-term coastal changes.

BACKGROUND

Several empirical formulas have been developed, linking DOC to wave conditions, especially extreme wave height with the understanding that active sediment transport and subsequent morphology change in deeper water should be mainly driven by extreme conditions. Hallermeier (1977, 1978, 1981, and 1983) developed an empirical formula to compute DOC (D_c) using extreme wave conditions (Equation 1), specifically the significant wave height that exceeded 12 hours per year (H_{s_12hr}) and its associated peak wave period (T_{p_12hr}). Udo *et al.* (2020) suggested that the accuracy of the Hallermeier formula can be limited by the accuracy and availability of wave data, and its generalization of variable coastal geology and morphology (Udo *et al.* 2020). The Hallermeier (1977, 1978, 1981, and 1983) formula is based mainly on laboratory data and some supporting field measurements from coasts of the Pacific Ocean and the Gulf of Mexico. It was determined empirically based on lab and field data but supported by the understanding of the initiation of sediment transport by wave motion, especially extreme energetic waves. Statistical analysis determining extreme wave height and period is strongly influenced by the temporal scales, i.e. the duration over which the statistics are conducted (Hallermeier 1978).

$$D_c=2.28H_{s\_12hr}-68.5(H^2_{s\_12hr}/gT^2_{p\_12hr}) \quad (1)$$

The two coefficients in Equation 1 were determined through laboratory testing of different extreme wave conditions, scaled based on varying coastal environments in the United States (Hallermeier 1978). The first term carries the most weight while the second term adjusts based on wave steepness (Hallermeier 1978). Nicholls *et al.* (1998) suggested that Equation (1), referred to here as the Hallermeier formula, tends to overpredict DOC at a medium time scale (1 year to 10 years). Birkemeier (1985) re-evaluated the Hallermeier formula using additional field data from the USACE Field Research facility in Duck, NC, and proposed a revised formula, referred to here as the Birkemeier formula (Equation 2). The Hallermeier and Birkemeier formulas have the same form but with different coefficients:

$$D_c=1.75H_{s\_12hr}-57.9\,(H^2_{s\_12hr}/gT^2_{p\_12hr}) \quad (2)$$

Since the first term in Equations (1) and (2) carries most of the weight, the Hallermeier formula (Equation 1) yields a DOC value that is roughly 1.3 times higher than the Birkemeier formula (Equation 2). Houston (1995) argued that the extreme wave parameter, H_{s_12hr} and T_{p_12hr} in this case, can be difficult to determine and therefore may carry considerable uncertainties. Houston (1995) suggested that the annual average significant wave height (H_{s_avg}) would be a much easier parameter to obtain and could be used to predict DOC. Houston (1995) proposed formula is referred to here as the Houston formula (Equation 3),

$$D_c=6.75H_{s\_avg} \quad (3)$$

In order to more directly incorporate the influence of temporal scale in the calculation of DOC, Stive *et al.* (1992) and Nicholls *et al.* (1996) suggested that the extreme wave parameter should reflect the period during which the DOC was computed. The Nicholls *et al.* (1996) formula (Equation 4), referred to here as the Nicholls formula, carries an identical form as that of Hallermeier.

$$D_c=2.28H_{s\_12hr}-68.5\,(H^2_{s\_12hr}/gT^2_{p\_12hr}) \quad (4)$$

The difference between the Nicholls and Hallermeier formulas is in the definition of the extreme wave height and period, $H_{s\_12hr\_N}$ and $T_{p\_12h\_N}$. Nicholls *et al.* (1996) suggested that $H_{s\_12hr\_N}$ and $T_{p\_12h\_N}$ should be the 12-hour exceedance wave height and the associated peak wave period over the entire study period. This can result in a much larger wave height than the annual extreme (12-hr) wave-height values for a multi-year duration.

In all the above formulas, the D_c is referred to Mean Low Water (MLW). These formulas link the DOC to wave height and wave period, therefore, the larger the wave height the deeper the predicted DOC value. These empirical formulas were developed based on data from sandy beaches and do not consider the impact of hardbottom or rock outcrops (Robertson *et al.* 2008). These formulas using only wave conditions may not perform as well for mixed energy or tide-dominated coasts where tidal forcing cannot be neglected. Furthermore, regional geologic characteristics which can have significant control on morphology change (Valiente *et al.* 2019) are not included in the empirical formulas.

The State of Florida has been measuring beach profiles annually along the nourished beaches for nearly three decades using a statewide R-monument system, i.e. permanently established benchmarks spaced every ~300 m alongshore with accurate horizontal and vertical positions. The R-monuments and a typically pre-determined roughly shore-perpendicular survey azimuth allow the annual beach-nearshore surveys to be conducted consistently. The beach-profile surveys typically extend far offshore and beyond the DOC as defined above. Since many beaches along the Florida coast receive regular nourishment, the time-series beach-offshore-profile data are available at numerous locations, although the amount of data available among the sites varies. All the data are available from the Florida Department of

Environmental Protection (FDEP). Since roughly 2000, due to the advancement of the RTK GPS (Real-Time Kinematic Global Positioning System) technology the accuracy of the offshore profile survey has improved significantly, particularly in terms of tide correction which has substantial influence on elevation measurements. The R-monument system and the accurate positioning technology allow improved quality control on time-series beach-profile surveys as described in the FDEP survey standards (FDEP 2014).

For the determination of DOC, the accuracy of the offshore portion of the profile survey is particularly important. The offshore portions are collected using vessel-mounted precision echo sounding equipment synchronized with RTK-GPS. Water depth measurements by echo sounding equipment and subsequently the quality of the bathymetry are often influenced by water level variations, water temperature, and wave conditions. In order to minimize the impact of these conditions, FDEP has established depth check parameters and detailed specifications on beach-nearshore profile surveys (FDEP 2014). Sound speed variations have been corrected during data processing, in compliance with the U.S. Army Corps of Engineers hydrographic survey standards (FDEP 2014).

In this paper, time-series beach profiles from 12 study sites along the Florida coast, including three from the northwest Gulf coast, three from the west Gulf coast, and six from the Atlantic coast, were analyzed. These 12 study sites were chosen in order to evaluate how the different oceanographic and geologic factors of each coast impact the DOC along the Florida coastline. Time-series beach-offshore profiles surveyed between 2000 and 2019 were analyzed to determine the DOC. Because this study was based on time-series beach profiles, the study sites were also chosen based on availability of data, and the locations with the most profile data were prioritized. At each study site, time-series beach-offshore profiles from seven FDEP R-monuments, spaced from 2 to 24 km alongshore, were extracted. Between 9-20 beach surveys at each R-monument were obtained. In total, 1,268 beach-offshore surveys from the 12 study sites were analyzed.

This paper aims to answer the question "what are the dominant factors that determine the DOC?" Understanding the controlling factors will allow for improved empirical formulas and more accurate DOC predictions. The factors that were explored here include wave conditions, the seaward slope of the outer bar, influence of the inner shelf bathymetry, and influence of regional geology. Wave conditions and the seaward slope of the outer bar can be readily quantified, while quantifying regional geology and inner shelf bathymetry can be difficult. Taking advantage of the large and accurate dataset, the uncertainties associated with the determination of DOC via time-series beach-offshore profiles were examined.

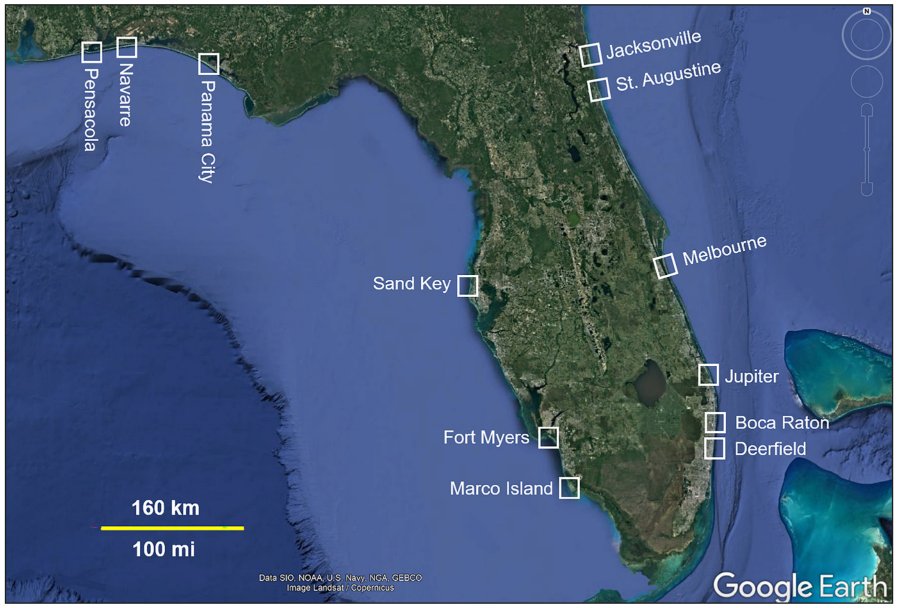


Figure 1. The 12 study sites along the Florida coast.

STUDY AREA

The coast of Florida (Figure 1) provided an ideal case for the study of DOC, due to a large variation of oceanographic and morphologic conditions. All of the study sites are considered critically eroded shorelines which is defined by Florida Administrative Code 62B-36.002(5) as "a segment of the shoreline where natural processes or human activity have caused or contributed to erosion and recession of the beach or dune system to such a degree that upland development, recreational interests, wildlife habitat, or important cultural resources are threatened or lost. Critically eroded shorelines may also include peripheral segments or gaps between identified critically eroded areas which, although may be stable or slightly erosional now, their inclusion is necessary for continuity of management of the coastal systems or for the design integrity of adjacent beach management." This "critically eroding shoreline" identification often provides justification for beach nourishment. All the beaches in this study are nourished, although with different nourishment lengths and renourishment intervals. Mitigating damages caused by hurricanes and tropical storms is also a large component of the management of these critically eroding shorelines. The northwest Florida Gulf coast is highly vulnerable to hurricane impacts (Wang *et al.* 2006; Wang and Horwitz 2007; Houser *et al.* 2008; Houser and Hamilton 2009; Claudino-Sales *et al.* 2008, 2010; Wang *et al.* 2020). The west Florida Gulf coast, e.g. the greater Tampa Bay area, has not had a direct hurricane hit for about 100 years, although several distal passages occurred (Cheng and Wang 2019; Cheng *et al.* 2021). The Atlantic coast is also vulnerable to hurricane impacts, in addition to generally higher waves (FDEP 2017).

Along the northwest coast of Florida there are three study sites (Figure 1 and Table 1). The Pensacola site stretches 11 km alongshore. Pensacola is the most western location of all the study sites. This study site is located along the western end of the 80-km long Santa Rosa barrier island and may be influenced by Pensacola Pass ebb shoal (Figure 1). The Pensacola site has a small tidal range of about 0.38 m and an average offshore significant wave height of 0.6 m, based on hindcast wave model WAVEWATCHIII (https://polar.ncep.noaa.gov/waves/wavewatch/). This site was chosen because of its characteristic geologic and oceanographic conditions along the Santa Rosa barrier

Table 1.
The longshore extent and basic oceanographic conditions at the 12 study sites.

Study site	Longshore extent (km)	Nearby inlet	Average wave height (m)	Tidal range (m)	NAVD88 relative to MLW (m)	Tropical storm passages (2000-2019)
Pensacola	11	Y	0.60	0.38	0.11	5
Navarre	2	N	0.64	0.38	0.13	5
Panama City Beach	24	Y	0.54	0.43	0.14	4
Sand Key	17	N	0.45	0.84	0.30	3
Fort Myers	2	Y	0.27	0.77	0.49	5
Marco Island	2	N	0.38	0.68	0.54	5
Jacksonville	2	N	0.83	1.71	0.91	7
St. Augustine	2	Y	0.85	1.57	0.91	7
Melbourne	7	N	0.94	1.21	0.81	6
Jupiter	2	Y	0.98	0.90	0.72	7
Boca Raton	2	N	0.85	0.67	0.67	7
Deerfield	2	N	0.85	0.73	0.67	7

island and because this location has one of the most complete and comprehensive data sets, with at least one survey each year from 2000 to 2019, excluding 2005 and 2013. Most of these surveys were conducted during the summer months between May and August. Exact survey dates varied and were likely influenced by weather conditions. The Pensacola beach area was nourished in 2003, 2006, and 2016.

The second site, Navarre Beach, is located to the east of Pensacola, also on Santa Rosa barrier island. This site stretches 1.8 km alongshore and is far from any present-day tidal inlets. This site has a significant wave height that is similar to Pensacola at about 0.6 m, with the same tidal range of 0.38 m. Four tropical storms and one hurricane made landfall within 100 km of these two sites during the time frame of this study, with the strongest being Hurricane Dennis in 2005. Within the FDEP historic shoreline database there were 11 surveys conducted in the Navarre beach area from 2005 to 2019; similarly to Pensacola, most of these surveys occurred in the summer months. The Navarre beach area was nourished in 2006, 2010, and 2016. The Pensacola and Navarre study sites were chosen to investigate potential spatial variation of the DOC along an 80-km barrier island.

The third study site along the northwest coast is Panama City Beach. This site extends about 24.4 km alongshore, the longest of all the study sites. The ebb shoal of St. Andrews Inlet near the southwest end of this site may have some influence on the DOC here. The Panama City site is again characterized by a small tidal range of 0.43 m and has an average significant wave height of about 0.5 m. Three tropical storms and one hurricane made landfall within 100 km of this study site. Hurricane Michael, a Category 5 storm in 2018, was the strongest. This study site was chosen because of the excellent availability of survey data with 20 surveys in this area from 2000 to 2018. The Panama City beach area was nourished in 2002, 2004, 2006, 2011, and 2016.

Three study sites were investigated along the west Florida Gulf coast (Figure 1 and Table 1). The Sand Key study site is located on a barrier island and spans 16.8 km alongshore. This study site was chosen to examine the influence of hardbottom along the Gulf coast, and to also investigate how the general morphology and shape of the barrier island may impact the DOC, as the studied area curves around a gentle headland. Survey data was collected between 2000 and 2014, with data missing from 2003, 2007, and 2011. Most of these surveys were conducted in the winter months. Nourishment has been conducted regularly in this area and occurred three times during the study period in 2005, 2012, and 2018. This area has an average offshore significant wave height of about 0.5 m and a tidal range of about 0.84 m. Three storms passed within 100 km of Sand Key during this study, two tropical storms and Hurricane Irma in 2017 (Cheng and Wang 2019).

The Fort Myers site (Figure 1) stretches alongshore for 2 km. This site is located at the southern mouth of the Charlotte Harbor estuary. The average offshore significant wave height in this area is about 0.3 m with a tidal range of 0.77 m. This site has different sediment characteristics in the offshore area, with a relatively high mud content due to its proximity to a very large estuary (Brutsche *et al.* 2014). This study site had nine surveys conducted from 2000 to 2019, however, there were no available data between 2001 and 2009. Two nourishments occurred in the Fort Myers area in 2004 and 2011.

The southernmost Gulf site is Marco Island, which extends alongshore for 1.8 km. This area has an offshore significant wave height of about 0.4 m and a tidal range of about 0.68 m. Marco Island is the southernmost barrier island along the Florida Gulf Peninsula, transitioning to mangrove coast, i.e. the Ten Thousand Islands. This study site had survey data from 2006 to 2019, with surveys occurring annually, however at different times throughout the year. The general Marco Island area had been nourished many times throughout the study period, in 2001, 2005, 2006, 2010, 2011, 2013, 2016, 2018, and 2019. The Marco Island site is within a relatively close proximity to the Fort Myers site; however, the sediment characteristics are different. The Fort Myers and Marco Island sites were influenced by five storms within a 100-km radius, three hurricanes and two tropical storms. The strongest storm was Hurricane Wilma in 2005. Along the three west Gulf coast sites, the tidal range decreases from north to south.

Six study sites were examined along the Florida Atlantic coast (Figure 1 and Table 1). Jacksonville Beach is the northernmost site stretches 1.8 km alongshore. The average offshore significant wave height at this site is 0.8 m with a tidal range of 1.71 m. This study site had 16 surveys conducted during the study period from 2000 to 2019, with a gap in the available data between 2001 and 2004. The Jacksonville Beach area was nourished in 2003, 2005, 2011, 2016, and 2019.

The St. Augustine study site extends about 1.8 km, with a pier located roughly in the middle of the area. The surveys used for this study site were conducted between 2003 and 2019, with no seasonal pattern. The St. Augustine area was nourished in 2000 and 2012 during the study period. The average offshore significant wave height is about 0.9 m with a tidal range of about 1.57 m. The above two sites have the largest tidal range and were influenced by seven storms passing within a 100-km radius, six tropical storms and Hurricane Matthew in 2016.

The Melbourne study site spans 6.7 km alongshore with an average offshore significant wave height of about 0.9 m and a tidal range of 1.21 m. The Melbourne site is sheltered by the Cape Canaveral headland to the north; this provides an opportunity to further investigate if or how the morphology and shape of the barrier island and surrounding area may influence the DOC. The survey data used for this study site was collected annually between 2002 and 2019, excluding 2003. The Melbourne beach and greater Cape Canaveral area has been nourished frequently with projects occurring in 2000, 2004, 2007, 2010, 2014, and 2019. This area was impacted by six storms within 100 km, two hurricanes and four tropical storms.

The Jupiter Beach study site extends 1.8 km alongshore, just to the south of Jupiter Inlet. The offshore significant wave height is 1.0 m with a tidal range of 0.90 m. The Jupiter survey data set was one of the smallest included in this project with nine surveys ranging from 2008 to 2015. This site is the only Atlantic coast site that has an inlet in close proximity, and it is just north of the area where hardbottom and rock outcrops begin to occur frequently. The Jupiter and Jupiter Island area has been nourished many times during the study period, in 2002, 2003, 2007, 2012, 2013, 2014, and 2015.

The Boca Raton site spans 1.8 km alongshore, with an average significant wave height of 0.9 m and a tidal range of 0.67 m. This study site had 19 surveys from 2002 to 2019 annually excluding 2008 and 2013. The greater Boca Raton area had been nourished annually from 2002 excluding 2003.

The southernmost study site is Deerfield Beach, which extends 1.8 km. This site is quite close to the Boca Raton site, about 11 km. This study site had 20 surveys conducted from 2000 to 2017. For three years (2008, 2011, and 2012), quarterly surveys were conducted, while all the other sites had annual surveys. The nourishment data for this area is included in the greater Boca Raton area. This site has an average significant wave height 0.9 m and a tidal range of 0.73 m. Seven storms influenced the three southern sites within a 100-km radius. Four of these storms were hurricanes, with the strongest being Hurricane Wilma in 2005. Both the Boca Raton and Deerfield sites have offshore reef tracts and variable hardbottom and rock outcrops. The three southern Atlantic coast sites (Jupiter, Boca Raton and Deerfield) are sheltered by the Bahama Bank to a certain degree. The Boca Raton and Deerfield sites have a relatively narrow continental shelf (Figure 1).

METHODOLOGY

Time-series beach-offshore profile data from 2000 to 2019, in terms of distance to R-monuments (following identical or similar azimuth) and elevation (NAVD88), were obtained from the FDEP's Historic Shoreline Database. The survey accuracy specifications for the onshore portion are related to the technical standards for the GPS and must meet or exceed the GPS derived standards, 5 cm in the vertical and ~0.9 m for the horizontal position (FDEP 2014). Any surveys in which the benchmark coordinates were not identical were excluded. The cross-shore coverage of the profiles varied among the 12 study sites (Figure 1); the majority of surveys extended to about 1,200 m offshore. The Jupiter and St. Augustine sites extended farther at 1,900 m and 1,800 m offshore respectively, however in most figures here the offshore portion was clipped in order to better emphasize the area of interest. At all the sites, the offshore extent was much farther than the measured DOC. Each survey included in this study was comprised of an onshore beach survey and an offshore survey with the maximum offshore depth ranging from about -4 m at Fort Myers to -21 m at Deerfield, depending on the morphologic characteristic of the inner continental shelf. Only a few profiles were not included in the DOC analyses here. The majority of this small number was because they did not have the offshore portion of the survey. All of the survey data posted on the FDEP's Historic Shoreline Database has been collected and submitted in accordance with the Department's Physical Monitoring Standards. The beach portion of these surveys was inspected further for quality control by Department quality control engineers (FDEP 2014). Because all the empirical formulas calculating DOC use Mean Low Water (MLW) as the reference, the NAVD88 elevations (used in the surveys) were converted to MLW (Table 1) based datum information from nearby NOAA tide stations. The profile surveys were typically conducted annually along nourished beaches.

Seven FDEP R-monuments at each study site were selected. Each survey referred back to the same set of FDEP R-monuments in order to depict changes with time. At some of the R-monuments, the azimuth of the profile lines varied slightly within 10 degrees. This occurred at a few of the R-monuments in five study sites – Pensacola, Sand Key, Fort Myers, Jupiter, and Boca Rotan. Various alongshore extents (Table 1) were selected to investigate potential influence of longshore variation. Each profile was interpolated at 1.52-m (5-ft) interval to calculate an average profile and associated bed-level variations.

All time-series beach-offshore profiles at each R-monument were plotted to identify apparent errors and/or outliers, which were then removed from further analysis. Overall, the FDEP data are of high quality, with 6.6% of the total 1358 profiles being removed. The few rejected profiles should not have had significant influence on the determination of the DOC. An average profile was calculated along with the standard deviation about the mean at each R-monument. Figure 2 illustrates an example (R10) from Panama City Beach, showing the convergence of all of the surveys and the DOC annotated with a black line.

At all the profile locations, a point of convergence of the time-series profiles was identified (Figure 2A). In order to develop a consistent and repeatable method and reduce subjectivity in the determination of DOC, the following procedures using the standard deviation about the mean of elevation change were applied for all the profile locations. Figure 2B illustrates the distributions of standard deviation with respect to distance to the benchmark. This same analysis was conducted with respect to elevation. A persistent trend was observed at all the profile locations, as shown in Figure 2B. The standard deviation decreased rapidly with respect to both distance and elevation before stabilizing at a certain distance to the benchmark (Figure 2B) and elevation. This pivotal point indicated

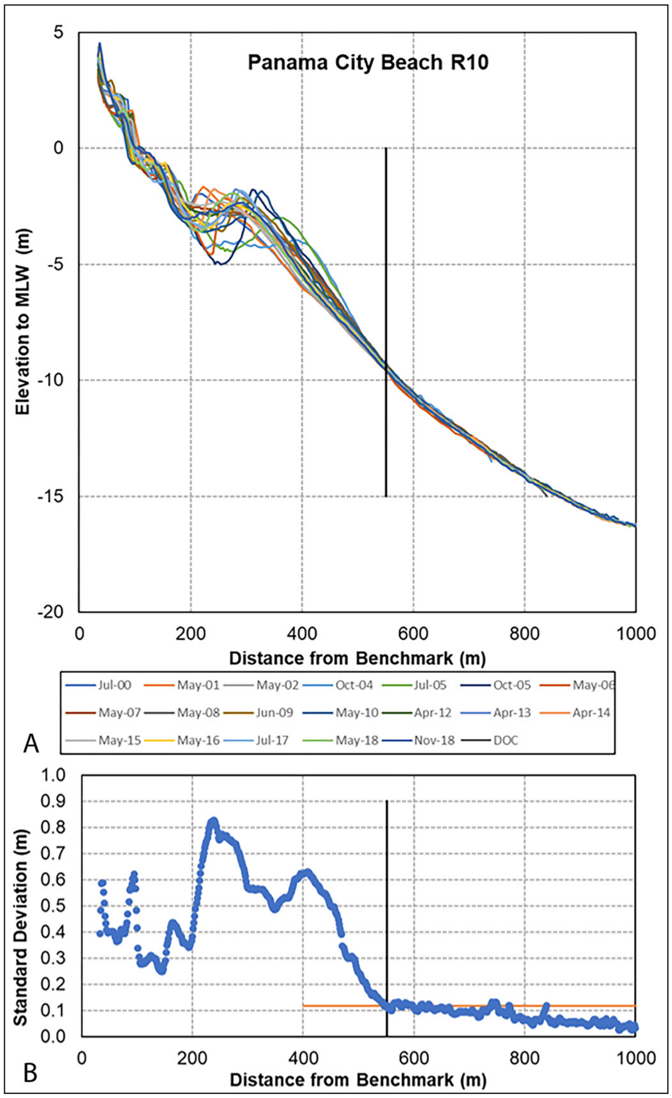


Figure 2. Determination of DOC from time-series beach-offshore profiles. (A) annual beach profiles surveyed between 2000 and 2019 with vertical line indicating DOC. (B) Standard Deviation of bed-level change with respect of distance, with the horizontal line indicating the "threshold elevation STDev" and vertical line indicating DOC.

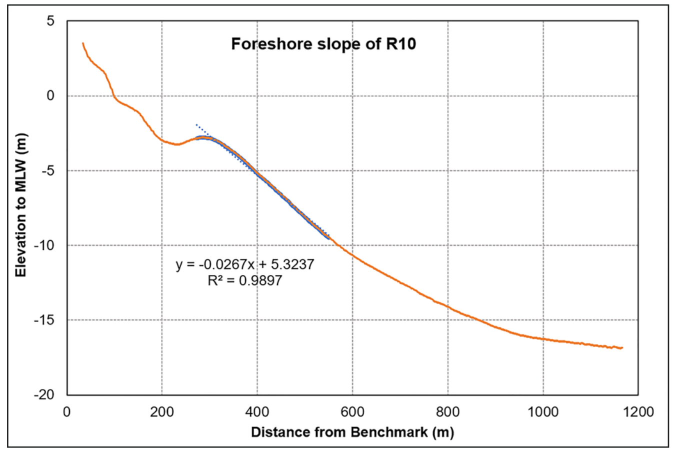


Figure 3. Determination of the seaward slope of the outer bar.

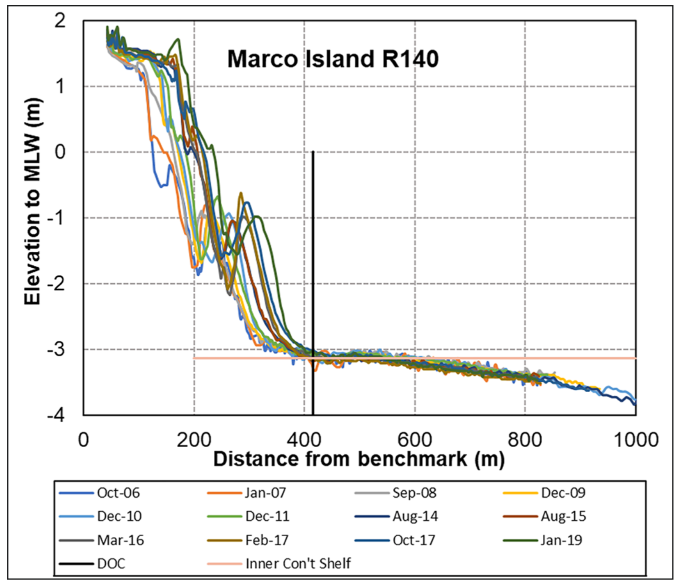


Figure 4. Annual beach-offshore profiles from Marco Island at FDEP monument R140, with vertical line indicating DOC and horizontal line indicating the largely flat inner continental shelf.

the DOC and its distance to shoreline. In order to eliminate subjectivity associated with visual observations, the following procedure was adopted. Across a 122-m (400-ft) section of the profile where the standard deviation values became low and stabilized, an average value was obtained, as indicated by the horizontal line in Figure 2B. This standard deviation value is referred to as the "threshold elevation STDev" in the following discussion, denoted with the orange horizontal line (Table 2). The shallowest depth this horizontal line crossed was determined as the DOC. The offshore distance of the DOC was defined as that to the Mean Sea Level (MSL) shoreline location. The same procedures, using the plotted surveys, standard deviation vs. elevation, and standard deviation vs. distance plots to determine the DOC were followed at all 84 R-monuments.

In addition to wave conditions, morphological characteristics should also have significant influence on the DOC. In this study, two morphologic parameters were determined in the context of DOC — seaward slope of the outer bar and depth of the inner shelf (depth of inner shelf can impose a morphologic limit on DOC). It was hypothesized that steep seaward slope of the outer bar could favor offshore transport and therefore a deeper DOC. Most of the profiles examined in this study have a sandbar, referred to here as the outer bar. It is worth noting that the sandbar may be absent from profiles in other location. However, the presence or absence of the sandbar did not influence the determination of the slope, as discussed in the following.

The seaward slope of the outer bar was calculated based on the DOC determined using the above method and the average profile (Figure 3). A 244-m (800-ft) section of the averaged beach profile landward of the DOC was selected (Figure 3 highlighted section). This 244-m length was chosen to ensure that the bathymetry landward of DOC was captured for each location. This distance was adjusted slightly for shallower closure depths along the west Gulf coast where between 121-151 m (400-500 ft) were used to determine the slope. The consistent 244

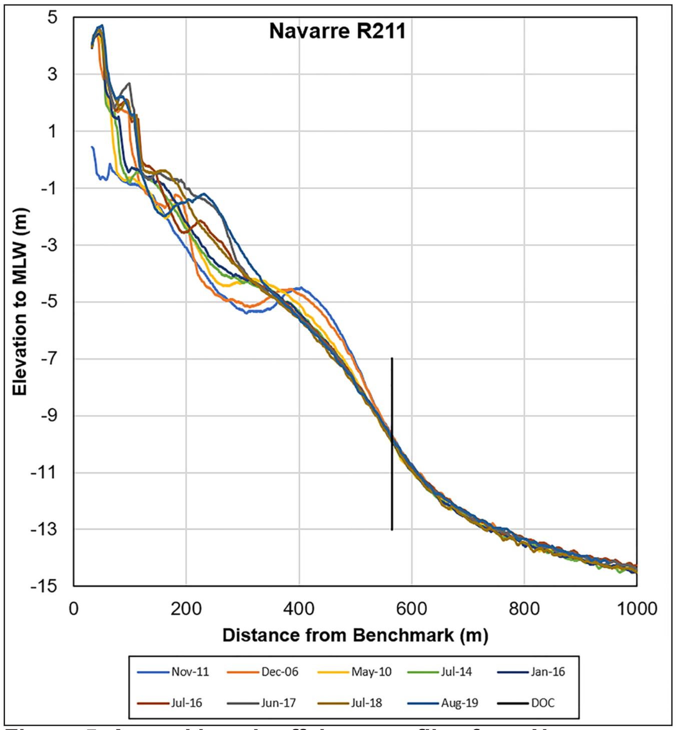
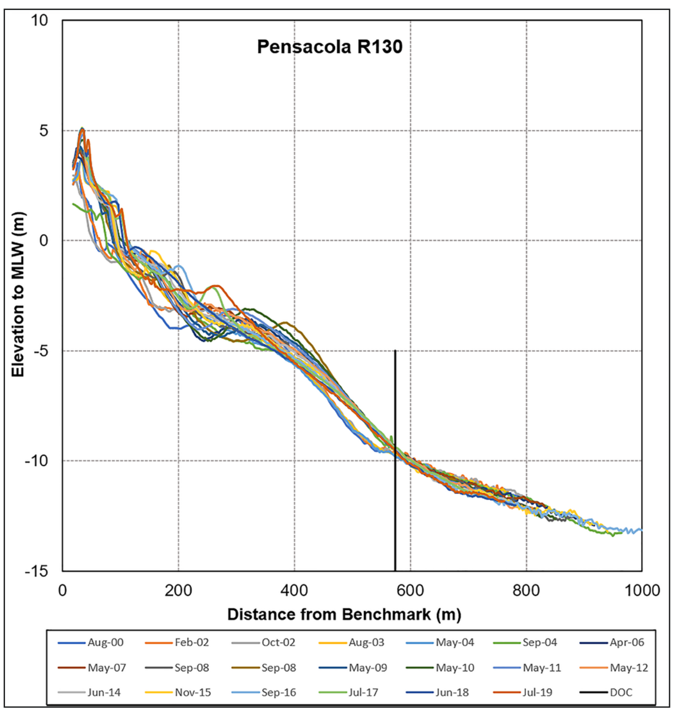


Figure 5. Annual beach-offshore profiles from Navarre Beach at FDEP monument R211 with vertical line indicating DOC.



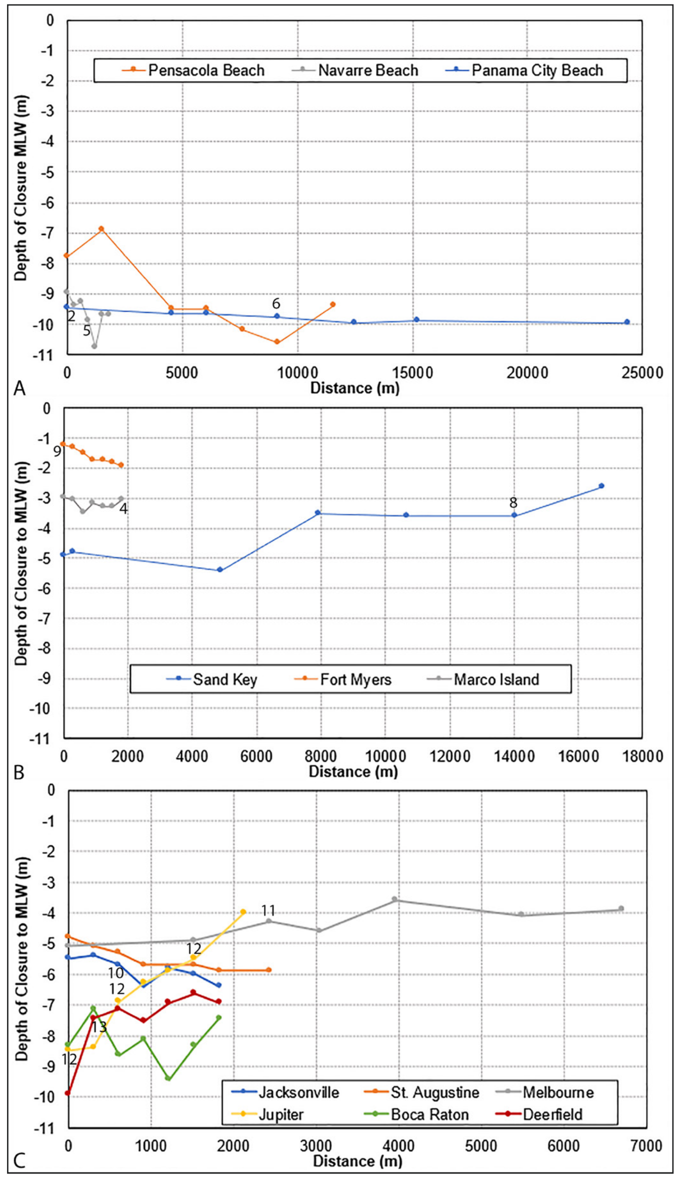


Figure 6 (left). Annual beach-offshore profiles from Pensacola Beach at FDEP monument R130 with vertical line indicating DOC.

Figure 7 (above). Alongshore variation of DOC. (A) Northwest Florida Gulf coast sites. (B) West Florida Gulf coast sites. (C) Florida Atlantic coast sites. Numbers within each panel correlate with those of the figures illustrating example profiles. Note that horizontal scales differ among the three panels.

m was used for the northwest Gulf and Atlantic coasts. This slope can vary quite a bit depending on the nearshore morphologic features that were included, using a consistent distance, rather than nearshore features to determine the slope should help reduce subjectivity. A linear trendline was then fit through this section, and the slope of the linear fit was referred to as the seaward slope of the outer bar. The goal of this portion of the study was to determine the slope of the profile landward of the DOC to examine whether it was a controlling factor of the DOC.

At some of the study sites, e.g. Marco Island (Figure 4), the inner shelf became quite flat stabilizing the elevation at this portion of the profile, which would impose control on the DOC as the bed-level elevation is mostly fixed. This inner-shelf depth was determined at sites with a rather flat shelf, which is denoted with a horizontal line in Figure 4. This depth was estimated somewhat qualitatively, without any statistical measures. However, the trend of a flat inner shelf was quite apparent. At some study sites, the water depth continued to increase seaward (Figure 5), then the inner-shelf depth was identified as N/A, to indicate that it did not impose a morphologic limit on DOC.

At each study site, computed wave data from the numerical model WAVE-

Table 2.
Summary of the measured DOC and associated wave and morphological conditions.

Location	DOC (m)	Threshold elevation of STDev (m)	Distance from shoreline (m)	Depth of inner shelf (m)	Slope of outer bar (m)	$H_{s\_0.137\%}$ (m) $T_{p\_0.137\%}$ (s)	H_{s_12hr} (m) T_{p_12hr} (s)	H_{s_48hr} (m) T_{p_48hr} (s)
Pensacola	-9.12 +/-1.32 +/-1.32	0.15	544	-14.5	1:51	4.01 11.4	3.47 9.5	4.65 12.1
Navarre	-9.66 +/-0.58	0.09	464	N/A	1:46	4.38 10.7	3.77 9.3	4.83 11.8
Panama City	-9.76 +/-0.18	0.11	519	-17.0	1:39	3.69 10.1	3.31 9.1	4.64 11.3
Sand Key	-4.06 +/-0.99	0.14	263	-4.9	1:35	2.87 9.6	2.55 8.5	3.33 10.5
Fort Myers	-1.60 +/-0.26	0.05	205	-1.8	1:76	2.01 8.1	1.77 7.7	2.40 8.2
Marco Island	-3.17 +/-0.17	0.05	188	-3.5	1:58	2.42 9.1	2.06 7.8	3.08 9.9
Jacksonville	-5.88 +/-0.40	0.18	377	-10.4	1:57	3.55 9.8	3.17 10.0	4.62 11.1
St. Augustine	-5.48 +/-0.43	0.16	391	-6.2	1:71	3.61 10.3	3.25 10.1	4.81 11.7
Melbourne	-4.35 +/-0.54	0.16	264	-12.0	1:68	3.80 11.3	3.36 10.9	4.79 11.5
Jupiter	-6.48 +/-1.6	0.18	705	N/A	1:86	4.94 11.2	4.50 11.3	6.09 11.1
Boca Raton	-8.20 +/-0.76	0.19	416	-8.7	1:44	4.55 10.5	3.97 10.5	6.09 11.5
Deerfield	-7.50 +/-1.11	0.13	380	N/A	1:48	4.50 10.6	3.91 10.6	5.91 11.6

WATCHIII in the offshore area from 2005 to 2019 were extracted. Long-term measured wave data were only available at a few locations along the Florida coast. Statistical analysis was conducted based on the 15-year wave data to obtain the wave parameters used in the empirical formulas. The extreme wave condition, H_{s_12hr} and T_{p_12hr} used in the original Hallermeier (Equation 1) and Birkemeier (Equation 2) formulas, were not clearly defined for multi-year durations. Two methods were used in this study to determine the H_{s_12hr} and $T_{p\_12hr.}$ Method one averaged the annual H_{s_12hr} and T_{p_12hr} over the entire study period. Method two averaged the highest 0.137% wave which is equivalent to 12 hours per year and referred to as $H_{s\_0.137\%}$ and $T_{p\_0.137\%}$ in the following. In addition, another extreme wave condition H_{s_48hr} and T_{p_48hr} was examined representing the average of the highest wave during a 48-hour span over the entire study period.

RESULTS

The coast of Florida encompasses a large range of oceanographic and geologic conditions. The northwest coast faces the Gulf of Mexico with a wide (~100 km) continental shelf and small diurnal tides. Due to its east-west orientation, this coast is vulnerable to direct hits by hurricanes and tropical storms. The west Gulf coast has a very wide (~250 km) continental shelf. The Florida Atlantic coast tends to have higher average waves as compared to the Gulf coast and is quite susceptible to impacts by tropical storms.

Northwest Florida Gulf Coast

The northwest Florida Gulf Coast sites included Pensacola Beach, Navarre Beach, and Panama City (Figure 1). At each site, beach-offshore profiles at seven FDEP R-monuments were analyzed to determine the DOC. From west to east (Figure 1), at Pensacola Beach (Figure 6) the average DOC from the seven R-monuments was -9.12 m relative to MLW. This was the shallowest DOC as compared to the other sites along this coast (Table 2). The average threshold of elevation variation in terms of standard deviation about the mean (threshold elevation STDev) of the seven R-monuments was 0.15 m. Along the 11-km stretch of shoreline, the seven measured DOC values varied from -6.89 m to -10.59 m, with a standard deviation of 1.32 m (Figure 7). The two westmost R-monuments had much shallower DOCs than the other five. These two sites were closer to the Pensacola Pass ebb shoal, the migration of this shoal or relic shoals in this area likely have influenced the DOC at these two locations. The average seaward slope of the outer bar at the Pensacola study site was 1:51 (Table 2). The depth of the flat part of the inner shelf, as defined above, was 14.6 m, much deeper than the DOC.

At Navarre Beach (Figure 5) the average DOC from the seven profiles was -9.66 m relative to MLW. The average threshold elevation STDev of the 7 R-monuments was 0.09 m, indicating a tighter convergence than that at the Pensacola site (Table 2). Along the 2-km longshore stretch of the coast, the DOC values varied from -8.97 m to -10.77 m, with a standard deviation of 0.58 m (Figure 7). The wave climate and orientation of the shoreline was similar to that of the Pensacola study site; however, the Pensacola site had more variation near the inlet skewing the DOC shallower than Navarre. The average seaward slope of the outer bar at the Navarre Beach site was 1:46. The depth of the inner shelf continued to increase seaward with no apparent flat portion.

At Panama City Beach the average DOC was -9.76 m relative to MLW. The average threshold elevation STDev of the 7 R-monuments was 0.11 m. Along the 24 km longshore stretch of the coast, the DOC values varied from -9.46 m to -9.69 m, with a standard deviation of 0.18 m (Figure 7). This site had the longest longshore extent of all the study sites; however, it had one of smallest alongshore variations of DOC. The orientation of the coastline is also slightly different than the other northwest Gulf coast as they are largely east-west oriented, while Panama City begins to curve north-south at the easternmost R-monuments (Figure 1). However, because the measured DOC values are quite uniform alongshore, this shoreline orientation change does not appear to have an impact. This site also has an existing inlet near the study site at the southeast end, however the deepest DOC -9.69 m was measured there, unlike at Pensacola, where the shallower DOCs were measured closer to the inlet. This was likely influenced by the size of the inlet and ebb shoal. The average seaward slope of the outer bar at the Panama City site was 1:39 (Table 2). The depth of the flat portion of the inner shelf was at about 17.1 m below MLW, much deeper than the measured DOC. Overall, along the 150 km section of the studied northwest Florida Gulf coast, the DOC was rather consistent ranging from 9.12 m at Pensacola Beach to 9.76 m at Panama City Beach.

West Florida Gulf Coast

The West Florida Gulf Coast sites from north to south included Sand Key, Fort Myers, and Marco Island (Figure 1). At Sand Key the average DOC from the seven profile locations was -4.06 m relative to MLW. The average threshold elevation STDev of the seven R-monuments was 0.14 m. The Sand Key site had an alongshore extent of 17 km, the longest among the west Gulf sites. The seven measured DOC values varied from -2.56 m to -5.38 m, with a standard deviation of 0.99 m (Figure 7). The depth of the flat portion of the inner shelf was averaged to

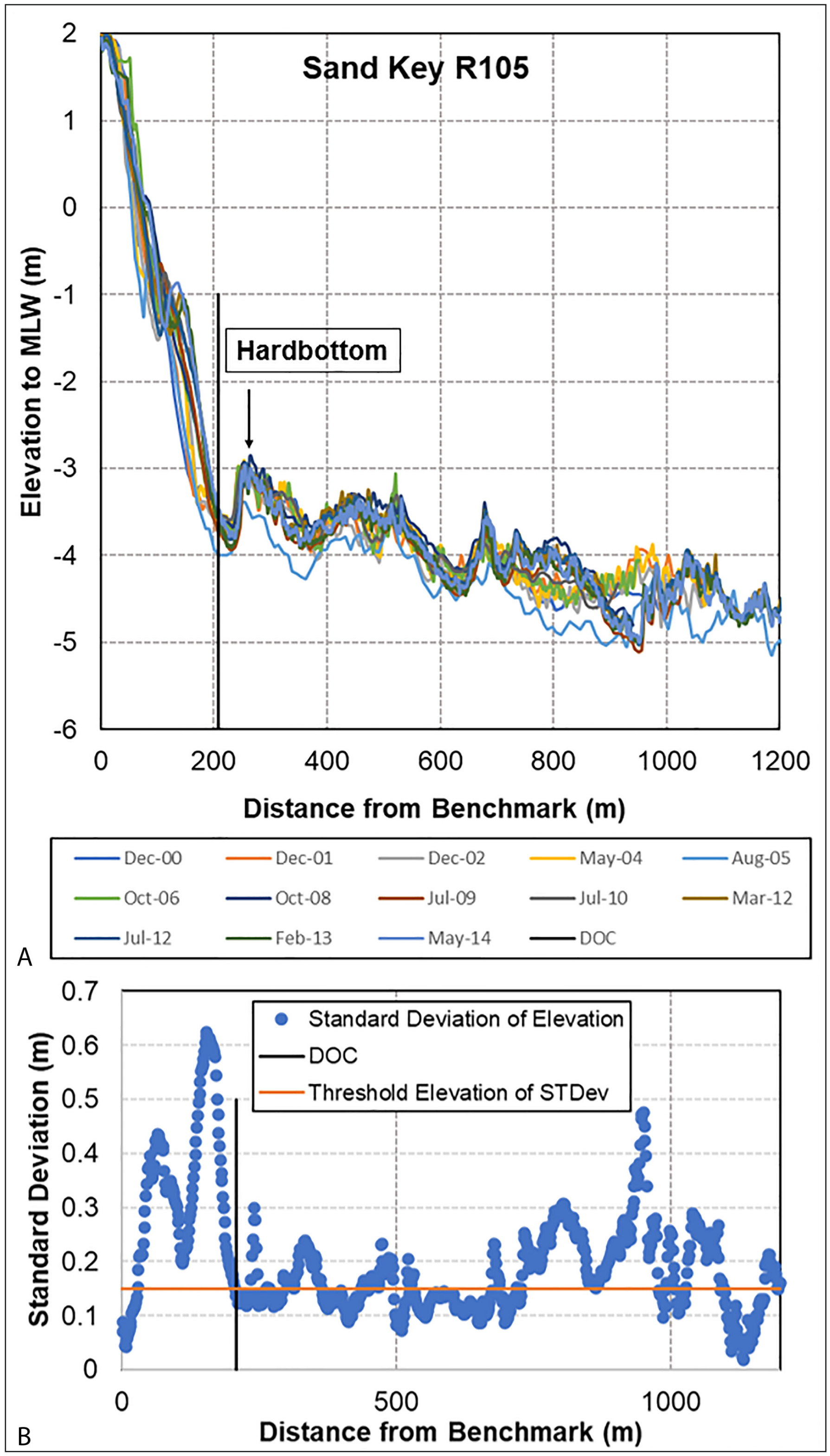
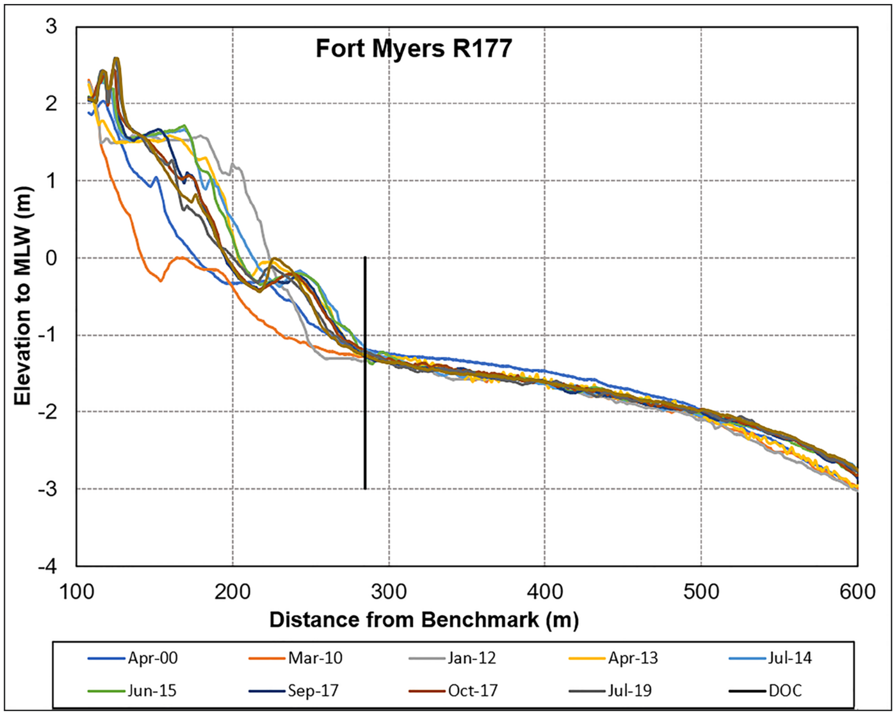


Figure 8. (A) Time-series beach-offshore profiles from Sand Key Beach at FDEP monument R105, with vertical line indicating DOC. An example of the hardbottom is marked by the arrow. (B) Standard Deviation of bed-level change with respect of distance, with the horizontal line indicating the "threshold elevation STDev" and vertical line indicating DOC.



Figures 9. Time-series beach-offshore profiles from Fort Myers Beach at FDEP monument R177, with vertical line indicating DOC.

be at about 4.9 m relative to MLW, with a southward decreasing trend. Unlike other study sites, substantial elevation fluctuations occurred in the offshore portion of almost all the Sand Key profiles (Figure 8). These fluctuations and the southward shallowing trend are associated with the exposure of hardbottom and its regional trend (Wang and Davis 1999). At all the seven profile locations, the DOC occurred at the landward edge of the largely flat hard bottom and was possibly controlled by the hardbottom (Figure 8). The average seaward slope of the outer bar at the Sand Key study site was 1:35 (Table 2).

At Fort Myers site the average DOC was quite shallow at -1.60 m relative to MLW. The average threshold elevation STDev of the seven R-monuments was 0.05 m, indicating a tight convergence among all of the profiles at the DOC. The Fort Myers study site had an alongshore extent of 2 km. The seven measured DOC values varied from -1.21 m to -1.91 m, with a standard deviation of 0.26 m (Figure 7). The depth of the flat portion of the inner shelf was at about 1.8 m, which was within the range of DOC values. The bathymetry of the inner shelf was rather smooth (Figure 9), unlike that at the Sand Key site, which contributed to the increased uniformity of the DOC alongshore. The Fort Myers site has an extensive and flat muddy sediment (Brutsche *et al.* 2014), that imposes a limit on the shallow DOC. The average seaward slope of the outer bar at the Fort Myers site was 1:76, much gentler than at the sites discussed above (Table 2).

At the Marco Island site, the average DOC from the seven profiles was -3.17 m relative to MLW. The average threshold elevation STDev of the seven R-monuments was 0.05 m, indicating a tight convergence at the DOC. The Marco Island site had an alongshore extent of 2 km. The DOC had less alongshore variation than the other two west Florida Gulf sites ranging from -2.96 m to -3.46 m, with a standard deviation of 0.17 m (Figure 7). The depth of the flat portion of the inner shelf was about 3.5 m, which is slightly deeper than the DOC, and did not show any characteristics of hardbottom (Figure 4). The average seaward slope of the outer bar at the Marco Island site was 1:58 (Table 2). Compared to the northwest Gulf coast discussed in the previous section, the west Gulf coast had a much shallower DOC (Table 2), and with a substantial alongshore variation as influenced by the inner continental shelf morphology.

Florida Atlantic Coast

The Florida Atlantic Coast included six study sites: Jacksonville, St. Augustine, Melbourne, Jupiter, Deerfield, and Boca Raton, spanning almost the entire stretch of coast (Figure 1). The northernmost site was Jacksonville Beach. The average DOC from the seven profiles was -5.88 m relative to MLW. The average threshold elevation STDev of the 7 R-monuments was 0.18 m (Table 2). The greater threshold elevation STDev as compared to the Gulf sites might be related to the rougher survey conditions influenced by higher waves and larger tidal range. These rougher conditions could have influenced the quality of the survey offshore causing larger elevation variations. The Jacksonville site had an alongshore extent of 2 km (Table 1). The DOC ranged from -5.39 m to -6.39 m, with a standard deviation of 0.40 m (Figure 7). The average seaward slope of the outer bar was 1:56 (Table 2). The depth of the flat portion of the inner shelf was determined to be at 10.4 m, much deeper than the DOC (Figure 10).

At the St. Augustine Beach site, the average DOC from the seven profiles was -5.48 m relative to MLW, slightly shallower than the Jacksonville site (Table 2). The average threshold elevation STDev of the 98 profiles was 0.16 m (Table 2). This site had an alongshore extent of 2 km (Table 1). This study site has a pier structure in the middle of the site. The DOC ranged from -4.79 m to -5.89 m, with a standard deviation of 0.43 m and a southward deepening trend, similar to the Jacksonville site (Figure 7). The pier structure located in the middle of the study site did not appear to influence the DOC as the southward deepening trend was not altered at this location. The average seaward slope of the outer bar at the St. Augustine site was 1:71 (Table 2). The depth of the flat portion of the inner shelf was determined to be at about -6.2 m, deeper than the DOC.

At the Melbourne Beach site the average DOC from the seven profiles was -4.35 m relative to MLW (Table 2). This was the shallowest DOC along the Florida Atlantic Coast (Table 2). The average threshold elevation STDev of the seven R-monuments was 0.16 m (Table 2). This site had the longest alongshore extent of any of the Atlantic sites at 7 km, south of the Cape Canaveral headland (Figure 1). The DOC ranged from -3.89 m to -5.09 m, with a standard deviation of 0.54 m (Figure 7). The Melbourne study site generally had a shallowing trend southward, opposite of the trend observed at the St. Augustine site. The average seaward slope of the outer bar at this site was 1:68 (Table 2). The depth of the flat portion of the in-

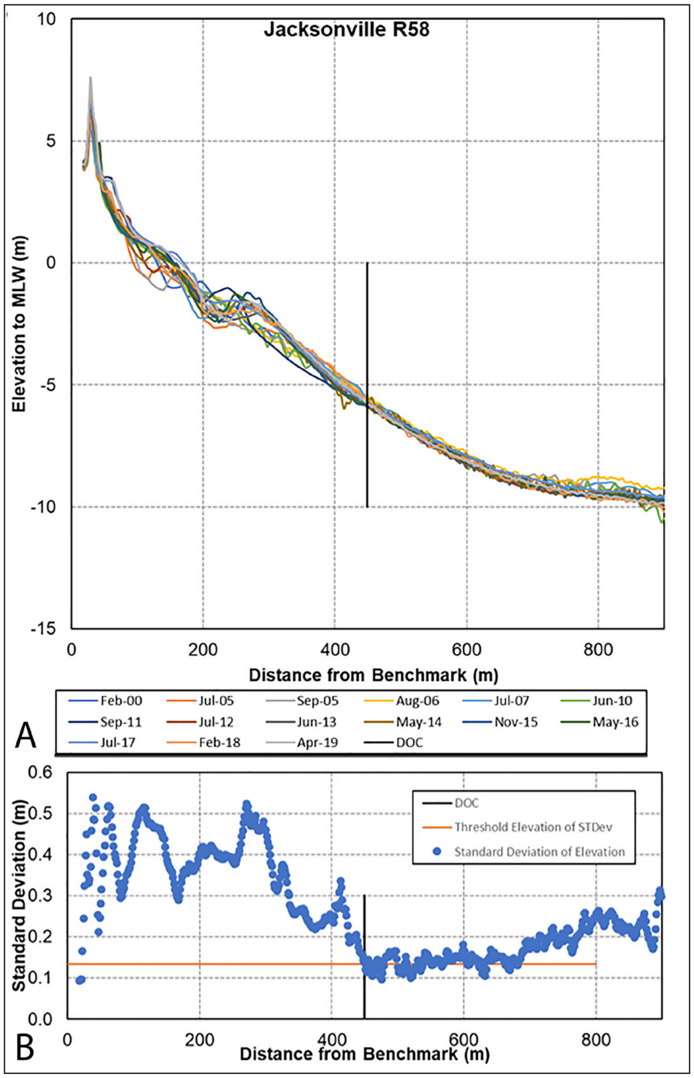


Figure 10 (right). (A) Time-series beach-offshore profiles from Jacksonville Beach at FDEP monument R58, with vertical line indicating DOC. (B) Standard Deviation of bed-level change with respect of distance, with the horizontal line indicating the "threshold elevation STDev" and vertical line indicating DOC.

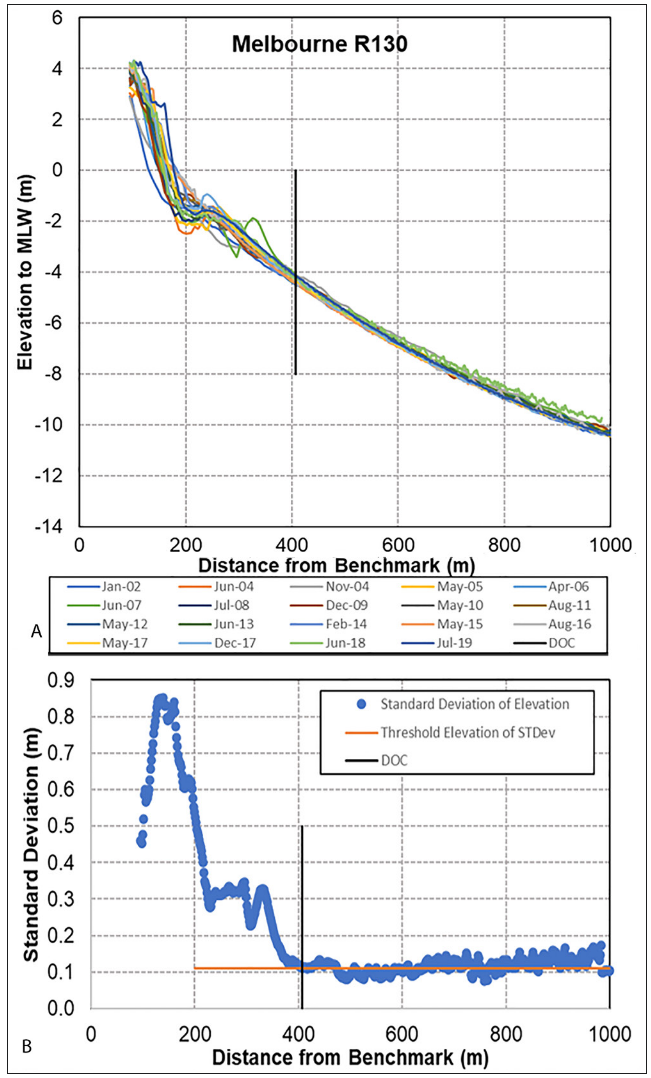


Figure 11. (A) Time-series beach-offshore profiles from Melbourne Beach at FDEP monument R130, with vertical line indicating DOC. (B) Standard Deviation of bed-level change with respect of distance, with the horizontal line indicating the "threshold elevation STDev" and vertical line indicating DOC.

ner shelf was at about 12.0 m below MLW.

Compared to all the other sites, the profiles at the Melbourne site converged toward the DOC considerably gentler (Figures 11 and Figure 2). For example, at the Panama City Beach site, the standard deviation about the mean elevation decreased rather rapidly from about 0.65 m to 0.10 m (Figure 2), in comparison from 0.33 m to 0.10 m at the Melbourne site (Figure 11). Although the same method and threshold were applied at all the study sites, the less apparent profile convergence might have induced a larger uncertainty in the DOC determination at the Melbourne site.

At the Jupiter Beach site, the average DOC from the seven profiles was -6.48 m relative to MLW (Table 2). The average threshold elevation STDev of the seven R-monuments was roughly 0.18 m (Table 2). This site had a larger threshold elevation of STDev, than most of the other sites, which means the profiles do not converge as tight as other sites. This might increase the uncertainty in determining the DOC. This site had the largest average significant wave height, which could increase the survey uncertainty, which subsequently resulted in greater threshold elevation of STDev. This site had an alongshore extent of 2 km (Table 1), with a large alongshore variation of DOC ranging from -3.98 m to -8.48 m, with a standard deviation of 1.60 m and a decreasing trend toward the south (Figure 7). This is the largest standard deviation among the measured DOC values at all 12 sites, which could be linked back to the higher threshold elevation of STDev. The average seaward slope of the outer bar at this site was the gentlest among the Atlantic sites at 1:86 (Table 2), considerably gentler than most of the other sites. The depth of the inner shelf continued to increase seaward with no apparent flat portion at the Jupiter study site. The bar-and-trough feature varied considerably alongshore at this site (Figure 12). At the northern end of the study site, R13, which is next to an inlet, the bar-and-trough feature was much wider in the cross-shore direction than that at R18. This resulted in a deeper DOC which was also farther offshore. The bar-and-trough feature and the DOC at profile R15 located in the middle of the study site were consistent with the above southward-decreasing trend.

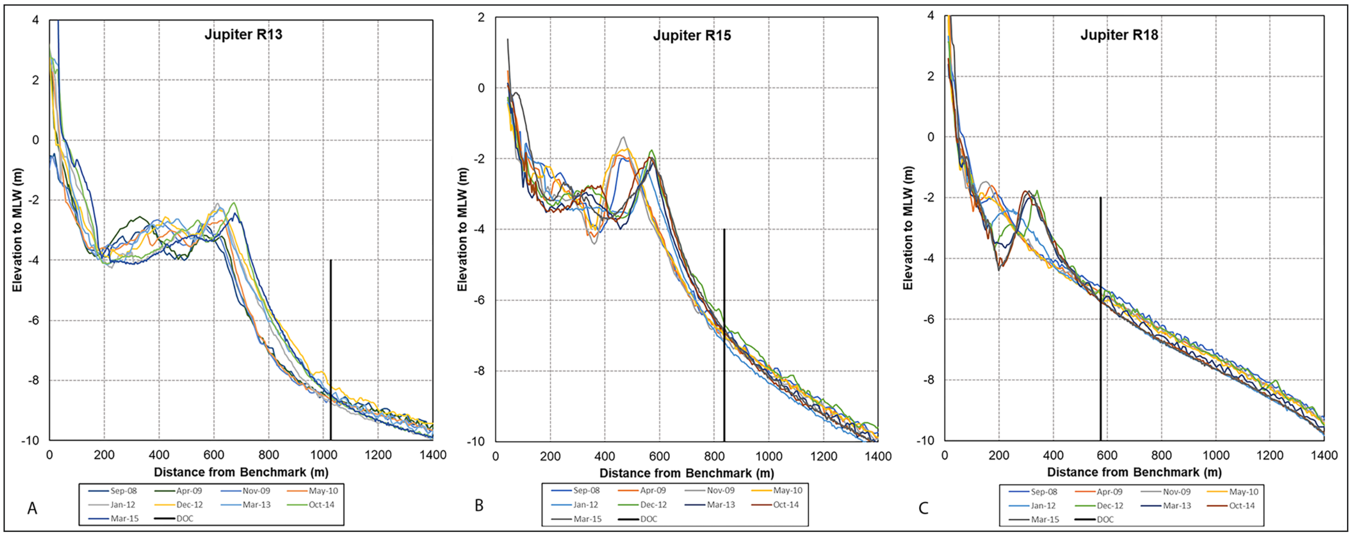


Figure 12. Alongshore time-series beach-offshore profiles from Jupiter at FDEP monuments (A) R13, (B) R15, and (C) R18, with vertical line indicating DOC.

The average DOC at the Boca Raton site from the seven profiles was -8.20 m relative to MLW (Table 2). This study site had the deepest DOC along the Atlantic Coast. The average threshold elevation STDev of the seven profile locations was 0.19 m, the greatest of all site (Table 2). This study site extended alongshore for 2 km (Table 1). The DOC values ranged from -7.13 m to -9.43 m, with a standard deviation of 0.76 m (Figure 7). The average seaward slope of the outer bar at this site was 1:44 (Table 2). This site did have a flatter portion of the inner shelf at -8.7 m MLW.

The southernmost study site was Deerfield Beach site, which was just 11 km south of the Boca Raton site, the average DOC from the seven profiles was -7.50 m relative to MLW (Table 2). The average threshold elevation STDev of the seven profile locations was 0.13 m (Table 2), the smallest along the Florida Atlantic coast. This site extended alongshore for 2 km (Table 1). The DOC values ranged from -7.13 m to -9.93 m, with a standard deviation of 1.11 m and no apparent north to south trend (Figure 7). Between the Boca Raton inlet, north of the Deerfield study site, and Hillsboro Inlet to the south, nearshore reefs and hardbottom occurred frequently but in a discontinuous pattern (Robertson *et al.* 2008), which could influence the determination of the DOC in this area. The average seaward slope of the outer bar at this site was 1:48 (Table 2). Similar to the Jupiter site, the inner shelf continued to increase seaward with no apparent flat portion. The offshore portion of the Deerfield profiles illustrated a steep slope seaward of roughly 10 m water depth (Figure 13). Along the Deerfield coastline there are reef tracts offshore that could be the cause of this drop off (Robertson *et al.* 2008).

Overall, the northwest Florida Gulf Coast had a considerably deeper DOC as compared to the other study sites on the west Florida Gulf and Atlantic coasts. The DOC values ranged from 9.12 m to 9.76 m with the least alongshore variation relative to the other coasts. This study area generally had the steepest seaward slope of the outer bar. The west Florida Gulf coast had a much shallower DOC with values ranging from 1.60 m to 4.06 m. The Florida Atlantic coast showed the most alongshore variation with the DOC values ranging from 4.35 m to 8.20 m.

The degree of convergence of the time-series beach profiles can be used as an indicator of accuracy in the determination of DOC. In this study, the degree of convergence was quantified by the standard deviation of the bed-level change over time (Figure 2). The temporal elevation variations are controlled by sedimentation/erosion as well as the survey accuracy. At the DOC this value was referred to as the "threshold elevation STDev." Since each study site contained seven profile locations, seven threshold elevation STDev values were determined. The average values of the seven profile locations are listed in Table 2. A higher threshold elevation STDev is associated with a higher uncertainty of the determination of the DOC.

The threshold elevation STDev values at the 12 sites ranged from 0.05 m to 0.19 m, suggesting a reasonable degree of convergence of profiles surveyed over the 19-year period. The northwest Florida Gulf coast threshold elevation STDev values ranged from 0.09 m to 0.15 m. The west Florida Gulf coast had the smallest threshold elevation STDev ranging from 0.05 m to 0.14 m. The generally calm wave conditions might have allowed more accurate profile survey and subsequently smaller threshold elevation STDev. In contrast, the Florida Atlantic coast has generally higher waves and larger tidal range, which may have contributed to the larger threshold elevation STDev, ranging from 0.13 m to 0.19 m.

DISCUSSION

The DOC values are controlled by various factors, including regional geologic and oceanographic settings, site specific morphologic characteristics, and wave conditions, particularly the energetic conditions. The study sites along the coast of Florida provided a wide range of these factors. In this section the control and or influence of these factors on DOC are discussed.

Influence of inner continental shelf morphology and geology on DOC

The DOC values at the three west-central Florida Gulf sites were apparently influenced by the geology and morphology of the inner continental shelf (Figures 4, 8, and 9). At these three sites the values of the DOC were similar to the depths of the inner continental shelf (Table 2). At the Sand Key site, the inner shelf is composed of hardbottom which is largely unerodable. The irregular surface of the hardbottom was captured in the profile

(Figure 8). Quantifying and determining beach changes become more complicated when hardbottom is present in combination with loose sediment because hardbottom and rock outcrops respond less sensitively to wave conditions (Robertson *et al.* 2008). At the Fort Myers Beach site, the shallow DOC appeared to be limited by the inner shelf depth. This is illustrated by the seaward propagation of the time-series beach profiles over the flat inner shelf (Figure 9). The muddy and cohesive sediment on the inner shelf may behave differently than non-cohesive sandy sediment in terms of erosion and deposition. The small threshold elevation STDev of 0.05 m indicated a tight convergence of the profiles. However, the prolonged suspension and subsequent deposition of mud-sized sediment associated with energetic conditions can result in subtle elevation change over a large and flat area. This may not be resolved by the time-series surveys nor the method used in this study for the determination of DOC.

At the Marco Island study site, the inner shelf appeared to also play a role in determining the DOC (Figure 4). The profiles propagated seaward and converged over the flat inner shelf (Figure 4). This is similar to the case at Fort Myers Beach, but the converging depth was deeper, at 3.17 m versus 1.60 m. The threshold elevation STDev was 0.05 m indicating a tight convergence of the profiles at this location (Table 2).

At other sites the depth and morphology of the inner shelf did not appear to impose a limit on the DOC. The local exposure of hardbottom at some of the Florida Atlantic sites might have some influence on the relatively large alongshore variation. However, the hardbottom did not appear to impose a persistent limit on the DOC (Finkl and Andrews 2008), as that observed along the west Florida Gulf coast. The southward decrease of the tidal range along the Florida Atlantic coast, from 1.71 m at Jacksonville Beach to 0.67 m at Boca Raton, did not induce an apparent regional trend of DOC change.

Influence of seaward slope of the outer bar on DOC

The seaward slope of the outer bar (Figure 3) may play a significant role in the DOC. Theoretically, a steeper seaward slope would favor offshore sand transport by increasing the contribution of gravitational force. The study sites encompassed

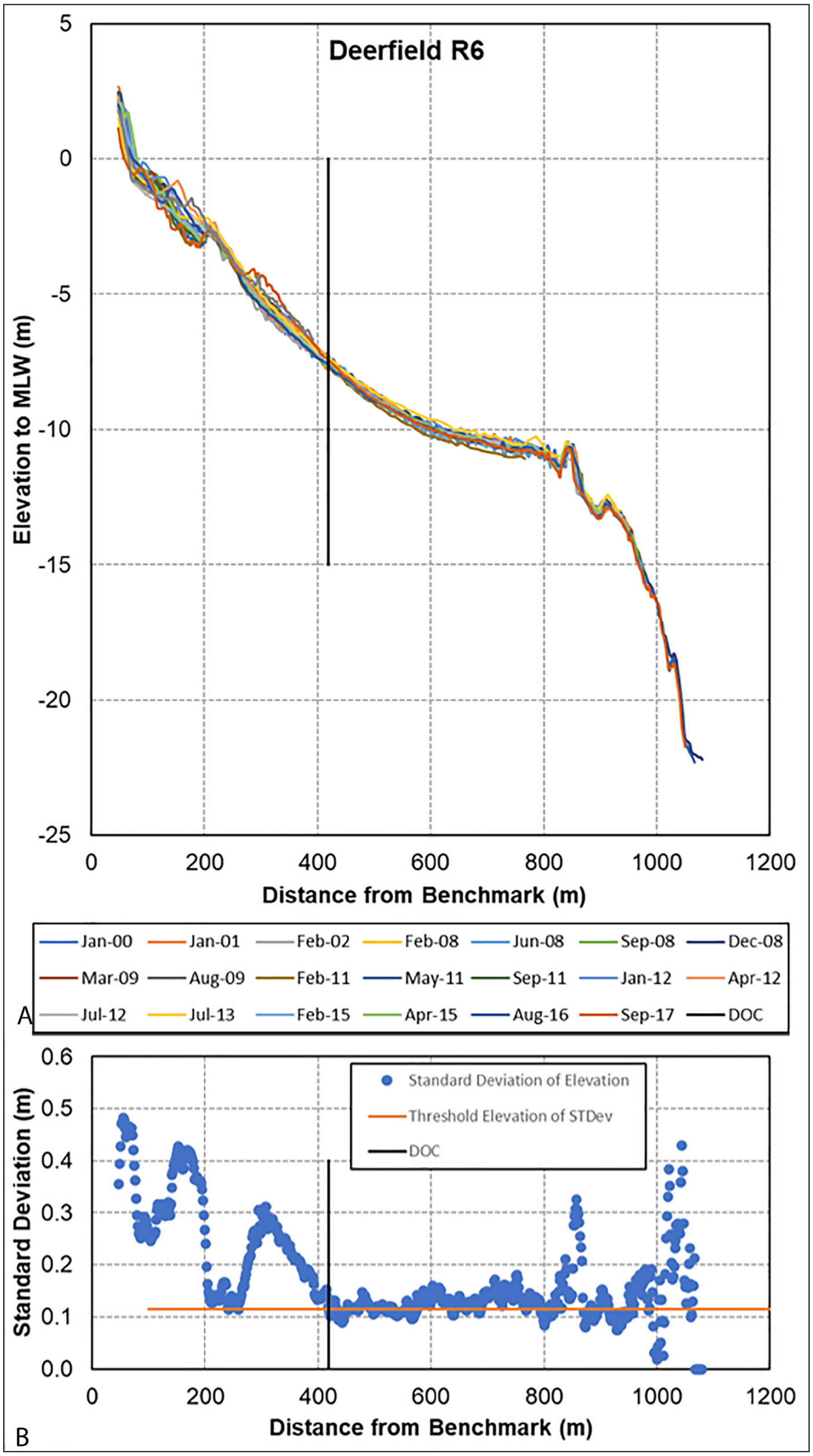


Figure 13. (A) Time-series beach-offshore profiles from Deerfield Beach at FDEP monument R6, with vertical line indicating DOC. (B) Standard Deviation of bed-level change with respect of distance, with the horizontal line indicating the "threshold elevation STDev" and vertical line indicating DOC.

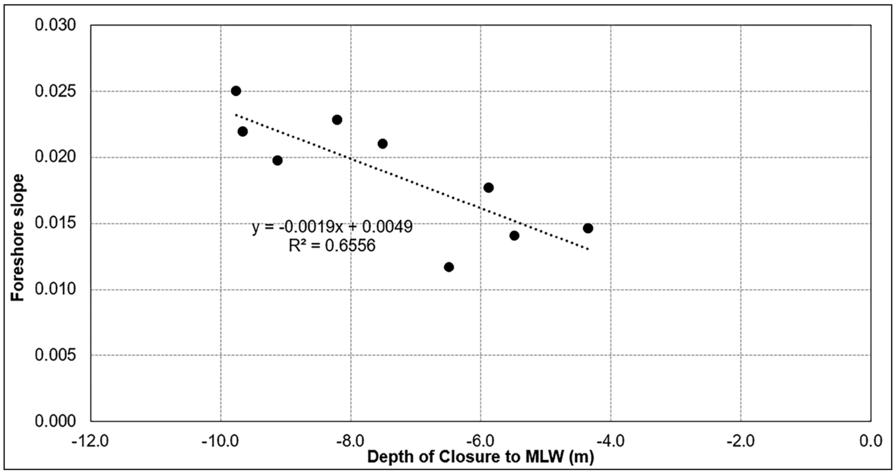


Figure 14. Relationship between seaward slope of the outer bar and DOC.

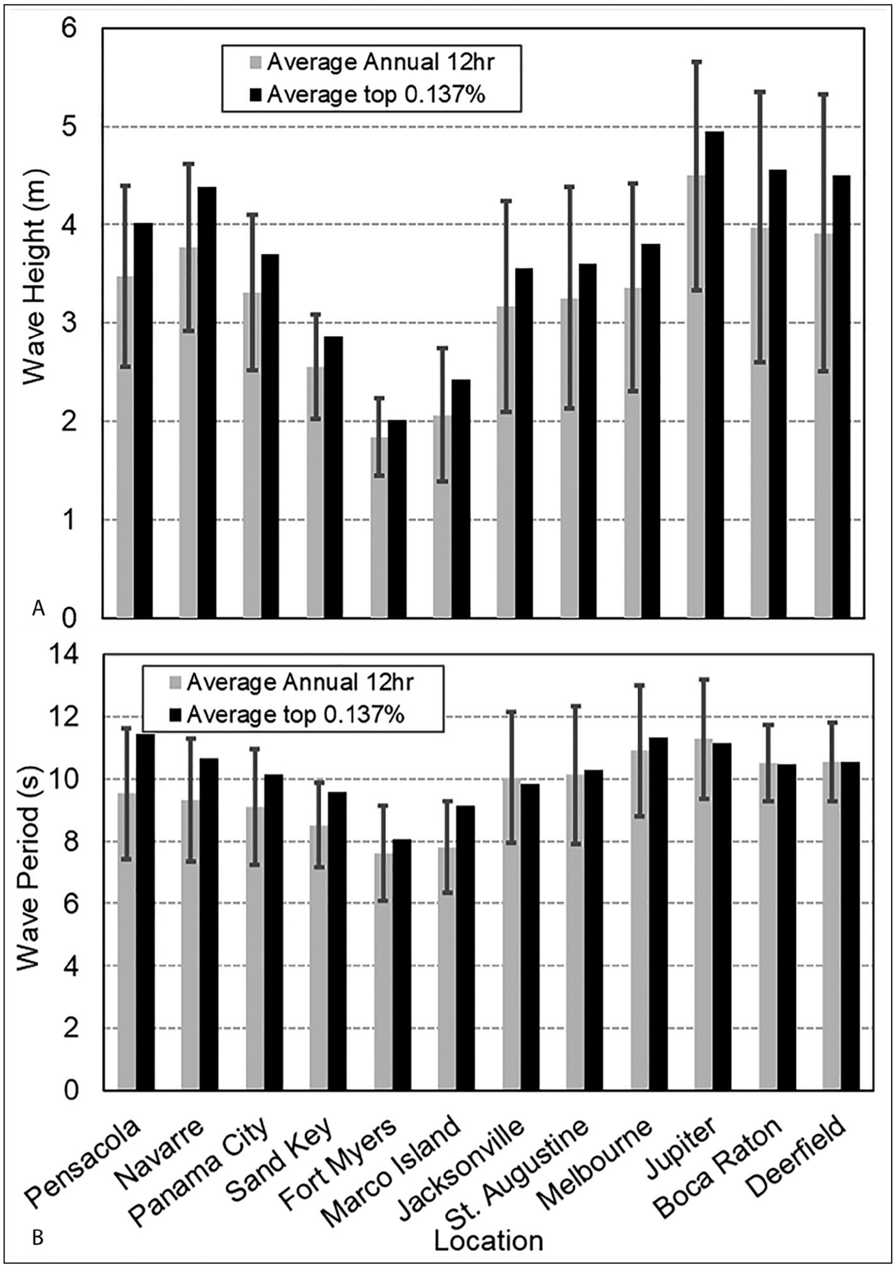


Figure 15. Comparison between the average of the annual 12-hour exceedance and average top 0.137% (A) wave height. (B) wave period.

a large range of seaward slope of the outer bar, from 1:39 to 1:86, providing an opportunity to evaluate the influence of slope on DOC. The three west Florida Gulf coast sites were not included in this analysis because of the likely morphological constraints imposed by the flat inner continental shelf.

For the three northwest Florida Gulf coast and the six Atlantic coast sites, steeper seaward slope of the outer bar corresponded to deeper DOC (Figure 14). A linear relationship between the seaward slope of the outer bar and DOC was identified with a correlation coefficient R^2 of 0.66. This is consistent with the understanding that steep seaward slope of the outer bar would enhance offshore sand transport and therefore lead to deeper DOC. All the existing formulas predicting DOC (Equations 1 through 4) did not include slope as a parameter. Based on the relationship shown in Figure 14, including seaward slope of the outer bar may lead to more accurate calculation of DOC, as discussed in the following.

Performance of the existing empirical formulas

The performance of the existing empirical formulas was evaluated based on the measured DOC. In the original Hallermeier (Equation 1) and Birkemeier (Equation 2) formulas the two parameters, H_{s_12hr} and T_{p_12hr}, were defined largely over a one-year period. For multi-year analysis, 19 years in this case, the H_{s_12hr} and T_{p_12hr} can be defined in different ways. In this study 19 years of beach-offshore profile data were analyzed. However, the WAVEWATCHIII data were available from 2005 to 2019, or over a 15-year period. As discussed in the METHODOLOGY section, two H_{s_12hr} and T_{p_12hr} definitions were tested. The first method defined multi-year H_{s_12hr} and T_{p_12hr} as the average of the annual values. For this case annual H_{s_12hr} and T_{p_12hr} were averaged over the 15-year period. In terms of percentage of occurrence, H_{s_12hr} and T_{p_12hr} occur 0.137% of the time. Therefore, the second method averaged the highest 0.137% of the waves and associated peak period ($H_{s\_0.137\%}$ and $T_{p\_0.137\%}$) over the 15-year period. Figure 15 compares the extreme wave heights and periods at the 12 study sites. The annual variation of the H_{s_12hr} and T_{p_12hr} are illustrated by the error bar. As expected, the $H_{s\_0.137\%}$ was higher than the annual average of the H_{s_12hr}. For the 12 study sites the ratio between the $H_{s\_0.137\%}$ and the annual average of the H_{s_12} was quite consistent at 1.13 with a standard deviation of 0.03. This is unexpected because the top 0.137% highest waves can be dominated by one or two extremely energetic and long-lasting storms impacting a specific site. However, the rather uniform ratio between $H_{s\_0.137\%}$ and H_{s_12hr} at all the 12 study sites spanning nearly the entire Florida barrier-island coast suggests that energetic wave conditions induced by one or two extreme storms did not dominate over the 12-hr annual wave statistics over a long period of time, 15 years in this case.

The DOC values at the nine study sites (excluding the three west Florida Gulf coast sites) were calculated using the four empirical formulas (Equations 1 through 4). In order to determine the best performing empirical formula, the measured DOC versus the calculated DOC values (Equations 1 through 4) were plotted with a linear trend line inserted (Figure 16). An intercept at 0,0 (i.e. the formulas should yield a zero for a measured zero value) was forced for all the linear curve fitting. A slope above 1.0 means the formula consistently overpredicted the DOC and a slope less than 1.0 means a consistent under-prediction. Based on the four plots (Figure 16B) the formula that yielded the closest-to-1 slope was the Birkemeier formula (Equation 2).

In order to evaluate the calculated values at each study site, Figure 17 il-

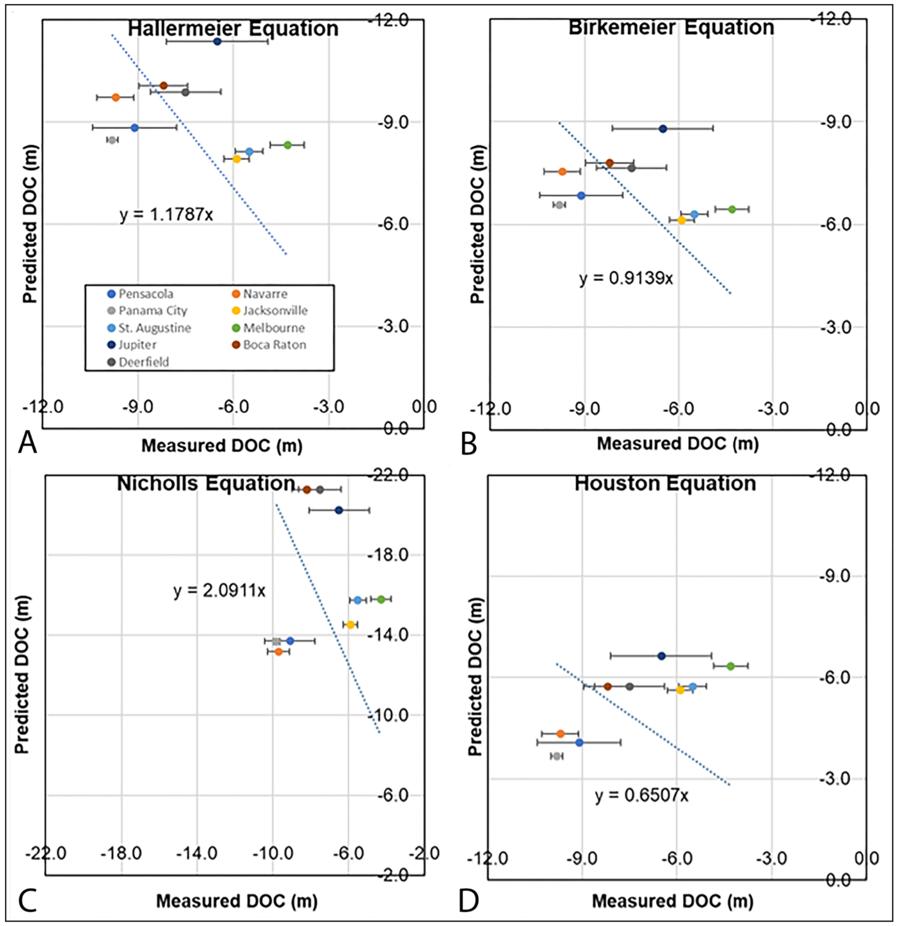


Figure 16 (top right). Relationship between the calculated values using the four existing formulas and the measured values: (A) Comparison between the Hallermeier equation (Equation 1) and the measured values; (B) Comparison between the Birkemeier equation (Equation 2) and the measured values; (C) Comparison between the Nicholls equation (Equation 3) and the measured values; and (D) Comparison between the Houston equation (Equation 4) and the measured values.

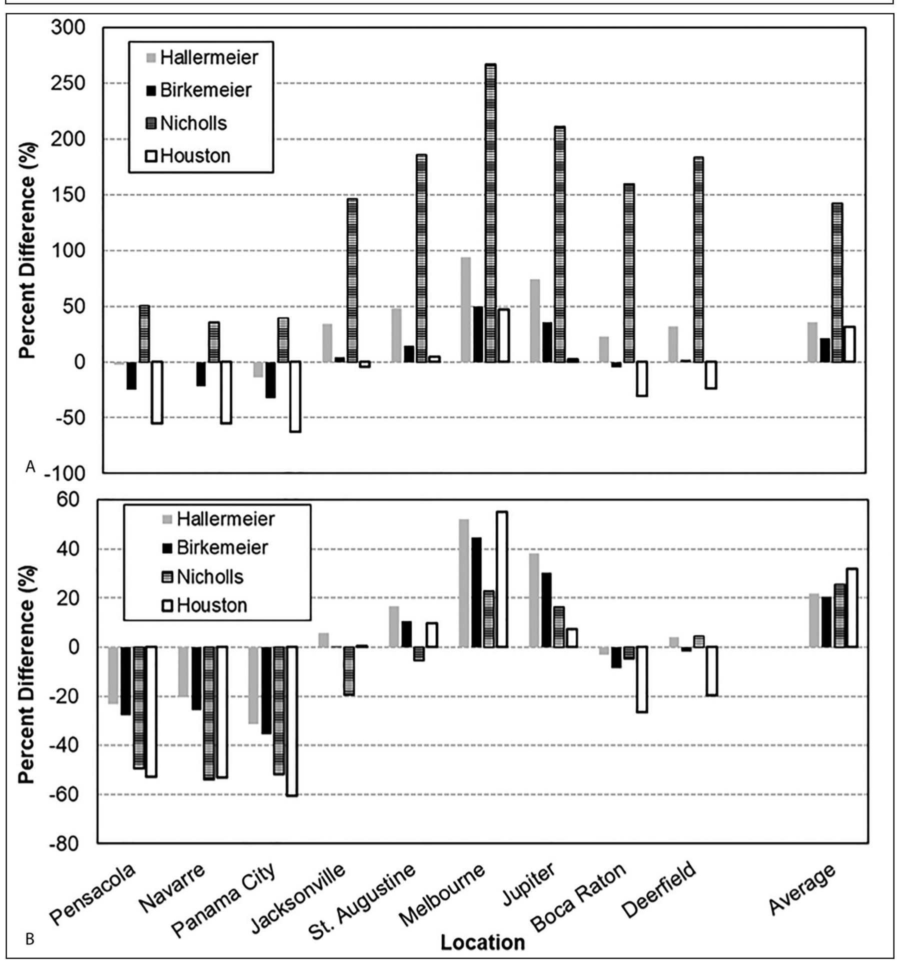


Figure 17 (right). Performance of the four empirical formulas in terms of percent difference between the predicted and measured DOC. The column labeled "average" represents average of the absolute value of the percent difference. (A) The original coefficients as listed in Equations 1 through 4, and (B) adjusted coefficients to achieve the smallest "average" values.

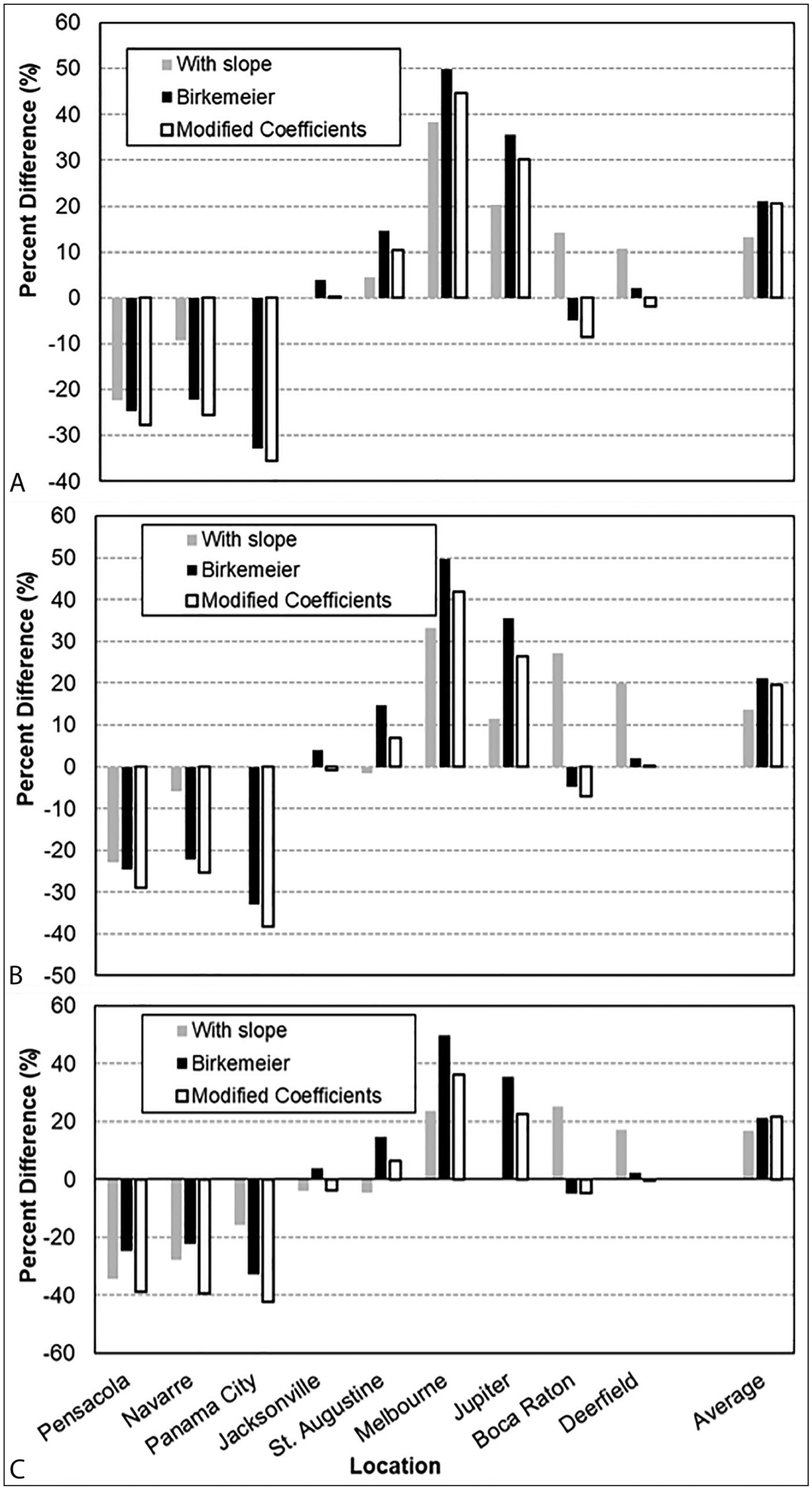


Figure 18. Performance of the Birkemeier formula including the slope correction in terms of percent difference between the calculated and measured DOC. The column labeled "average" represents average of the absolute value of the percent difference: (A) Using average of the annual 12-hour exceedance wave height and associated peak wave period; (B) Using the average top 0.137% wave height and associated wave period; (C) Using the average 48-hour exceedance wave height and associated wave period.

lustrates the percent difference between the calculated and measured DOC. For the Hallermeier (Equation 1) and Birkemeier (Equation 2) the average annual H_{s_12hr} and T_{p_12hr} were used. The overall performance of each equation was evaluated based on the average of the absolute value of the percent differences, shown in the last column (labeled as "average") in Figure 17. This was conducted to avoid cancellation of overprediction (positive percentage) and underprediction (negative percentage) during the averaging.

Using the original coefficients as included in Equations 1 through 4, the Nicholls formula (Equation 4) overpredicted the measured values by a large margin of up to 267.3% (Figure 17A). On average it overpredicted by 142.2%. This formula uses the same coefficients as the Hallermeier equation, however the $H_{s\_12hr\_N}$ and $T_{p\_12h\_N}$ wave conditions are much more extreme producing much larger wave heights and longer wave periods. This produces a much larger prediction value than the measured values (Table 3). The Houston formula (Equation 3) underpredicted six out of the nine measured values, with an average of 31.7% (17A and Table 3). This formula (Equation 3) uses the average significant wave height which unlike the three other equations that use statistically extreme wave conditions. It did however predict the Jupiter site well; this site had a large average significant wave height but shallower DOC than the two sites to the south (Table 1 and 2). The Hallermeier formula (Equation 1) overpredicted seven out of the nine measured values, with an average of 35.7% (Figure 17A). The two underpredicted values were located along the northwest Gulf coast Pensacola and Panama City; both had deeper DOCs, however the average wave conditions were not the most energetic within the data set. The Birkemeier formula performed the best with an average difference of 21.2% (Figure 17A). It overpredicted six out of the nine DOC values, underpredicting Pensacola, Panama City, and Boca Raton, all which had deep DOC values.

In an attempt to improve the performance of all the formulas, the coefficients were adjusted to achieve the lowest average of the absolute percent differences (Figure 17B). As expected, the Nicholls formula (Equation 4) improved significantly with an average percent difference reduced to 25.4% from 142.2%. Since

Hallermeier (Equation 1) and Birkemeier (Equation 2) have a similar form and use the same wave conditions, the best performing Hallermeier (Equation 1) formula had the same coefficients as the Birkemeier (Equation 2) formula. Adjusting the coefficient in the Houston formula (Equation 3) did not lead to an improved prediction. Adjusting the coefficient for the Birkemeier formula (Equation 2) resulted in minor improvement, 20.5% versus 21.2% (Figure 17B).

In summary, the Birkemeier formula (Equation 2) with the original as well as the slightly adjusted coefficients yielded the closest values to the measured ones (Figure 17 and Table 3). For the nine sites the largest over prediction of 44.6% occurred at Melbourne Beach, while the largest underprediction of 35.6% occurred at Navarre Beach (Figure 17B). The performance of the other three formulas were considerably worse than the Birkemeier formula (Equation 2) and therefore, were not further analyzed. In the following, the possibility of improving the Birkemeier formula (Equation 2) by incorporating the seaward slope of the outer bar and applying different extreme wave conditions were examined.

Toward improving the DOC prediction

Since the measured DOC values showed a solid relationship with the seaward slope of the outer bar (Figure 14), this parameter should be included in the formula for DOC calculation. In addition, the definition of extreme wave conditions can have significant influence on the calculation. Based on the performance of the Houston formula (Equation 3), applying the average significant wave height yielded less accurate predictions of the DOC as compared to the Birkemeier formula (Equation 2) (Figure 17A and Table 3). At the other end of the spectrum, the extreme wave height used in the Nicholls formula (Equation 4), i.e. 12-hour exceedance wave height over a 15-year period, appeared to be too extreme (Figure 17A and Table 3). Here, the 48-hour exceedance wave height and associated peak wave period over the 15-year period (H_{s_48hr} and T_{p_48hr}), the average of annual H_{s_12hr} and T_{p_12hr}, and the $H_{s\_0.137\%}$ and $T_{p\_0.137\%}$ were applied in the Birkemeier formula (Equation 2) with the goal of improving the prediction.

Various modifications to improve the predictions of the Birkemeier formula, including incorporating slope, adjusting empirical coefficients, and using different statistical wave conditions, were attempted. Figure 18A shows the results from the original Birkemeier formula using the average annual H_{s_12hr} and T_{p_12hr}, formula with adjusted coefficients, and formula with modified coefficients in addition to including the seaward slope of the outer bar. The seaward slope of the outer bar was added to the adjusted Birkemeier equation through a "slope correction," which was the average slope of the study site multiplied by a set of coefficients based on the wave statistics used. The slope correction resulted in greater predicted DOC of sites with steeper slopes. By adjusting the empirical coefficients, the overall prediction as indicated by average percent difference improved slightly to 20.5% from 21.2% (Figure 18A and Table 4). The largest overprediction at Melbourne Beach was reduced from 49.8% to 44.6%. Melbourne Beach was an abnormal case study as it did not follow the same trends in standard deviation and had large uncertainty associated with its measured value. The formula over predicted the measured value by about 2 m (Table 4). This suggests that at this study

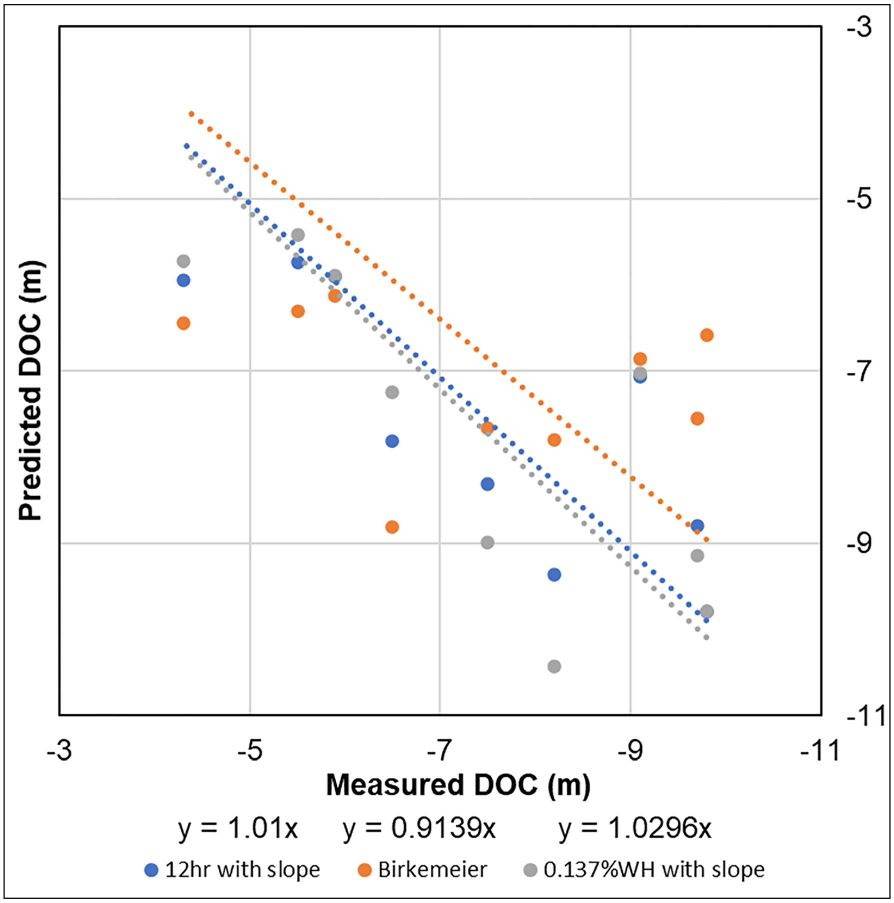


Figure 19. Comparison between calculated values using the improved formulas and the measured values.

Table 3.
Predicted values of the four existing formulas

Location	Measured DOC (m)	Hallermeier (m)	Birkemeier (m)	Nicholls (m)	Houston (m)
Pensacola	-9.12	-8.84	-6.86	-13.70	-4.07
Navarre	-9.66	-9.72	-7.55	-13.17	-4.32
Panama City	-9.76	-8.48	-6.58	-13.68	-3.67
Jacksonville	-5.88	-7.92	-6.13	-14.51	-5.62
St. Augustine	-5.48	-8.14	-6.30	-15.73	-5.74
Melbourne	-4.35	-8.33	-6.44	-15.79	-6.34
Jupiter	-6.48	-11.36	-8.80	-20.24	-6.63
Boca Raton	-8.20	-10.06	-7.80	-21.27	-5.72
Deerfield	-7.50	-9.88	-7.66	-21.27	-5.73

Table 4.
Predicted DOC values using the Birkemeier equation with modified coefficients and the slope correction using H_{s_12hr}, $H_{s\_0.137\%}$, and H_{s_48hr}.

Location	Measured DOC (m)	Wave condition	Birkemeier (m)	Modified coefficients (m)	Slope correction (m)
Pensacola	-9.12	H_{s_12hr}	-6.86	-6.58	-7.06
Pensacola		$H_{s\_0.137\%}$	-7.75	-6.46	-7.03
Pensacola		H_{s_48hr}	-9.02	-5.56	-5.98
Navarre	-9.66	H_{s_12hr}	-7.55	-7.22	-8.80
Navarre		$H_{s\_0.137\%}$	-8.65	-7.25	-9.14
Navarre		H_{s_48hr}	-9.45	-5.86	-7.01
Panama City	-9.76	H_{s_12hr}	-6.58	-6.31	-9.80
Panama City		$H_{s\_0.137\%}$	-7.24	-6.06	-9.79
Panama City		H_{s_48hr}	-9.11	-5.67	-8.26
Jacksonville	-5.88	H_{s_12hr}	-6.13	-5.90	-5.91
Jacksonville		$H_{s\_0.137\%}$	-6.99	-5.85	-5.89
Jacksonville		H_{s_48hr}	-9.10	-5.68	-5.67
St. Augustine	-5.48	H_{s_12hr}	-6.30	-6.07	-5.74
St. Augustine		$H_{s\_0.137\%}$	-7.04	-5.88	-5.42
St. Augustine		H_{s_48hr}	-9.41	-5.85	-5.25
Melbourne	-4.35	H_{s_12hr}	-6.44	-6.22	-5.94
Melbourne		$H_{s\_0.137\%}$	-7.32	-6.10	-5.73
Melbourne		H_{s_48hr}	-9.40	-5.85	-5.32
Jupiter	-6.48	H_{s_12hr}	-8.80	-8.46	-7.82
Jupiter		$H_{s\_0.137\%}$	-9.81	-8.22	-7.25
Jupiter		H_{s_48hr}	-12.44	-7.97	-6.50
Boca Raton	-8.20	H_{s_12hr}	-7.80	-7.49	-9.36
Boca Raton		$H_{s\_0.137\%}$	-9.09	-7.62	-10.43
Boca Raton		H_{s_48hr}	-12.30	-7.82	-10.28
Deerfield	-7.50	H_{s_12hr}	-7.66	-7.36	-8.31
Deerfield		$H_{s\_0.137\%}$	-8.96	-7.51	-8.99
Deerfield		H_{s_48hr}	-11.85	-7.50	-8.80

site, the average annual H_{s_12hr} and T_{p_12hr} from the offshore WAVEWATCHIII station may not have accurately represented the nearshore conditions. Given that this site is located a short distance south of a protruding headland, sheltering of northerly approaching waves (e.g. generated by winter storms) should be considered. The maximum under-prediction worsened from 32.9% to 35.6% at different sites.

By incorporating the seaward slope of the outer bar in combination with the modified coefficients, the largest overprediction was reduced from 44.6% to 38.2%, which was about 1.6 m for Melbourne Beach (Table 4). The Melbourne beach site had gentler slope of 1:68, which led to modest improvement. The largest underprediction was reduced from 35.6% to 22.4% at different sites although both along the northwest Gulf coast. One of the largest underpredictions was at Pensacola Beach where the measured DOC was -9.1 m and the predicted value was -7.06 m. This represented an improvement of 0.5 m by adding the slope correction factor (Table 4). At the Navarre study site including the slope correction resulted in the predicted DOC of -8.8 m versus the measured value of -9.7 m, which represented an improvement of nearly 0.8 m from the -7.22 m without the slope (Table 4). Adding the slope brought the predicted value to within a meter of the measured value. The prediction at the Panama City Beach study site improved the most by including the slope. Using the modified coefficients, the computed value was -6.3 m versus a measured value of -9.8 m, i.e., a 3.5 m under-prediction. With the inclusion of the slope, the predicted value deepened to -9.8 m and matched the measured value (Table 4).

Along the northwest Gulf coast, incorporating the slope improved the computed values significantly at all three sites. Because of the steeper slope, the slope correction in combination with the slightly adjusted coefficients led to greater computed values and matched the measured values more closely. This substantial improvement in the three northwest Gulf sites resulted in an overall improvement of the average absolute difference from 20.5% to 13.3% for all the nine sites.

To examine the influence of extreme wave conditions on the calculation of DOC, the $H_{s\_0.137\%}$ and $T_{p\_0.137\%}$ values were used (Figure 18B). The computed DOC values using the average annual H_{s_12hr} and T_{p_12hr} were still included in Figure18B (black bar labelled Birkemeier) for comparison with the original formula. By adjusting the empirical coefficients and using the $H_{s\_0.137\%}$ and $T_{p\_0.137\%}$, the overall prediction as indicated by average percent difference improved slightly to 19.5% from the 21.2% (Figure 18B and Table 4). The larger $H_{s\_0.137\%}$, as compared to the original H_{s_12hr}, (Figure 15) brought the underpredicted values closer to the measured values. The largest overprediction at Melbourne Beach was reduced from 49.8% to 41.9%, while the maximum under-prediction worsened from 32.9% to 38.2% at different sites. By incorporating the seaward slope of the outer bar in combination with the modified coefficients, the largest overprediction was reduced from 41.9% to 33.2% at Melbourne Beach. The use of higher extreme wave conditions improved the prediction at Melbourne Beach by 0.2 m (i.e. -5.7 m versus -5.9 m), in comparison with the measured -4.4 m (Table 4). The largest underprediction was reduced from 38.2% to 22.8% at different sites. These underpredictions occurred again along the northwest Gulf coast. Overall, by using the $H_{s\_0.137\%}$ and $T_{p\_0.137\%}$ values in combination with slope correction and minor adjustment of the coefficients, the average of the absolute percent difference was improved from 20.5% to 13.6%. The improvement was slightly less than using the original H_{s_12hr} and T_{p_12hr}.

To further examine the influence of extreme wave conditions on the calculation of DOC, the H_{s_48hr} and T_{p_48hr} values were used (Figure 18C). This was used as an alternative to the rather extreme 12-hr waves for the Nicholls formula (Equation 4). Overall, the average of the absolute percent differences was improved from 20.5% to 16.9%. This slight improvement was less than the 13.3% by using the original H_{s_12hr} and T_{p_12hr}.

In summary, the Birkemeier formula applying the average of the annual 12-hr waves (H_{s_12hr} and T_{p_12hr}) and the average of the highest 0.137% waves ($H_{s\_0.137\%}$ and $T_{p\_0.137\%}$), combined with a correction using the seaward slope of the outer bar (*S*) yielded the closest DOC values as compared to the measured DOC. For the nine study sites, the modified Birkemeier formula resulted in an average absolute percent difference of slightly above 13% (Figure 18A and B). The two definitions of the extreme wave condition yielded similar results, which was expected because of the largely constant $H_{s\_0.137\%}/H_{s\_12hr}$ ratio. Using the original average annual H_{s_12hr} and T_{p_12hr} (Figure 18A) the modified Birkemeier equation is:

$$D_c=(56.7S)^{5.25}[1.72H_{s\_12hr}-45(H^2_{s\_12hr}/gT^2_{p\_12hr})] \quad (5)$$

Using the average highest 0.137% waves, i.e. $H_{s\_0.137\%}$ and $T_{p\_0.137\%}$ (Figure 18B), the modified Birkemeier equation is:

$$D_c=(57.4S)^{4.69}[1.43H_{s\_12hr}-57.3(H^2_{s\_0.137\%}/gT^2_{p\_0.137\%})] \quad (6)$$

The short-duration extreme wave conditions over an extended period, e.g. 12 or 48 hours over 15 years as examined in this study, resulted in less accurate DOC predictions (Figure 18C and Table 4) as compared to the longer duration extreme wave conditions. Figure 19 compares the three formulas, the original Birkemeier, the improved version using the H_{s_12hr} and T_{p_12hr}, and the improved version using the $H_{s\_0.137\%}$ and $T_{p\_0.137\%}$. Similar to the case shown in Figure 16, a 0,0 interception was forced. Overall, the improved version using the H_{s_12hr} and T_{p_12hr} (Equation 5) yielded a slope of 1.01 which was the closest to 1, versus 1.03 for the $H_{s\_0.137\%}$ and $T_{p\_0.137\%}$ version (Equation 6) and 0.91 for the original Birkemeier formula (Equation 2). The slope correction significantly improved predictions at sites with a steeper slope, northwest Florida Gulf Coast sites for this case.

Most of the improvement (i.e. from 20.5% to 13.3% and 13.6%) respectively, can be attributed to the slope correction. The original coefficients in the Birkemeier formula were adjusted just slightly. Based on limited analyses, $H_{s\_0.137\%}$, $H_{s\_12hr\_N}$, and H_{s_48hr}, the original 12-hour exceedance wave conditions (H_{s_12hr} and T_{p_12hr}) yielded the closest prediction. It is worth noting that more and systematic extreme wave condition analysis should be conducted to further confirm the above finding.

CONCLUSIONS

A total of 1,268 beach-offshore profiles, surveyed between 2000 and 2019, from 12 sites along the Florida Gulf and Atlantic coasts were analyzed to determine the DOC. At each site, seven profile locations were examined. The DOC at a specific site was represented by the average value of the seven profile locations. The hindcast wave data from 2005 to 2018 were obtained from the WAVEWATCHIII model. Statistical wave conditions from the 15-year data were applied to reproduce the measured DOC using various existing empirical formulas. Based on the above data set and analyses, the following conclusions were reached:

1) At all the 12 sites, the time-series profiles demonstrated an apparent convergence point indicating the presences of a DOC. The bed-level change at the DOC as quantified by the standard deviation of the elevation variation ranged from 0.05 m to 0.19 m. The calmer west Florida Gulf coast resulted in a tighter profile convergence with a smaller standard deviation of 0.05 m. The higher standard deviation of up to 0.19 m was attributable to the more energetic Florida Atlantic coast.

2) The studied northwest Florida Gulf coast yielded the deepest DOC along the Florida coast ranging from 9.12 m to 9.76 m with a relatively small alongshore variation. The DOC along the studied west Florida Gulf coast ranged from 1.60 m to 4.06 m and was influenced by the shallow flat inner continental shelf. Along the studied Florida Atlantic coast, the DOC ranged from 4.35 m to 8.20 m, with considerable alongshore variation.

3) Among the four empirical formulas examined in this study, the Birkemeier formula yielded the closest predictions to the measured values. Various extreme wave conditions were examined included the average of the annual 12-hour exceedance wave height and associated peak wave period over the 15-year period, the average of the highest 0.137% wave height and associated wave period, and the average of the top 48-hour and 12-hour exceedance wave height and associated wave period. The average of the annual 12-hour and the top 0.137% wave conditions yielded similar results. The more extreme wave conditions did not reproduce the measured DOC values as accurately.

4) For the nine study sites excluding the west Florida Gulf coast where the DOC was significantly influenced by the inner shelf, the Birkemeier formula reproduced the measured DOC values within a range of 44.6% overprediction and 35.6% underprediction. The average of the absolute percent differences was 20.5%.

5) A linear relationship between the seaward slope of the outer bar and DOC was identified. Incorporating the seaward slope of the outer bar in the Birkemeier formula improved the accuracy of the DOC prediction, with the average absolute precent difference improved to 13.3% from 20.5%.

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