CONTROL OF A SINGLE ENERGETIC EVENT ON THE LONG-TERM DEPTH OF CLOSURE

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Abstract: The depth of closure (DOC) is defined as the most landward depth seaward of which there is no significant change in bottom elevation. In this paper, the short-term DOC associated with a proximal energetic storm was determined based on time-series beach-offshore profiles and compared to the long-term (20-year) DOC at 5 study sites along Florida coast. At all the profile locations the time-series beach-offshore profiles showed an apparent convergence indicating the presence of a DOC at both the storm and long-term scales. There is no apparent and consistent relationship between the long-term DOC and storm DOC, suggesting that the long-term DOC is not directly controlled by a single energetic storm. The short-term storm DOC demonstrated a higher spatial variation alongshore, as compared to the long-term DOC. Alongshore extent of the study site is not a determining factor for longshore variation. Finetuning a crucial parameter like the DOC would have implications for many coastal engineering and management projects, such as the design of beach nourishment.

Introduction

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 morphology change and the less active offshore area. 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 time scales from a single energetic event to a decade or longer duration (Nicholls et al. 1998; Hinton and Nicholls 1998). It is generally understood that a more energetic event will produce a deeper DOC (Hallermeier 1979; Birkemeier 1985). A longer temporal scale which would include more energetic events should result in deeper DOC. As the temporal scale increases, larger variations in the time-series profiles tend to occur (Nicholls et al. 1998). The spatial scale can also have considerable influence on the determination of DOC. A large study area would incorporate more spatial variation of geologic, morphologic, and oceanographic conditions. For example, morphological features on the inner continental shelf, like shoals and their subsequent migration near existing and ancient tidal inlets further complicate the DOC estimate, compared to a simpler continuous coastline (Barrineau et al. 2021). Regional geological characteristics can also have significant influence on DOC (Wright et al. 1986; Wright 1995), which can be incorporated into the analysis with larger spatial scales. However, the influence of geology on the DOC is not well understood and is not included in the existing empirical formulas. As emphasized in Kraus et al. (1999), the temporal and spatial scales associated with DOC values should be clearly specified.

Practically, the DOC is determined using times-series beach-offshore profile surveys (Royer et al. 2023). Empirical formulas have been developed by Hallermeier (1978), Birkemeier (1985), Houston (1995), and Nicholls et al. (1998) to determine DOC using wave conditions, particularly extreme wave height over a certain period. This provides a tool to determine the DOC of an area where long-term beach-offshore profile data are not available. It is generally understood that morphology change in the vicinity of the DOC is driven by energetic events (Nicholls et al. 1998). This paper aims to answer the questions: is the long-term DOC controlled by a single energetic event? If so, is the temporal scale of DOC determined by the interval between energetic events instead of simply the number of years?

Study Area

The coast of Florida provides an ideal setting for examining impact of energetic events on the DOC. The northwest Gulf coast, west Gulf coast, and Atlantic coast of Florida exhibit a large range of oceanographic and morphologic conditions along with varying vulnerability to hurricanes and tropical storms (Fig. 1). All beaches examined by this study have been determined to be critically eroding shorelines by the State of Florida. This status allows for periodical nourishment projects to be conducted. However, the length of and interval between each nourishment event differs. Both the length and interval are also influenced by extreme storms. 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 Atlantic coast of Florida is also particularly vulnerable to energetic storms while, the west Florida Gulf coast sees fewer storms than the other two coasts (Cheng and Wang, 2019; Cheng et al., 2021).

Along the northwest coast of Florida there are two study sites (Fig. 1). The Pensacola site stretches 11 km alongshore. 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 (Fig. 1). This area was impacted by four storms, passing or making landfall within a 50 km radius, during the study period (2000-2019). The strongest of these storms being Hurricane Dennis, which made landfall to the east of the Pensacola study site on July 10th, 2005 as a category 3 hurricane. The NOAA tide gauge inside Pensacola Bay measured a maximum surge of 1.19 m. A maximum wave height of 3.17 m was computed by WAVEWACHIII (WWIII) 20 km offshore. The second 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 (Fig. 1). This study site has been impacted by five proximal storms from 2000-2019. The strongest being Hurricane Michael, making landfall on October 10th, 2018 southeast of the study site at Mexico Beach, as a category 5 hurricane. A maximum storm surge of 1.31 m was measured by the nearby NOAA tide gauge. Maximum wave height of 5.56 m was computed by WWIII 20 km offshore.

The west Gulf coast site is Marco Island (Fig. 1), which extends alongshore for 1.8 km. Marco Island is the southernmost barrier island along the Florida Gulf Peninsula, transitioning to mangrove coast, aka, the 10 thousand islands. From 2000-2019, Marco Island has been impacted by four proximal storms. Hurricane Irma in 2017 influenced Marco Island as a category 3 storm on September 10th, 2017. This storm produced a maximum wave height of 3.84 m, in the generally low-energy Marco Island area. Maximum storm surge of 1.43 m was measured at the NOAA Naples Pier gauge 22 km northwest of the study site.

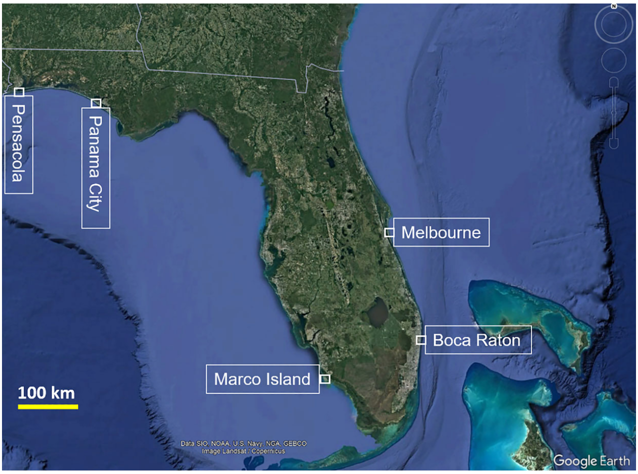

Fig. 1. The six study sites along the coast of Florida.

Along the Atlantic coast two study sites were examined. The first site is Melbourne Beach (Fig. 1), spanning 6.7 km alongshore and is sheltered by the Cape Canaveral headland to the north. There have been two hurricanes and three tropical storms from 2000-2019. Tropical storm Fay traveled directed over the study site on August 20th, 2008. The NOAA Trident Pier tide gauge 9 km north of the study site measured a storm surge of 0.47 m. The maximum wave height was 2.52 m calculated by WWIII 20 km offshore. Although this storm is not the most energetic, the track came in the closest proximity to the site. The Boca Raton site to the south spans 1.8 km alongshore (Fig. 1). Two hurricanes passed the study site from 2000-2019. Category 2 Hurricane Wilma in October of 2005 produced a 1.13 m storm surge measured at NOAA Virginia Key tide gauge 70 km south of the study site. The maximum wave height at 20 km offshore was 6.10 m as calculated by WWIII.

Methods

Time-series beach-offshore profile data from 2000 to 2019 were obtained from the FDEP's Historic Shoreline Database. The profile surveys were typically conducted annually in the summer. The method used to determine the long-term DOC was described in Royer et al. (2023). In this study the same method was used, however only three profiles were used, one pre-storm and two post-storm surveys. The same seven FDEP R monuments, used in the Royer et al. (2023) study, were used at each study site to examine longshore variability. The DOC values from Royer et al. (2023) are referred to here as the long-term DOC. Three profiles were selected from the same data set to determine the storm DOC.

The method used by Royer et al. (2023) is briefly summarized here. 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. An average profile was calculated along with the standard deviation about the mean at each R monument. At all the profile locations, a point of convergence of the time-series profiles was identified (Fig. 2, upper left and right panels). To develop a consistent and repeatable method and reduce subjectivity in the identification of DOC, the following procedures using the standard deviation about the mean of elevation change (STDev) were applied for all the profile locations. A decrease in the STDev occurs before stabilizing at a certain elevation (Fig. 2 lower left and right panels). Across a 122-m (400-ft) section of the profile where the STDev values became low and stabilized, an average value was obtained, as indicated by the horizontal line in Fig. 2 lower panels. This standard deviation value is referred to as the "threshold elevation STDev". The shallowest depth this horizontal line crossed was determined as the DOC. In Royer et al.

(2023) all profiles at each R monument were used. In this study the above procedure was applied to only 3 profiles. It is acknowledged here that the STDev computation using 3 profiles has limitations, however the same Royer et al. (2023) method was used for comparison with the long-term DOC. At each study site, computed wave data from WWIII from 2005 to 2019 were extracted to determine statistical wave conditions used in the empirical formulas.

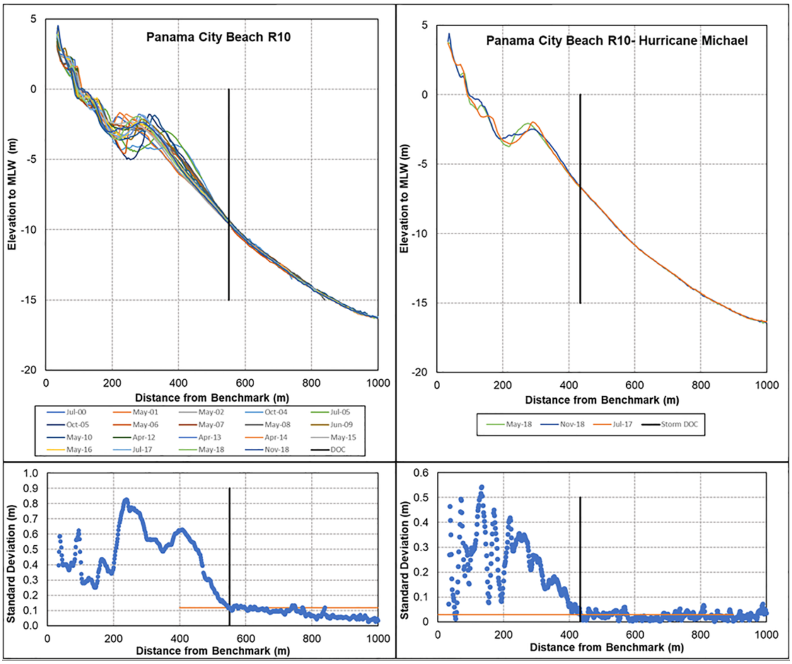

Fig. 2. Method for determining DOC.

Results

The coast of Florida encompasses a large range of oceanographic and geologic conditions and differing vulnerabilities to energetic storms. The northwest coast faces the Gulf of Mexico with an east-west orientation, this coast is vulnerable to direct landfalls by hurricanes and tropical storms. The west Gulf coast is less susceptible to direct landfalls than the northwest Gulf coast. The storms tend to move parallel to the coast. The Florida Atlantic coast is quite susceptible to direct landfalls as well as proximal passages. Storm DOC determined by this study are compared to the long-term DOC determined by Royer et al. (2023).

Northwest Gulf Coast

The northwest Florida Gulf coast sites included Pensacola Beach and Panama City Beach (Fig. 1). At each site, beach-offshore profiles at 7 FDEP R monuments were analyzed to determine the storm DOC. The storm DOC at Pensacola Beach was determined using Hurricane Dennis (Fig. 3, Right Panel). The average storm DOC of the seven R monuments was -9.25 m relative to MLW with a standard deviation of 1.43 m indicating a considerable longshore variation ranging from -6.53 m to -11.05 m. At Pensacola Beach (Fig. 3, Left Panel) the average long-term DOC from the 7 R-monuments was -9.12 m relative to MLW with a standard deviation of 1.32 m ranging from -6.89 m to -10.59 m (Royer et al. 2023).

At Panama City Beach the storm DOC was determined using beach-offshore profiles pre and post Hurricane Michael (Fig. 2, Upper Right Panel). The average storm DOC of the 7 R monuments was -7.02 m relative to MLW with a standard deviation of 1.02 m ranging from -5.55 m to -8.69 m. This is much shallower than the long-term DOC of -9.76 m with increased variation. The long-term DOC values varied from -9.46 m to -9.69 m, with a standard deviation of 0.18 m (Royer et al., 2023). This site had the longest longshore extent of all the study sites; however, it had one of smallest alongshore variations of long-term DOC, while the storm DOC had larger alongshore variation. At all 7 R-monuments the storm DOC was shallower than long-term DOC, the difference in the DOCs ranged from 4.11 m to 1.27 m. Overall, the Northwest Gulf coast sites has rather spatially uniform long-term DOC ranging from 9.12 m to 9.76 m to MLW, while the storm DOC did not show similar uniformity. It is worth noting that two different storms were examined at the two sites.

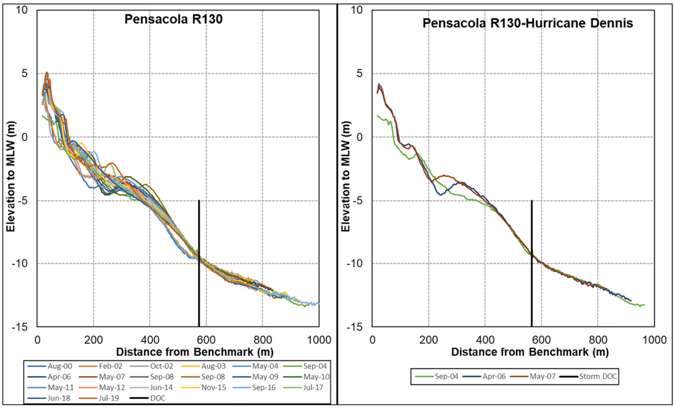

Fig. 3. Comparison of long-term DOC (left panel) and storm DOC (right panel). In both panels the DOC is denoted with a vertical black line.

West Gulf Coast

The west Gulf coast is represented by Marco Island (Fig. 1). The storm used to determine the storm DOC was Hurricane Irma. The average storm DOC of the 7 R monuments was -3.02 m relative to MLW with a standard deviation of 0.36 m ranging from -2.04 m to -3.35 m (Fig. 4, Right Panel). The average long-term DOC from the same 7 R monuments was -3.17 m relative to MLW with a standard deviation of 0.17 m ranging from -2.96 m to -3.46 m (Fig. 4, Left Panel) (Royer et al. 2023). The difference between the long-term and storm DOC at this site is relatively small. The depth of the flat portion of the inner shelf was about 3.5 m, which is slightly deeper than the DOC (Fig. 4). As discussed by Royer et al. (2023) the long-term DOC is significantly controlled by this flat inner shelf. The storm DOC and its similarity to long-term DOC is controlled by the inner shelf.

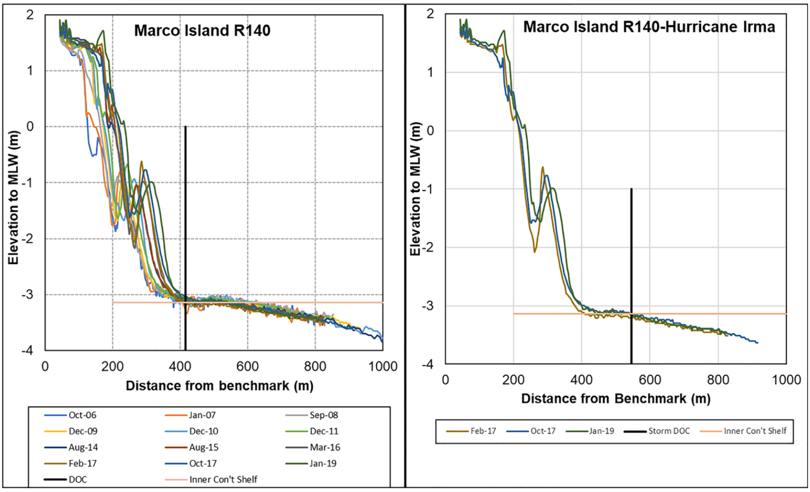

Fig. 4. Comparison of long-term DOC (left panel) and storm DOC (right panel). In both panels the DOC is denoted with a vertical black line.

Atlantic Coast

Two sites were examined along the Atlantic Coast, Melbourne and Boca Raton (Fig. 1). At the Melbourne Beach site the storm DOC analysis was conducted using Tropical Storm Fay. The average storm DOC of the seven R monuments was -5.86 m relative to MLW (Fig. 5, Right Panel). The storm DOC ranged from -5.05 m to -6.73 m to MLW with a standard deviation of 0.61 m. The average long-term DOC from the 7 R monuments was -4.35 m relative to MLW ranging from -3.89 m to -5.09 m, with a standard deviation of 0.54 m (Fig. 5, Left Panel) (Royer et al. 2023). The storm DOC is much deeper than the long-term DOC.

The southernmost site was Boca Raton (Fig. 1). The storm DOC analysis was based on Hurricane Wilma. The average storm DOC of the 7 R monuments was -8.57 m relative to MLW which is on average slightly deeper than the long-term DOC (Fig. 6, Right Panel). The storm DOC varied from -6.95 m to -9.49 m to MLW with a standard deviation of 1.03 m. The average long-term DOC at the Boca Raton site from the 7 R monuments was -8.20 m relative to MLW with a standard deviation of 0.76 m ranging from -7.13 m to -9.43 m (Royer et al. 2023).

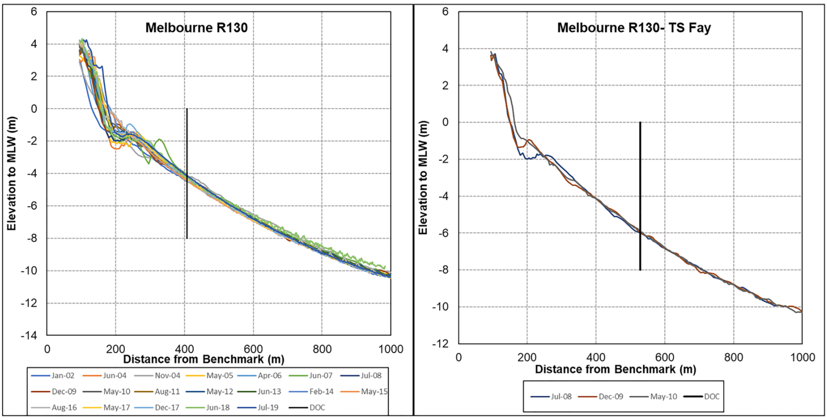

Fig. 5. Comparison of long-term DOC (left panel) and storm DOC (right panel). In both panels the DOC is denoted with a vertical black line.

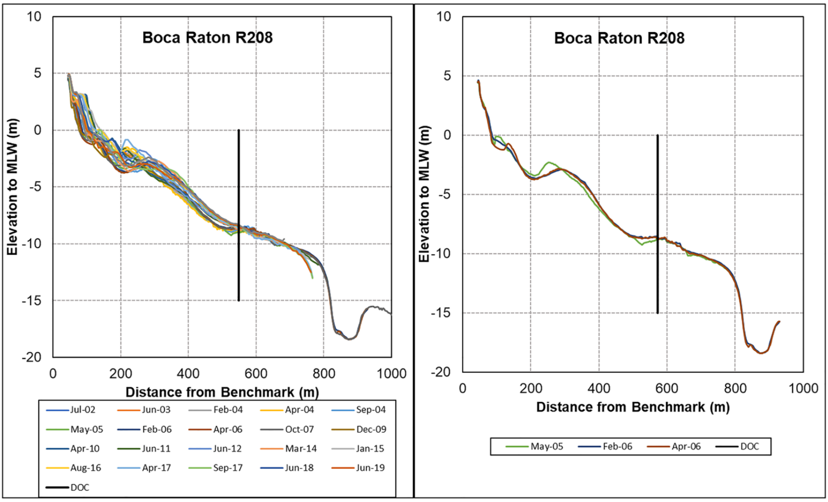

Fig. 6. Comparison of long-term DOC (left panel) and storm DOC (right panel). In both panels the DOC is denoted with a vertical black line.

Discussion

As described above, the various energetic events have differing levels of influence on the DOC, in comparison with the long-term DOC. At 3 of the 5 sites, Pensacola, Marco Island and Boca Raton, the storm DOC matched the long-term DOC reasonably well. At one of the sites the storm DOC was considerably deeper than the long-term DOC, while at another site, it was consistently shallower than the long-term DOC. This section discusses the relationship between the storm DOC and the long-term DOC.

Comparison Between Storm DOC and Long-term DOC

Two sites were examined along the northwest Florida coast. At the Pensacola site the storm DOC matched the long-term DOC closely, while the at Panama City site the storm DOC is much shallower. At the Pensacola site the storm DOC related to Hurricane Dennis is on average 0.13 m deeper than the long-term DOC, with slightly more alongshore variation (Table 1). The maximum storm wave associated with Hurricane Dennis was 3.17 m which is 0.3 m lower than the annually averaged 12-hour wave height that is used in the empirical formulas (Birkemeier 1985, Royer et al. 2023).

At the Panama City Beach site the storm DOC related to Hurricane Michael is on average 2.74 m shallower than the long-term DOC, with significantly more alongshore variation (Table 1). The maximum storm wave associated with Hurricane Michael was 5.56 m which is 2.25 m higher than the annually averaged 12-hour wave height. The much higher wave generated by Hurricane Michael did not result in a deeper storm DOC, while the much lower wave generated by Hurricane Dennis at the Pensacola site did result in a deeper DOC. This suggests that other aspects of the storm, in addition to peak wave height, may play a significant role in controlling the DOC.

At Marco Island the storm DOC related to Hurricane Irma is on average 0.15 m shallower than the long-term DOC, with slightly more alongshore variation (Table 1). The maximum storm wave associated with Hurricane Irma was 3.84 m which is 1.78 m higher than the annually averaged 12-hour wave height. At Marco Island the much higher wave did not result in a deeper DOC because it is controlled by the flat inner continental shelf (Fig. 4) (Royer et al. 2023).

At Melbourne Beach the storm DOC related to Tropical Storm Fay is on average 1.51 m deeper than the long-term DOC, with slightly less alongshore variation (Table 1). The maximum storm wave associated with Tropical Storm Fay was

Table 1. Comparison between storm DOC and long-term DOC and key controlling factors.

Location	Storm (Category)	Max surge (m)	Max storm wave height (m)	Storm wave period (s)	12_hr wave height (m)	12_hr wave period (s)	Avg. long-term DOC (m)	Avg. STDev long-term DOC (m)	Avg. Storm DOC (m)	Avg. STDev storm DOC (m)	Avg. of the difference (m)
Pensacola	Hurricane Dennis (H3)	1.19	3.17	10.9	3.47	9.5	-9.12	1.32	-9.25	1.43	-0.13
Panama City	Hurricane Michael (H5)	1.31	5.56	14.2	3.31	9.1	-9.76	0.17	-7.02	1.03	2.74
Marco Island	Hurricane Irma (H3)	1.43	3.84	11.1	2.06	7.8	-3.17	0.17	-3.03	0.36	0.15
Melbourne	Tropical Storm Fay	0.47	2.52	6.8	3.36	10.9	-4.35	0.76	-5.86	0.61	-1.51
Boca Raton	Hurricane Wilma (H2)	1.13	6.10	9.9	3.97	10.5	-8.20	0.54	-8.57	1.03	-0.37

2.52 m which is 0.84 m lower than the annually averaged 12-hour wave height. Although the storm wave generated by Tropical Storm Fay was lower than the annually averaged 12-hour wave height, it is related to a deeper DOC.

At Boca Raton the storm DOC related to Hurricane Wilma is on average 0.37 m deeper than the long-term DOC, with slightly more alongshore variation (Table 1). The maximum storm wave associated with Hurricane Wilma was 6.10 m which is 2.13 m higher than the annually averaged 12-hour wave height. This higher wave resulted in a slightly deeper DOC.

Royer et al. (2023) argued that slope of the outer bar should play a significant role in DOC and modified the commonly used Birkemeier formula as (Eq. 1):

$$D_C = (56.7S)^{5.25}\left[1.72H_{s\_12hr} - 45\left(\frac{H_{s\_12hr}^2}{gT_{p\_12hr}^2}\right)\right] \quad (1)$$

where H_{s_12hr} is the significant wave height that exceeded 12 hours per year averaged annually from 2005 to 2019. T_{p_12hr} is the associated peak wave period. S is the outer bar slope defined in Royer et al. (2023). Using 9 study sites, of which 5 were examined here, the modified Birkemeier formula resulted in an average absolute percent difference of slightly above 13% (Fig. 7), which represented a considerable improvement of the four existing empirical formulas. Royer et al. (2023) found that the annually averaged 12-hour exceedance wave height and period produced a closer match to the measured long-term DOC than more extreme wave conditions such as 12-hour or 48-hour exceedance during the study period (2005 to 2019). The storm DOC discussed above supports the above conclusion.

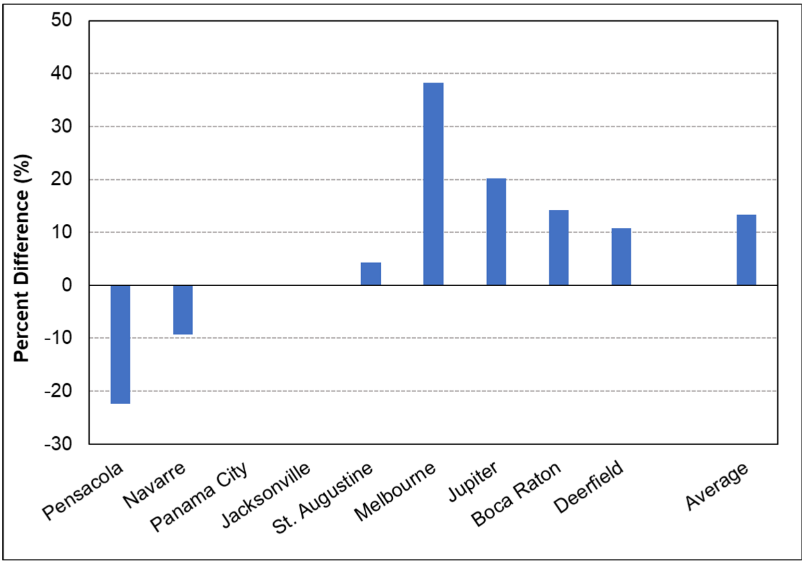

Fig. 7. Percent difference between the long-term DOC and predicted DOC using Eq. 1.

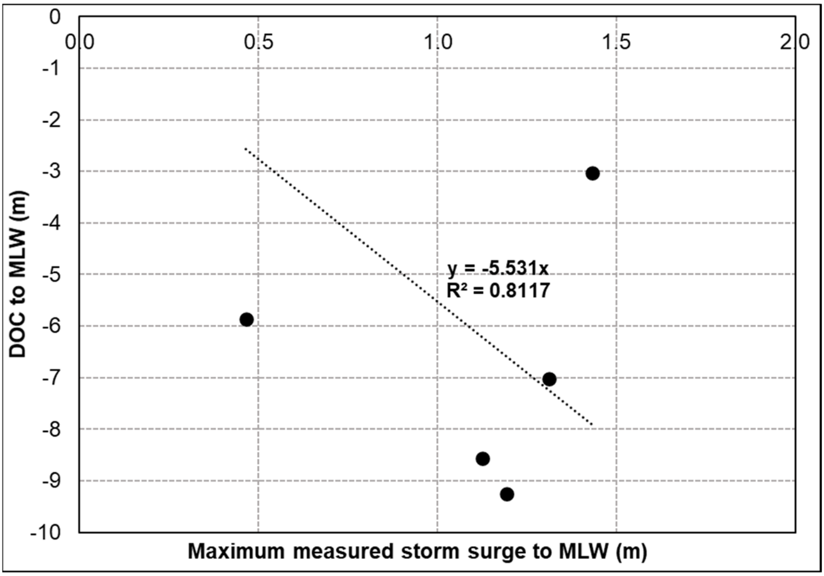

Fig. 8. Relationship between the measured storm surge and the storm DOC.

Relationship Between Storm Surge and DOC

In addition to storm wave height, another factor that could influence the DOC is storm surge. The measured storm surge and storm DOC are compared in Fig. 8. The large scatter of the 5 points suggests there is no simple relationship between DOC and measured storm surge. However, a simple linear fit of the 5 points suggests that a higher storm surge relates to a deeper DOC. Theoretically, a higher storm surge would lead to stronger undertow, which results in increased offshore transport and deeper DOC. It is worth noting that this discussion is preliminary based on limited DOC and storm data. Continued study will include more storms at more sites and computed undertow velocity and offshore sediment transport.

Alongshore Variation of Storm DOC and Long-term DOC

At 4 of the 5 study sites the alongshore variation of the storm DOC is greater than the long-term DOC (Fig. 9 and Table 1). The magnitude of alongshore variation, quantified by the STDev about the mean of the 7 R monuments, is not related to the spatial extent of the site. At Panama City Beach the 7 R monuments extended over 24 km alongshore, the long-term DOC is very consistent with a STDev of only 0.17 m. However, the storm DOC shows more variation with a STDev of 1.03 m and no apparent trend alongshore (Fig. 9B). The Pensacola site extended 11 km alongshore. Both the long-term and storm DOC showed large spatial variation following a similar trend (Fig. 9A). The Melbourne beach site extended 7 km alongshore. This site showed modest alongshore variation for both the long-term and the storm DOC, with the storm DOC varying slightly less than the long-term DOC. The long-term DOC is generally decreasing to the middle of the site then increasing to the south. The storm DOC shows the opposite trend, increasing towards the middle of the site, then decreasing to the south (Fig. 9D). The Boca Raton site spanned 2 km alongshore and is much shorter than the above three sites. The storm DOC has greater alongshore variation compared to the long-term DOC, however they follow a similar pattern with no apparent trend alongshore (Fig. 9E). Along the 2 km long Marco Island site, the spatial variation of both long-term and storm are relatively small (Fig. 9C). The storm DOC showed a southward shallowing trend, while the long-term DOC remained consistent alongshore (Fig. 9C).

The physical cause of the generally increased alongshore variation of storm DOC in comparison with long-term DOC is not apparent. The long-term DOC and its associated spatial variation are determined based on over 100 profiles at each site, while the storm DOC is determined using 21 profiles. The smaller alongshore variation of the long-term DOC may simply be associated with statistical stability.

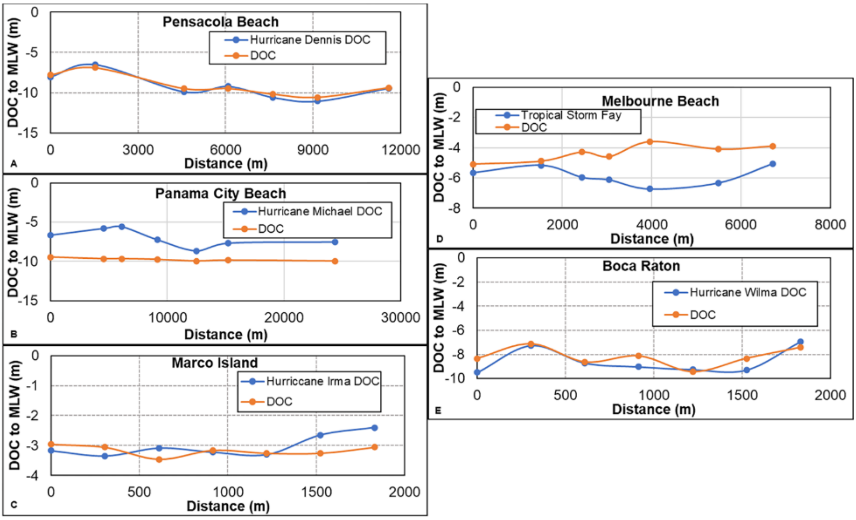

Fig. 9. Alongshore variation of storm DOC and the long-term DOC.

Conclusions

The following conclusions can be drawn from the analysis of storm DOC in comparison with the 20-year DOC:

1) At all the study sites the time-series beach-offshore profiles showed an apparent convergence indicating the presence of a DOC at both the storm and long-term (20-year) scales.
2) There is no apparent and consistent relationship between the long-term DOC and short-term DOC based on one storm that passed within a close vicinity of the study site, suggesting that the long-term DOC is not directly controlled by a single storm. This is consistent with findings from Royer et al. (2023) that the annually averaged 12-hour exceedance wave yields more accurate values of long-term DOC, than more extreme conditions such as 12-hour or 48-hour exceedance wave height, which tends to be controlled by one or a small number of extreme storms over the entire study period, 20 years in this case.
3) A higher storm wave as compared to the annually averaged 12-hour exceedance wave conditions did not yield a deeper storm DOC than the long-term DOC.
4) The short-term storm DOC demonstrates a higher longshore variation, as compared to the long-term DOC. The smaller alongshore variation in

long-term may be caused by statistical stability rather than physical processes.

5) Alongshore extent of the study site is not a determining factor for longshore variation.

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