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Investigating Coastal Geomorphological Response to the Passage of Hurricane Dean 2007 in the Southern Caribbean: Cocos Bay, Trinidad

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Abstract

Hurricanes form part of the annual weather phenomenon for many Caribbean territories during the months of June to November. Trinidad and Tobago lies south of the main hurricane belt and direct hits from these events are seldom, although, their associated effects from swell waves and spiral bands are experienced. This paper investigates the passage of Hurricane Dean on 17th August 2007, and its associated effects on the beach profiles and sediment of Cocos Bay. While this hurricane did not make landfall, the effects on the coastal system are due to the storm generated swells which travelled outwards from the storm centre toward the east coast of Trinidad. Data was collected from 2005 to 2007 and included littoral processes, beach profiles and sediment data using standard geomorphological techniques. The beach's response to the event varied spatially along the bay. While beach erosion is typical at other Caribbean beaches during the passage of these extreme weather systems, at Cocos Bay, some areas accreted while others eroded. Results indicate that the beach's response to this high energy event is dependent on the state of the beach prior to the event. Morphological change seem to be fuelled by bar formation and migration which is enhanced by the passage of a high energy event. A proper understanding of the effects of high energy events on low-latitude tropical beach systems exposed to the Atlantic is invaluable towards informing proper management in a region forecasted to have increased and enhanced Tropical Cyclonic activity due to global warming.

Keywords: beach system, beach erosion, beach accretion, extreme event, swells, beach sediment

1. Introduction

Trinidad and Tobago's geographical location places its east coast against the high energy environment of the Atlantic Ocean and its tropical cyclone generating potential. Each year, tropical storms and hurricanes ravage the Caribbean region. Though Trinidad is the most southerly, and not usually directly hit by such tropical storms, the swell waves they generate impact the east coast (Darsan, et al., 2013). There have also been occurrences where hurricanes have made landfall producing storm surges along the east coast. The passage of these cyclonic weather systems add energy to the existing coastal processes and can therefore have significant impact on the beach and coastal system's equilibrium.

The beach morphology of a coastal area is not static, but is dynamic, and changes in response to coastal processes and the movement of sediments. As such, morphology changes are influenced by wave energy, sediment characteristics, and their interaction. The beach profile area can be defined as extending from the low water of spring tides to the upper limit of wave action (King, 1972). Nearshore processes shape beach morphology (Hardisty, 1990), but there is feedback where morphology influences the processes at work in the nearshore (Komar, 1976). Beaches and their adjacent nearshore zones act as buffers to wave energy. As a result, they are sensitive to change over various timescales ranging from a few seconds to several years (Carter, 1991). Beaches can both adapt their shape very quickly to changes in wave energy, and also dissipate this energy with minor adjustments of the position of each sand or shingle grain (Pethick, 2001).

The passage of tropical storms and hurricanes during the hurricane season from 1st June to 30th November affects beach profiles in the Caribbean. Storms generate swells which can travel thousands of kilometers and superimpose their energy on the existing coastal systems, usually leading to increased wave heights on the coast, and associated beach changes (Coch, 1995). Eyre (1989) and Barker and Miller (1990) investigated the passage of Hurricane Gilbert with noted increases in surge and sea swell on the north, east and south-east coasts of

Jamaica. Dean et al. (1973), Bleuse et al. (1995), Pagney (1992) and Durand (1996) have investigated the impacts of hurricanes and tropical storms on the eastern Caribbean; while Michener et al. (1997) looked at the impacts on coastal wetlands and Gardner et al. (2005) on coral reefs.

All tropical depressions/storms/hurricanes which formed in the Atlantic Basin in 2007 passed to the north of Trinidad, as such there were no direct impacts, however spiral bands associated with the passage of these depressions/storms/hurricanes produced widespread flooding. On August 13th 2007, the Meterological Office began issuing bulletins for Tropical Depression #4 over the Central Atlantic Ocean. This Tropical Depression eventually intensified into Tropical Storm and eventually Hurricane Dean (Figure 1). While Hurricane Dean was ploughing through the southern Windward Islands, it modulated the ITCZ over Trinidad and Tobago. Cloudiness associated with the ITCZ produced widespread thunder showers over Trinidad and Tobago, which resulted in flash flooding in several districts (Trinidad & Tobago Meterological Service, 2007).

Cocos Bay was selected for this study because of the unique interconnection between the geological, hydro-geological, geomorphological, oceanographic and ecologically sensitive facets. Cocos Bay is a barrier beach that protects and impounds the (Ramsar listed) Nariva fresh water swamp, the largest in the country. The low-lying topography of the barrier beach makes it vulnerable to the effects of coastal flooding and erosion. At Cocos Bay, ongoing and accelerated coastal erosion makes this coastline vulnerable to the passage of hurricanes which has the potential to enhance negative coastal processes. Additionally, with the advent of global warming and the potential link to increased storm activity for the Caribbean region, and understanding of the beach's response to such events are invaluable in terms of planning and management of vulnerable coastlines. While this hurricane did not make landfall, it's passage provided a unique opportunity to study the effects of its swells on the coastal system of a low-latitude tropical beach (just south of the main hurricane belt) exposed to the Atlantic Ocean. While the effects on smaller pocket beaches in the Caribbean region have been well documented (Coch, 1995; Eyre 1989; Barker and Miller 1990 ; Dean et al. 1973; Bleuse et al. 1995; Pagney 1992; Durand 1996), this study intends to investigate the response (morphologically and sedimentologically) of an open bay, high energy dissipative beach system to the passage of a hurricane.

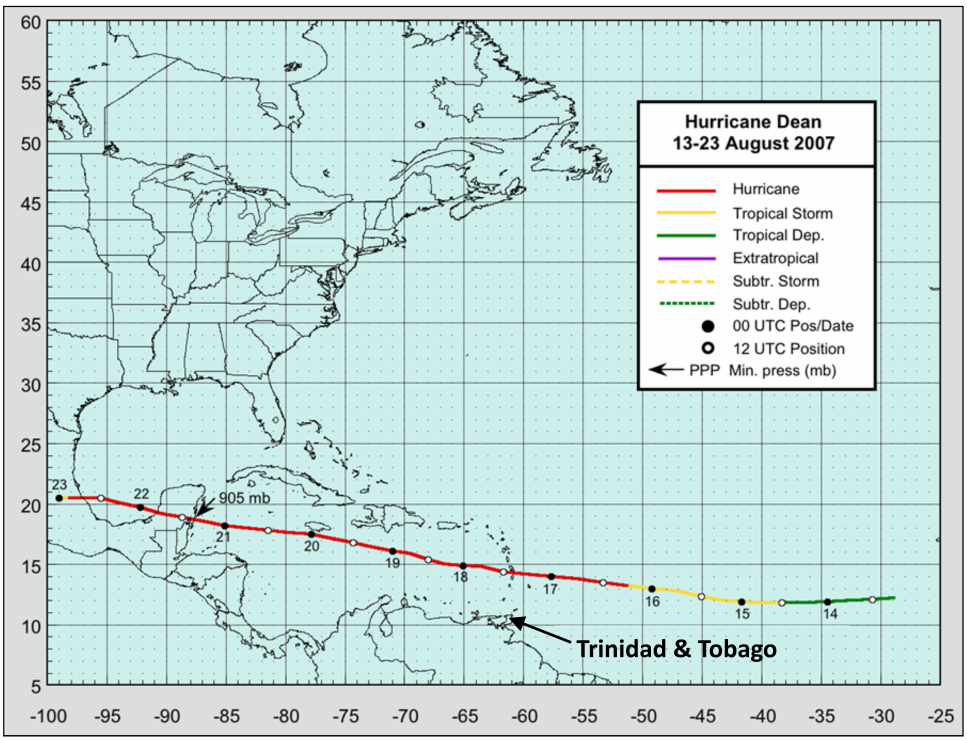


Figure 1. The path of Hurricane Dean, 13-23rd August, 2007

Source: National Hurricane Center, 2007.

2. Coastal Environment of Trinidad

Trinidad and Tobago, the most southerly of the Caribbean islands, is situated between 10º 02’ to 10º 50’ N latitude and 60º 55’ to 61º 56’ W longitudes. It is located on the continental shelf of South America and immediately adjacent to the outflow of the Orinoco River, and this determines to a great extent the nature and form of its coastal and marine environment. Trinidad’s coasts are influenced by the discharge of the Orinoco River, and the Guiana current that flows along the east coast of South America (Andel, 1967). Its location on the continental shelf explains why much of its exclusive economic zone lies in shallow enough depths to permit exploitation of petroleum, natural gas and other seabed resources.

Trinidad and Tobago has a tropical maritime climate with two distinct seasons; a wet and dry season. The prevailing wind system is the north-east trades, and the dominant wind direction is from the north-east in the dry season (December to May), and from the east in the wet season (May to December). The dominant ocean current influence in Trinidad and Tobago is the northern branch of the South Equatorial Current, the Guiana Current. As the Guiana Current approaches Trinidad and Tobago it divides into two streams, with the inner stream passing into the Columbus Channel in a predominantly westerly flow and then into the Gulf of Paria, while the outer passes up along the east coast of Trinidad. The tidal regime experienced is a function of the tide waves from both the Caribbean Sea and the Atlantic Ocean. The tidal regime is semi-diurnal with periods of approximately 12.5 hours. At high spring tides the maximum range is 1.2 metres with some slight variation from north to south. During the winter months, swells attack the coast from directions varying from north-west to north-east. On the east coast, deepwater wave attack is primarily from north-east to south-east, with an easterly approach being the most significant.

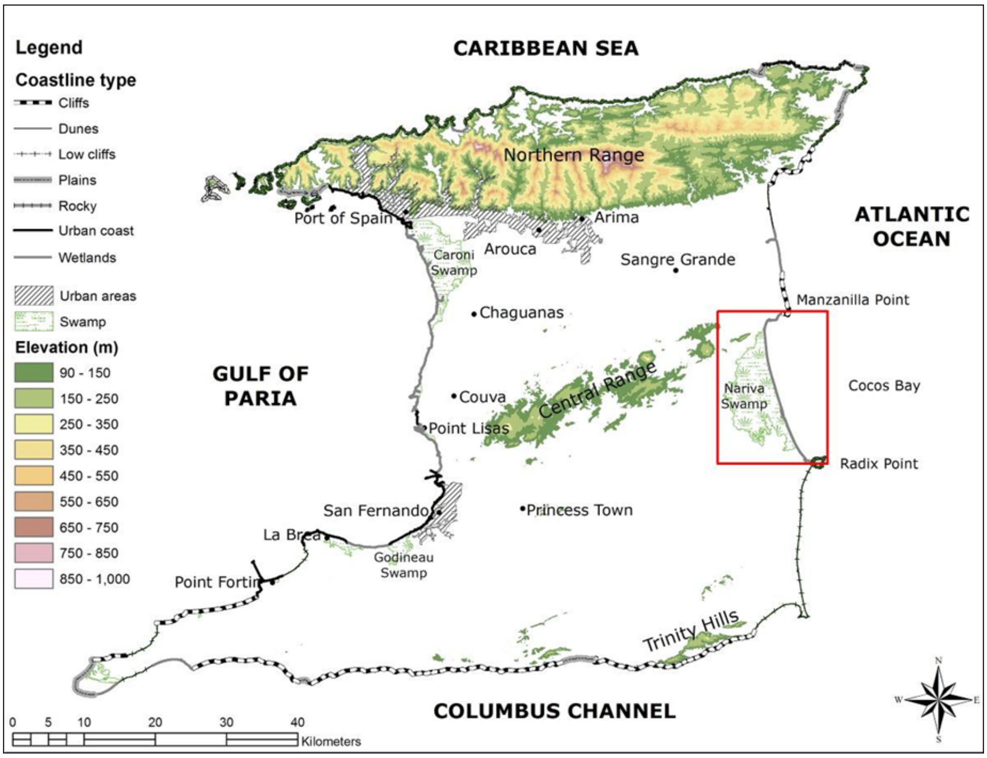


Figure 2. Coastal classification map of Trinidad showing the study area

Source: Darsan et al. (2012).

3. Study Area

The variations in direction and strength of the wave attack along with the variations in geologic structure have produced a wide range of coastal landforms on the beaches in Trinidad. Manzanilla beach at Cocos Bay has been classified as an open sea beach (Georges, 1983). The east coast of Trinidad is rugged in its northern section where the rocks of the Northern Range outcrop. Further south the coastline becomes gentler, where in the central regions the Nariva wetlands are found (Bertrand et at, 1992). The east coast of Trinidad is extremely varied with three stretches of low coast separated by prominent headlands. Manzanilla beach is found in Cocos Bay which is embraced by two prominent headlands, at Manzanilla Point and Radix Point (Figure 2). The Manzanilla beach is oriented north to south, and is exposed to the Atlantic Ocean. It is typically a barrier beach behind which east flowing rivers have ponded the extensive Nariva freshwater swamp. Manzanilla beach located on the east coast along the Manzanilla-Mayaro road. Manzanilla is a long beach of about 20 km, with brownish grey fine sand. Here, the sea bed dips gently downward from the coast towards the edge of the continental shelf approximately 100 kilometers away.

The Cocal area includes the Manzanilla beach in Cocos Bay and the Nariva Swamp. The Cocal sand bar known locally as Manzanilla beach, has a relationship with the Nariva Swamp whereby the swamp is protected from the marine environment by the barrier beach. The beach protects the swamp from salt water intrusion, helping to maintain the correct salinity levels that promote life in this wetland ecosystem (Darsan, 2005). The characteristics (including the geology and hydro-geology) of the sand bar are not well known having received little attention (Environmental Management Authority, 2001). The Cocal sand bar has a fairly low topography with some sections below sea level (Williams, 2000).

There is also significant erosion along several parts of the Manzanilla beach (Singh, 1997; Darsan, 2005), particularly near the Nariva River mouth; attributable to fresh water outflow and tidal inflow dynamics. The Nariva River also carries large quantities of particulates and nutrients to Cocos Bay which has implications for marine biota and productivity (Bacon et al., 1979). At several points along Manzanilla beach, the sand bar has been eroded from fresh water outflow and sea water inflow; creating points where salt water is able to directly penetrate and alter salinity in the Nariva Swamp (Environmental Management Authority, 2001).

The beach plan of Manzanilla shows that it takes the shape of a typical zeta-form beach. Here the northern section of the beach is sheltered from the oncoming dominant wind system (The North-East Trades), and the rest of the beach is largely exposed. This zeta-form has implications for wave energy and coastal processes, beach profiles and sediment characteristics along the bay (Figure 3).

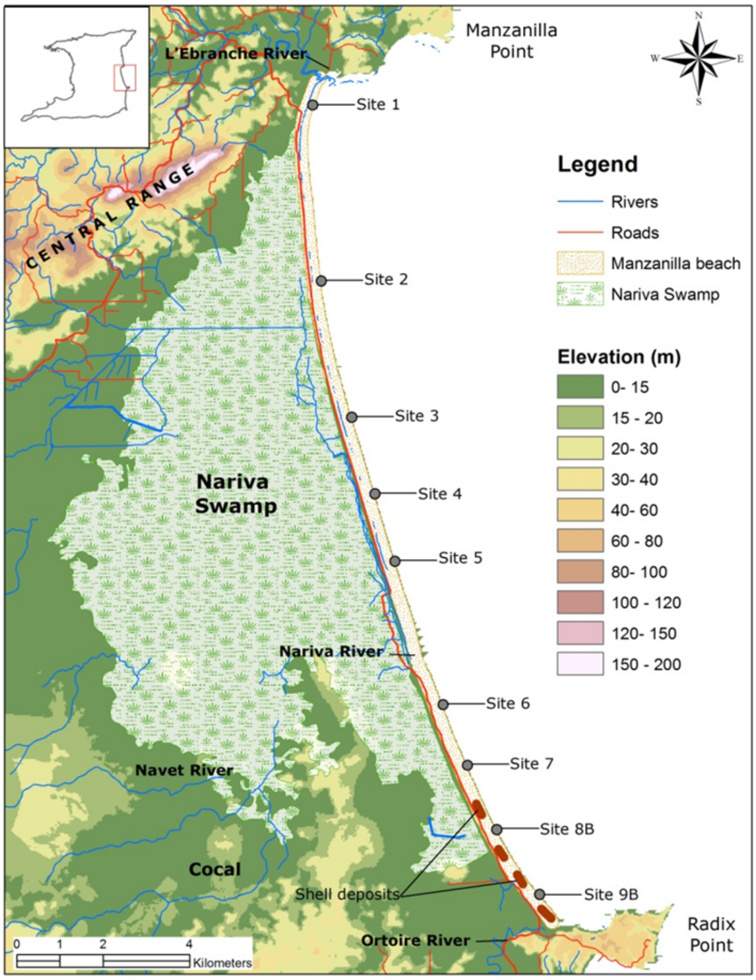


Figure 3. Morphology of Cocos Bay, Manzanilla, showing study sites

The sediment at Cocos Bay comprises a mix of clastic and carbonate sediments (Darsan 2005; 2012). The majority of the beach material has a clastic origin, with varying percentages of carbonates. In the upper and middle section of the bay, clastic sediment predominates, but in the southern section at sites 8B and 9B, shell deposits are found making the sediment predominantly carbonate (Figure 4).

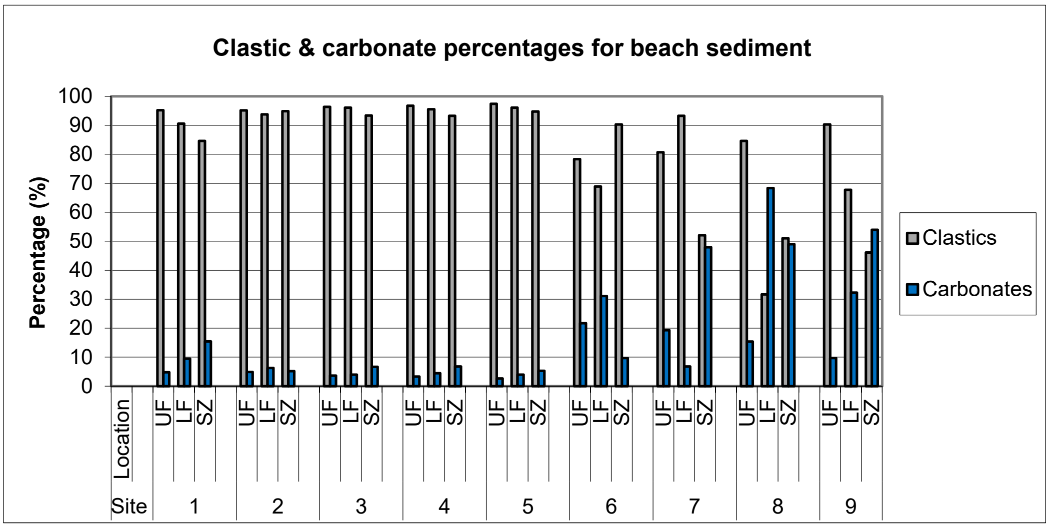


Figure 4. Composition of beach sediments at Cocos Bay

Source: Darsan (2012).

4. Methods

Beach profiles, littoral and sediment data were collected monthly from December 2005 to September 2007 at 9 sites, as part of a larger study (Figure 3). For this segment of the study, data were collected at 7 sites before the hurricane on 1st August 2007, 2 days after on 19th August 2007 and in the recovery period on 1st September, 2007. Data collection was done between the hours of 9:00am to 3:00pm at each location. Offshore wave data was obtained from NOAA's National Data Buoy Centre 2007, data buoy stations 41040 (Atlantic Ocean) and 42059 (Caribbean Sea) (http://www.ndbc.noaa.gov/hurricanes/2007/dean/).

4.1 Beach Profiles

Beach profiles were surveyed using a Topcon survey level, compass, 30m tape and graduated staff. The uneven ground surface interval method was employed, where the beach slope is measured over uneven distances, corresponding to breaks or changes in slope (Goudie, 1990). The surveying instrument was leveled before each survey to minimize collimation errors. The vertical heights along the profile transect were obtained from direct staff readings. The beachface angle was calculated as the average angle from the spring tide high water mark to the spring tide low water mark on each profile. The beachface angle was calculated as follows:

$$\sin \alpha = VH/L$$

where $\sin \alpha$ = slope (angle) of the segment (degrees)

L = length of the segment (m)

VH = vertical height (m)

4.2 Beach Volume

Beach profiles were used to obtain and compare beach volumes across each site. The analysis of beach volumes is a good indicator of a stable beach (Reeve, Chadwick, and Fleming, 2004; Farris and List, 2007). Beach volume changes that occurred on the profiles were analyzed using beach profile distances up to 80 m (the shortest profile lengths) from the benchmarks. While beach changes were occurring seaward of the 80 m mark, since all profiles did not extend beyond this distance, it was not possible to include for the purpose of this analysis. Beach volume changes during the passage of the hurricane were measured as deviations from the baseline established on 1st August 2007. Volumes were calculated as the area under each profile curve (using the trapezoidal rule) multiplied by 1, and expressed as m^3/m. Therefore the beach volumes represent 1 m width of profile up to 80 m from the benchmarks.

4.3 Littoral Processes

Nearshore coastal processes were obtained using Schnider (1981) and Goudie et al. (1990). The littoral observations included wind speed (measured against the Beaufort wind scale) and direction, wave and breaker types, wavelengths, wave heights and directions, and longshore current speed and direction. The wave height was measured directly with a 7.60 m extendable survey staff and was taken as the height difference between the wave trough and crest. Wavelength was measured as the distance between 2 wave crests. The wave approach was measured from the shoreline with a Brunton direct pointing compass which was pointed toward the oncoming waves and the direction recorded. The longshore speed was measured as the distance moved by a floating object in 60 seconds, represented as ms^{-1}. Wave velocity and energy were calculated as follows:

Wave velocity = Wavelength / Wave Period

Wave energy (E) = 1/8 pg H^2 (Dyer, 1986)

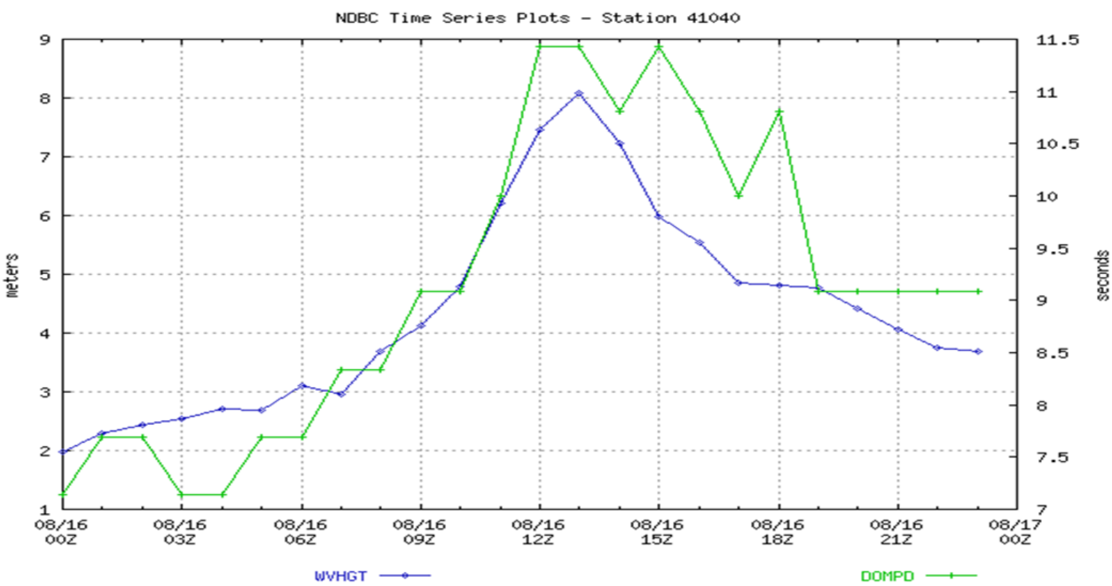
4.4 Sediment Grain Size

Sediment samples were obtained monthly from the upper foreshore (mean high water mark), lower foreshore (mean low water mark) and surf zone (15m seaward of the lower foreshore sample) at each site. Sediment samples were oven dried at 105° for 24 hours. A known weight of sample (120 g) was sieved at intervals using ½ ϕ using an automatic sieve shaker (Octagon digital) and ASTM E11 20 cm diameter sieves (mesh no. 5/8 to 230) for 15 minutes. Folk and Ward (1957) graphical computation method was utilized to calculate the statistical parameters of the grain size (mean, standard deviation, skewness and kurtosis). Statistical analysis of the results and graphical analysis of the data were performed using GRADISTAT software (Blott and Pye, 2001) version 5.

5. Results

5.1 Offshore Wave Conditions

During the passage of the hurricane, there was a substantial increase in the significant offshore wave height (from 2 m to 8 m) in the Atlantic Ocean from August 16th, 2007. Wave heights peaked on August 18th (10 m), in the Caribbean Sea. However, based on the wave direction, it is unlikely that these swells recorded at buoy station 42059 could impact the east coast of Trinidad. Based on these data, it is possible that the swell waves recorded by buoy station 41040 in the Atlantic would have been impacting the eastern coast of Trinidad by the following day, though at a much reduced wave height and energy (Figure 5).



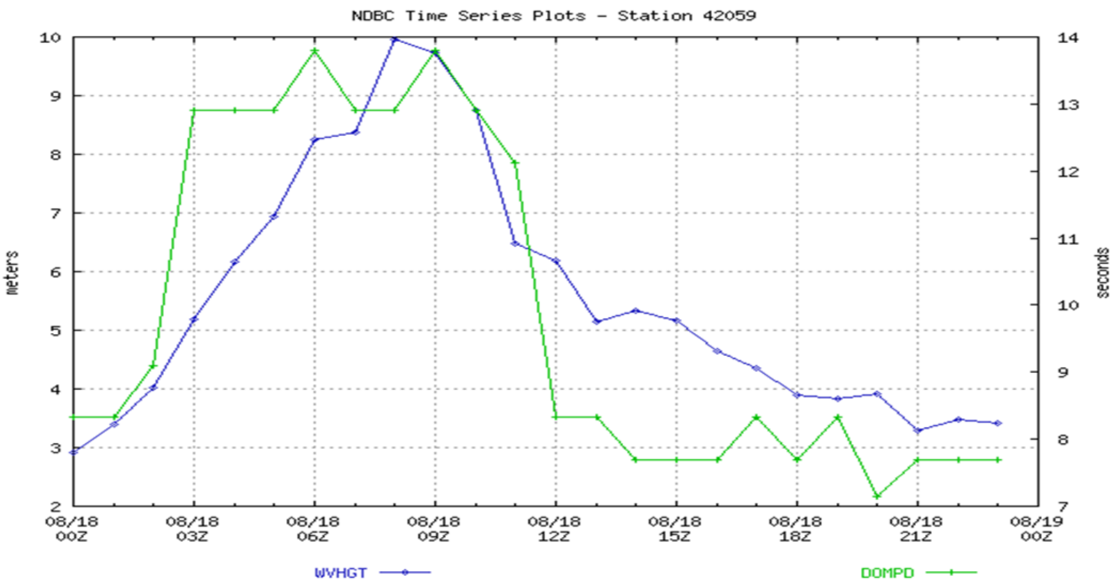


Figure 5. Significant wave height and dominant wave period in the Atlantic Ocean and Caribbean Sea during Hurricane Dean 2007

WVHGT: Significant wave height representing the average of the highest one-third of the waves during the wave sampling period.

DOMPD: Dominant Period representing the wave period (time between consecutive passes of the wave crests) of the waves with the most energy.

Source: National Data Buoy Centre 2007 (http://www.ndbc.noaa.gov/hurricanes/2007/dean/)

5.2 Littoral Processes

The nearshore coastal area of Cocos Bay is characterized as a high energy environment. It should also be noted that because of health and safety reasons, the survey on the 19th August 2007 was conducted 2 days after the most intensive storm related marine activity. Although the hurricane would have been moving away, the effects of its swell waves would have had some influence on the study area up to the 19th of August. Data on wind speeds collected on site, as well as at the national meteorological station at Piarco International Airport, did not record any increases to wind speed during the passage of the hurricane. The wind and wave approached from the east, and with the exception of site 3 which had a north flowing longshore current, the current generally flowed south at other sites. The data revealed that wave height, period and wavelengths were quite variable across the bay, with notable increases to wave height at sites 1, 5 and 8B (Table 1).

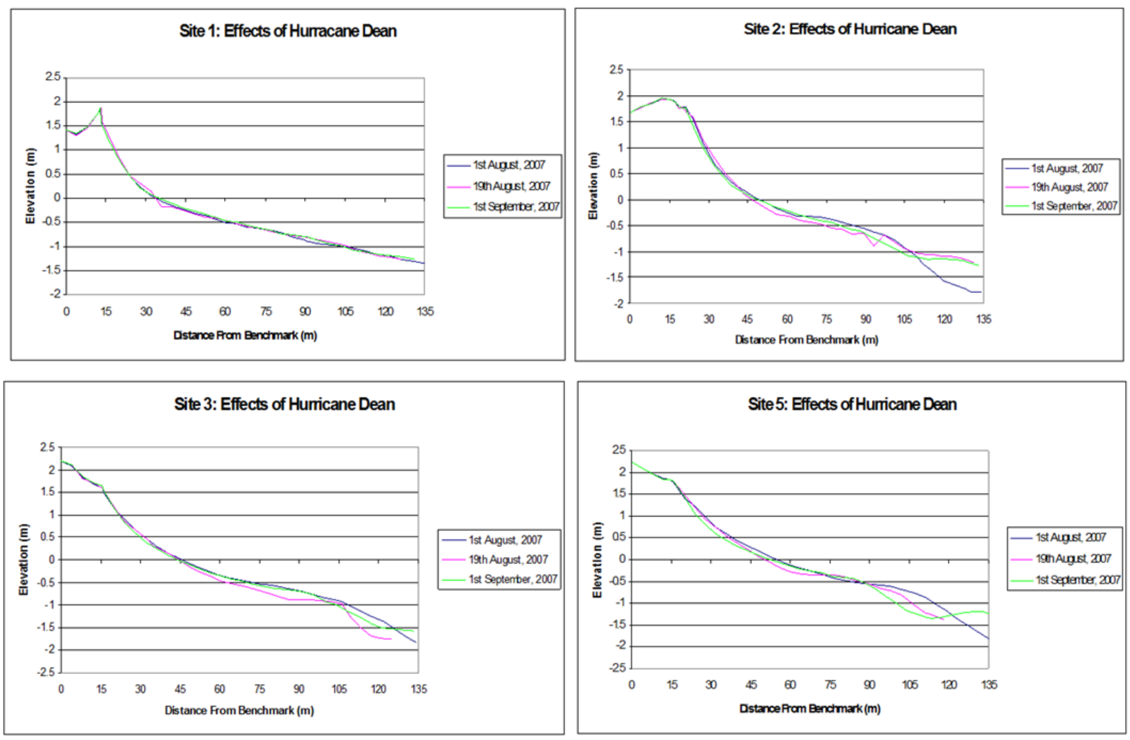
Table 1. Coastal Processes

1st August, 2007	**Site 1**	**Site 2**	**Site 3**	**Site 5**	**Site 6**	**Site 8B**	**Site 9B**
Wind Speed	2	2	2	2	2	2	2
Wind Direction	East	East	East	East	East	East	East
Wave Period	6.1s	5.4s	6.2s	5.9s	7.0s	6.8s	6.0s
Wave Height	0.5m	0.6m	0.6m	0.7m	0.2m	0.7m	0.9m
Wavelength	20.6m	14.2m	14.95m	9.85m	12.05m	18.7m	11.95m
Wave Approach	90º	90º	90º	90º	90º	90º	90º
Current Speed	0.10m/s	0.46m/s	0.20m/s	0.11m/s	0.35m/s	0.32m/s	0.39m/s
Current Direction	South	South	South	South	South	South	South
19th August, 2007	**Site 1**	**Site 2**	**Site 3**	**Site 5**	**Site 6**	**Site 8B**	**Site 9B**

Wind Speed	3	3	3	3	2	2	2
Wind Direction	East	East	East	East	East	East	East
Wave Period	6.7s	6.5s	6.4s	4.7s	11s	6.7s	7.6s
Wave Height	0.8m	0.3m	0.5m	0.9m	0.4m	0.9m	0.7m
Wavelength	18.5m	14.1m	18.05m	12.3m	8.15m	10.1m	17.5m
Wave Approach	90º	90º	90º	90º	90º	90º	90º
Current Speed	0.05m/s	0.24m/s	0.11m/s	0.23m/s	0.20m/s	0.21m/s	0.21m/s
Current Direction	South	South	North	South	South	South	South
1st Sept, 2007	**Site 1**	**Site 2**	**Site 3**	**Site 5**	**Site 6**	**Site 8B**	**Site 9B**
Wind Speed	0	1	1	1	1	1	1
Wind Direction	East	East	East	East	East	East	East
Wave Period	5.5s	5.8s	6.6s	8.0s	6.5s	6.5s	6.3s
Wave Height	0.65m	0.5m	0.7m	0.4m	0.4m	0.75m	0.7m
Wavelength	11.9m	17.8m	14.6m	22.45m	15.78m	15.55m	15.77m
Wave Approach	90º	90º	90º	90º	90º	90º	90º
Current Speed	0.09m/s	0.36m/s	0.18m/s	0.48m/s	0.24m/s	0.22m/s	0.12m/s
Current Direction	South	South	South	South	South	South	South

5.3 Beach Profiles

At site 1, the profile actually accreted on the upper foreshore and eroded on the lower foreshore region 2 days after the passage of Hurricane Dean, on 19th August, 2007. The erosion in the lower foreshore was due to a trough that developed due to the breaker line of waves from the hurricane, and was in-filled in the days following the hurricane. Some accretion was observed in the shallow surf zone region during this period. By September 1st 2007, the profile returned to its original shape where the deposited sediment on the upper foreshore due to the hurricane was removed to the surf zone region. The lower foreshore region did however experience some accretion following the hurricane up to 1st September, 2007 (Figure 6).



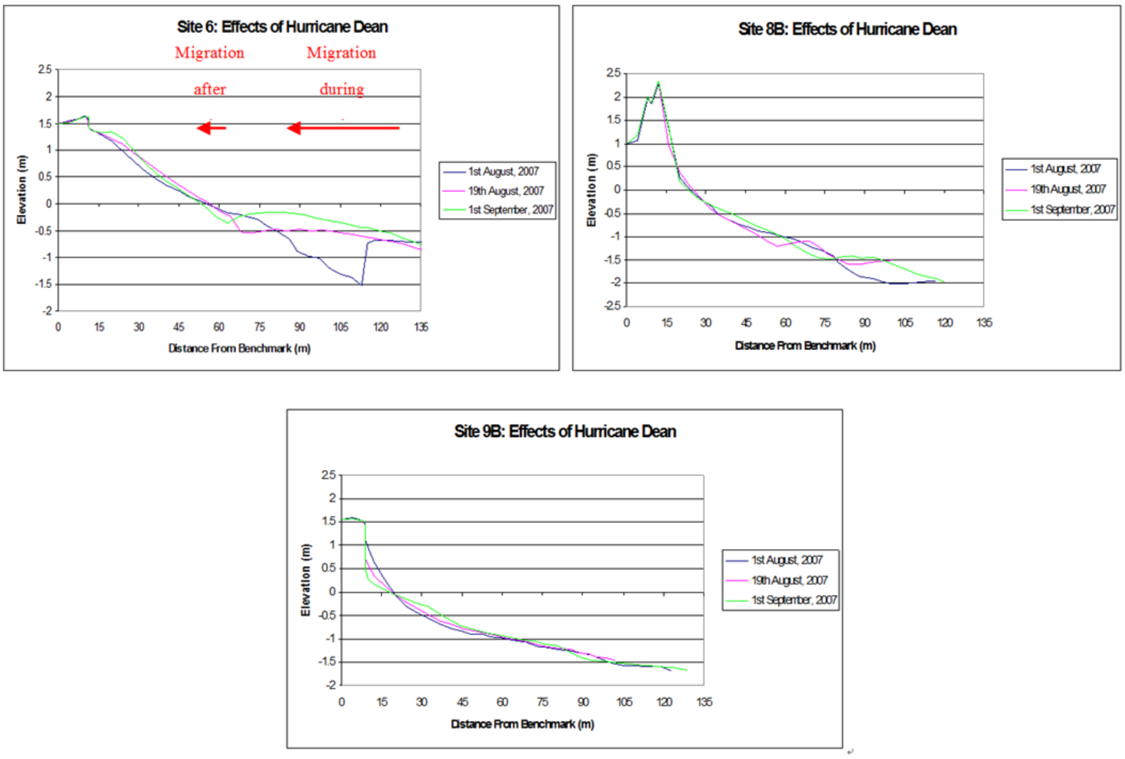


Figure 6. Beach profile response to Hurricane Dean

At site 2, the profile also accreted on the upper foreshore and eroded on the lower foreshore and shallow surf zone region (60-110 m from benchmark) 2 days after Hurricane Dean. In the deeper surf zone region (seawards of 110 m), there was significant accretion on 19th August, 2007, probably due to the deposition of the eroded sediments from the shallow surf zone. In the recovery period after the hurricane, the upper foreshore eroded as the deposited sediment on 19th August, 2007 was removed to the lower foreshore where it accreted (Figure 6 and Plate 1).

At site 3, there was no significant change to the upper foreshore however, the lower foreshore and surf zone regions experienced broad-scale erosion due to the hurricane. A bar developed in the surf zone around 105 m but the majority of the sediment was removed offshore. Following the hurricane, on 1st September 2007, the upper foreshore started to erode and some of this sediment was deposited on the lower foreshore. However landward bar migration deposited sediment on the lower foreshore and surf zone which helped to return the profile to its former shape prior to the hurricane (Figure 6).

Site 5 underwent erosion of the profile after the hurricane, with the lower foreshore and surf zone regions experiencing the most damage. Trough development on the lower foreshore and surf zone regions accounted for the erosion observed following the hurricane. After the hurricane, up to September 1st 2007, the upper foreshore continued to erode, however the lower foreshore and shallow surf zone regions accreted during this period. At this site, migration of offshore bars aided by the hurricane generated swell waves led to either accretion or erosion of the profile depending on the position of the bar crest (which led to accretion) and trough (which led to erosion) as they are driven shoreward (Figure 6).

Site 6 displayed the most dramatic change during this period and responded similarly to site 5, whereby the energy from the swell waves were able to fuel the landward migration of offshore bars which affected the shape of the profile. Before the passage of Hurricane Dean, there was a large trough located on the profile around 100 m to 115 m from the benchmark. After the passage of the hurricane, this trough was completely in-filled as a large offshore bar migrated landwards and deposited sediment on the beachface (upper and lower foreshore) changing the shape of the beachface from concave to convex (Figure 6). On the 19th of August (2 days after the hurricane), the trough had migrated to 70 m from the benchmark (moving a distance of 45 m). In the recovery period up to 1st September 2007, the same trough migrated by only 5m. By 1st September, 2007, a berm was deposited on the upper foreshore which represented the maximum landward migration of the offshore bar, with subsequent erosion of the lower foreshore due to the position of the trough. The surf zone accreted significantly as a second offshore bar migrated landwards in the recovery period.

At site 8B, the profile seaward of 20 m from the benchmark was analyzed, since a revetment was constructed landward of this 20 m mark. While a revetment has the ability to modify the beach system, and may lead to erosion at the base of the structure, the beachface actually accreted on August 19th 2007, with some erosion in the surf zone as the trough of an offshore bar was migrating landwards. In the deeper surf zone region (80-120 m from benchmark), accretion took place as the crest of a second bar was also migrating landwards. In the recovery period, erosion occurred on the upper foreshore with seawards transport of the eroded sediment towards the lower foreshore and shallow surf zone regions. Here again, offshore bar migration was the influential factor in determining whether the profile accreted of eroded during the passage of the hurricane (Figure 6).

Site 9B experienced severe upper foreshore erosion during the passage of Hurricane Dean. This eroded sediment was transported and deposited on the lower foreshore and to a lesser extent in the surf zone. In the recovery period, seaward movement of the eroded upper foreshore sediment led to the formation of a bar on the lower foreshore (around 30 m from the benchmark) and some deposition in the shallow surf zone (Figure 6).

5.4 Beach Sediment Folk & Ward Parameters

The hurricane did not greatly affect the mean grain sizes of the beach sediment across the sites except at sites 8B and 9B where the change in mean grain-sizes during the hurricane was a reflection of whether shell deposits at those locations were buried or removed by the hurricane event. In terms of the sorting, only at sites 8B and 9B did sorting change from well-sorted to poorly-sorted, and these included the areas where the shell deposits were found. The skewness and kurtosis of the sediments followed the same trend where the most significant changes occurred in the southern sites that had shell deposits (Figure 7).

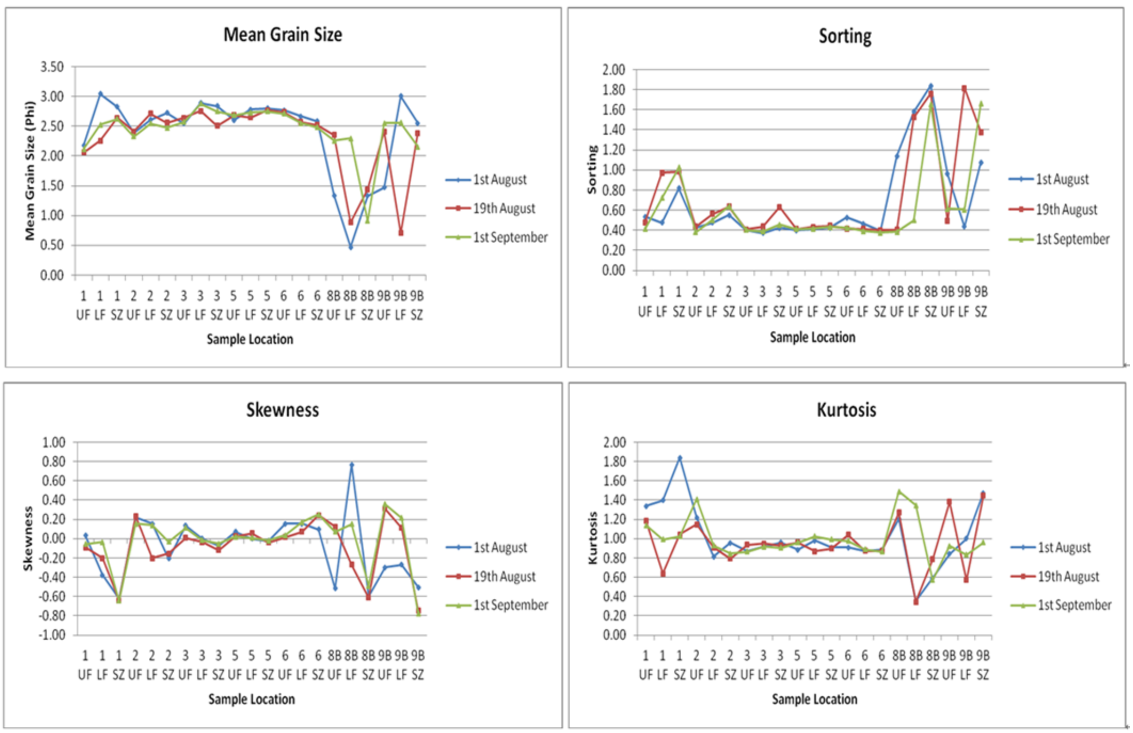


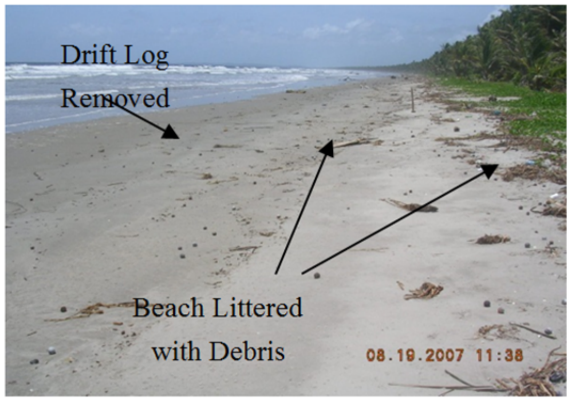
Figure 7. Folk and Ward (1957) sediment parameters

Sediment data revealed that most of the beach sediments were unimodal with the exception of sites 1, 8B and 9B which had bimodal distributions, and coarser grain-sizes. Site 1 displayed a bimodal distribution in the lower foreshore and surf zone samples, but had a unimodal distribution in the upper foreshore sample. Site 9B lower foreshore sample had a poorly sorted polymodal distribution after the hurricane. The sediment samples that were unimodal were well to moderately-sorted, while the bimodal distributions were moderately to poorly-sorted (Figures 8-10).

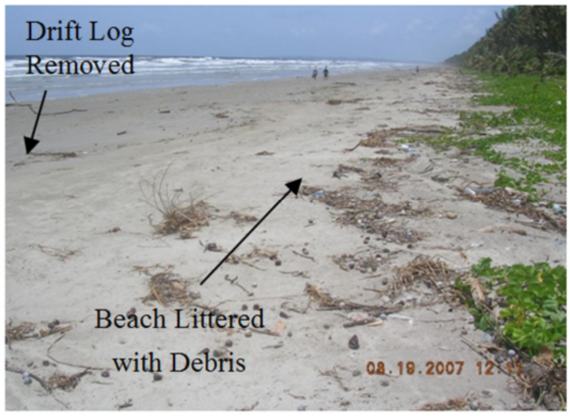
The lower foreshore sediment was most affected by the hurricane. At site 1, the unimodal distribution of the lower foreshore sediment changed to a bimodal distribution after the hurricane as new sediment was introduced from the L'Ebranche River. Site 9B lower foreshore sediment changed from a unimodal distribution to a poorly sorted polymodal distribution after the hurricane. At site 1, the changes to the sediment distribution were due to the introduction of new sediment from the river, whereas at sites 8B and 9B, a result of the burial or removal of the shell deposit.

Plate 1. Pre and post Hurricane Dean at selected sites

Site 2 **Before (31/7/07)** **After (19/8/07)**



Site 3



Site 5

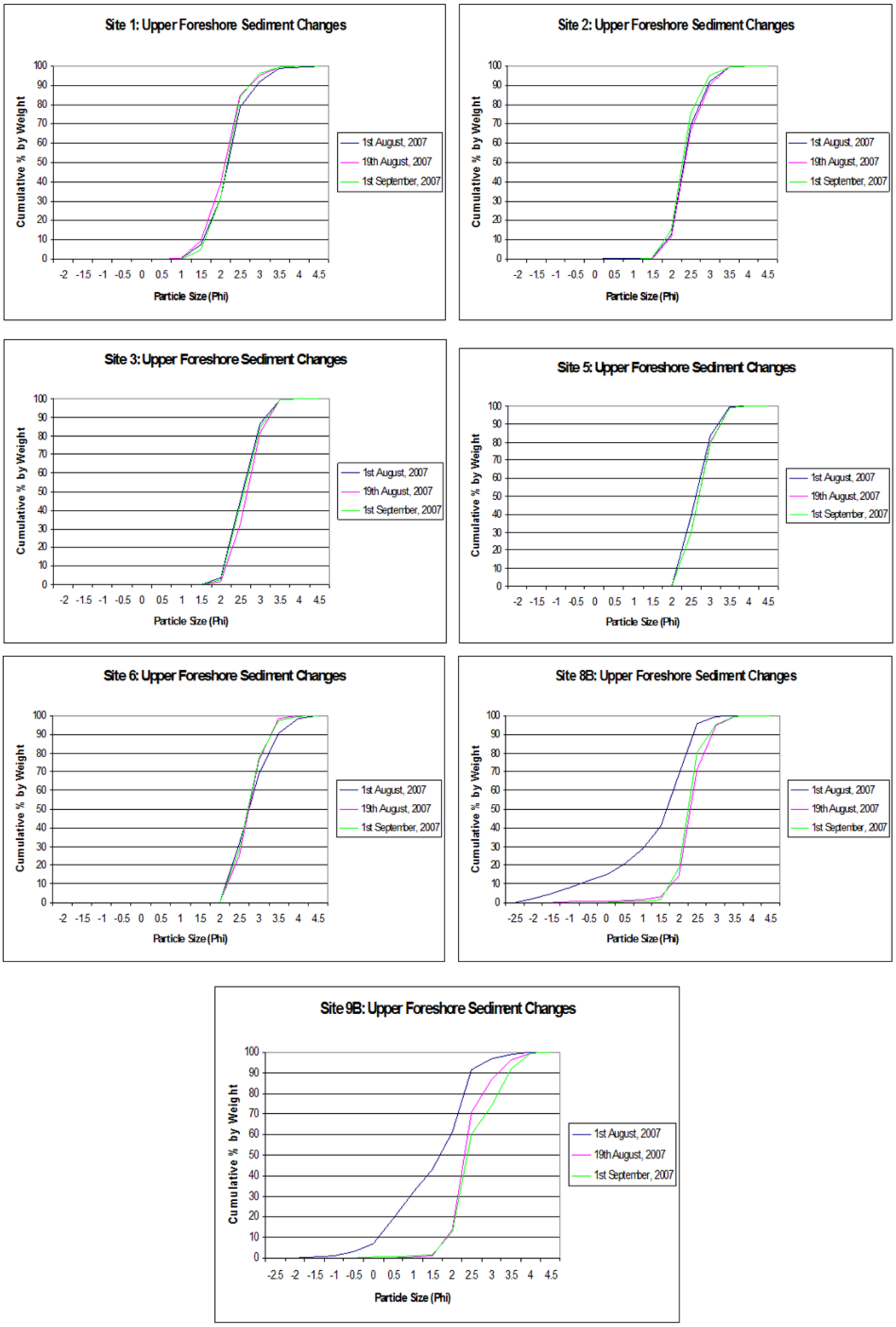
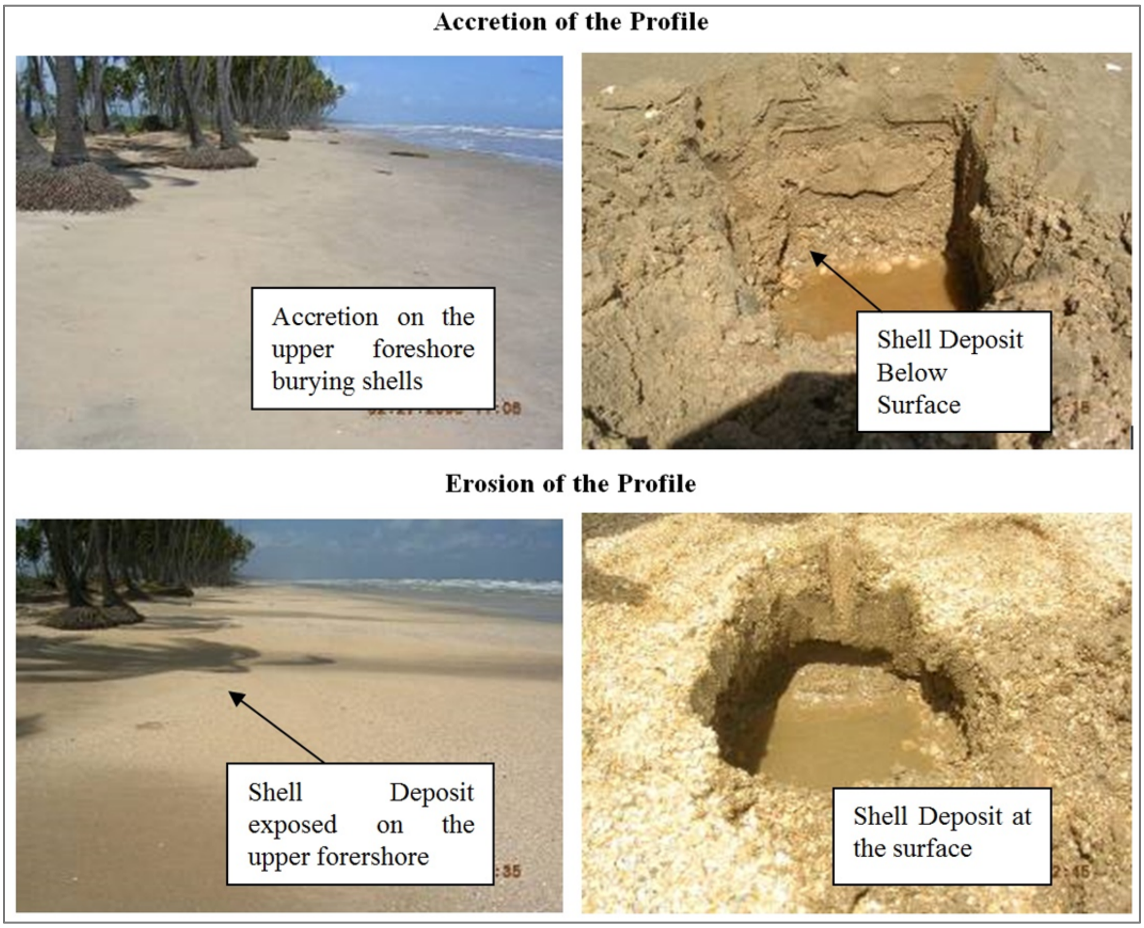


Figure 8. Upper foreshore sediment response to Hurricane Dean

5.5 Sediment Changes

The upper foreshore sediments at sites 1, 2, 3, 5 and 6 were not generally affected by the passage of Hurricane Dean's swell generated waves, despite the accretion that occurred on their respective upper foreshore regions. At site 8B, the sediment became finer after the hurricane as accretion buried most of the shells; while at site 9B the sediment became finer as the shells were removed by the hurricane's swell waves. In the recovery period, the sediment at sites 8B and 9B retained their new sediment characteristics (Figure 8 and Plate 2).

Plate 2. The burial and exposure of shell deposits on the upper foreshore at Site 8B



The lower foreshore sediments at sites 2, 3, 5, and 6 were also the least affected by the hurricane, despite the morphological changes seen on their respective lower foreshore regions. Site 1 experienced some fining as it became more of a mix of sediments and maintained this sediment characteristic after the event. This mix of sediment at site 1 was introduced by the outflow of the L'Ebranche River following the hurricane. Site 8B was not affected by the hurricane event; however in the days following and up to 1st September 2007, the sediment became fine as the shells in a trough were covered by sand eroded from the upper foreshore. Site 9B however, became substantially coarser just after the hurricane (with the deposition of shells that were removed from the upper foreshore). In the recovery period, the sediment at site 9B became fine again as a bar was accreting on the lower foreshore (Figure 9).

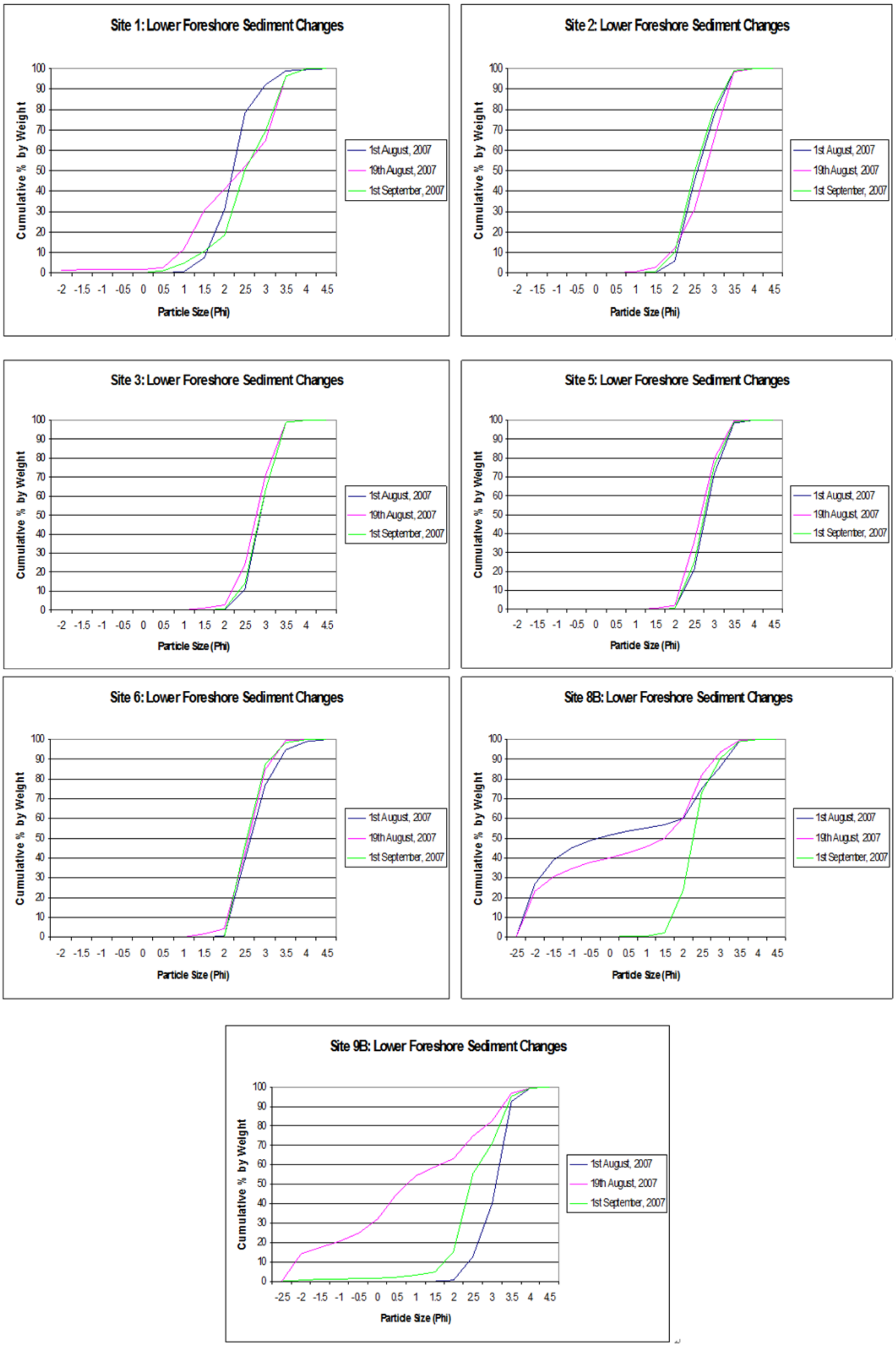


Figure 9. Lower foreshore sediment response to Hurricane Dean

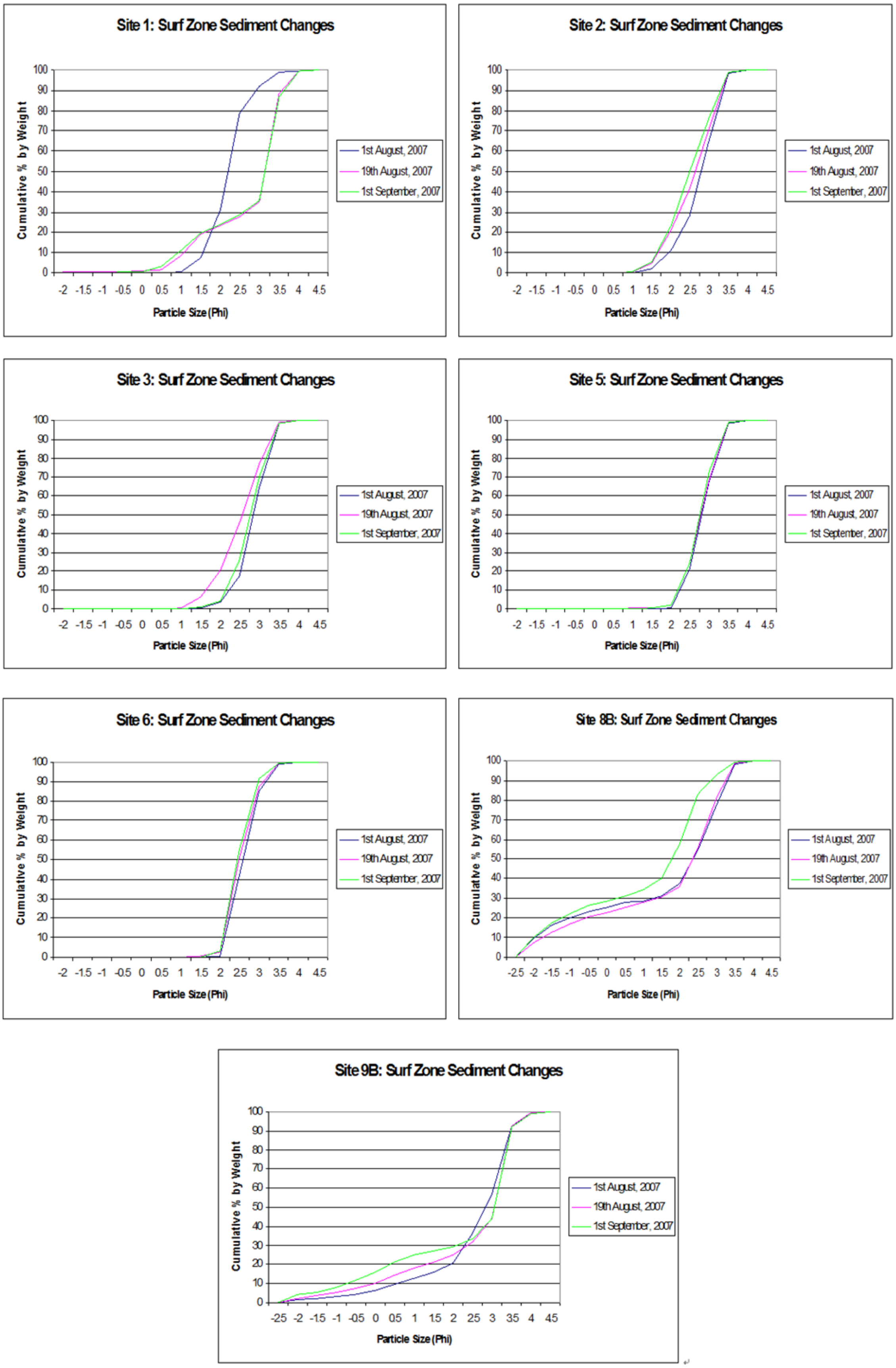


Figure 10. Surf zone sediment response to Hurricane Dean

The surf zone sediments at site 1 became fine after the hurricane but became more mixed (due to the influx of new sediment from the L'Ebranche River to the north), and maintained this new characteristic in the recovery period. Site 3 became coarser as the surf zone eroded, but changed back to its former sediment characteristics in the recovery period as the surf zone was repaired by accretion. Sites 2, 5 and 6 did not exhibit any changes in grain-size although their surf zones were undergoing radical changes due to the event. While the upper foreshore and lower foreshore sediments at site 8B and 9B were affected by the hurricane, the surf zone sediments were unaffected, despite the morphological changes observed in the surf zone (Figure 10).

6. Discussion

6.1 Littoral Processes and Beach Morphology

The coastal processes and mean beachface angles varied in their response to the passage of the hurricane. Since the hurricane did not make landfall, the observed changes to the coastal processes are due to the influence of local wind waves superimposed on the storm generated swells. The wave height and wave energy increased at sites 1, 5 and 8B, and this resulted in increased beachface angles at sites 1, 5 and 8B, which reflected the erosion that occurred on the lower foreshore regions at those sites (Figure 11).

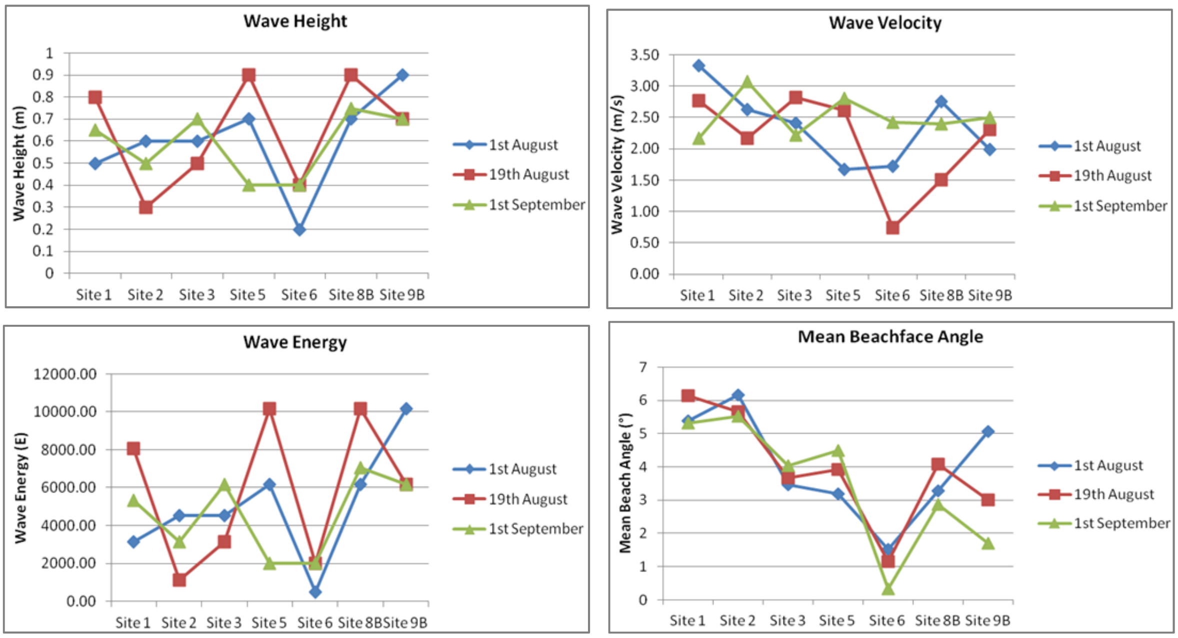


Figure 11. Coastal processes and beachface angles during Hurricane Dean

Using Pearson's Correlation on the coastal processes, a positive correlation existed between wave height and wave energy at a 0.01 significance level; as expected. There was however no correlation between mean beach angle and these coastal processes (wave height, wave velocity and wave energy). A linear regression test on the coastal processes variables and mean beach angles demonstrated that the only significant predictor of mean beach angle was wave energy, at a confidence level of 95%.

6.2 Beach Volume Changes

The passage of Hurricane Dean from the 13th to 23rd August 2007 had quantitatively varied effects on the beach volumes along Cocos Bay. On 19th August, sites 2, 3, 5, and 8B recorded negative beach volume changes as their respective profiles underwent erosion (Figure 12). However, sites 1, 6 and 9B experienced positive beach volume changes as accretion took place. This result is not surprising as sites 1, 6 and 9B were located in close proximity to the outflow of the three rivers that introduce sediment into Cocos Bay. It is possible that the sediment discharge from these rivers during the hurricane event may have been partially responsible for the accretion observed.

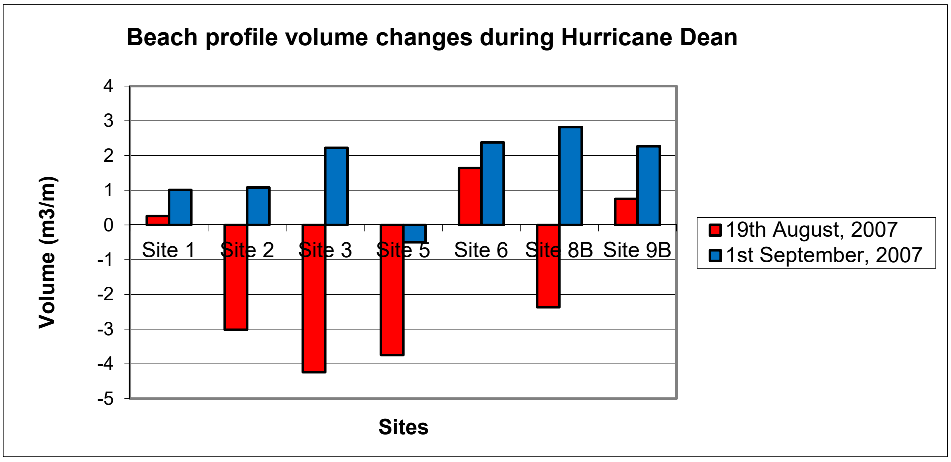


Figure 12. Beach volume changes during Hurricane Dean

Table 2. Showing beach volume changes during Hurricane Dean

Site	Hurricane 19th August, 2007 (m^3/m)	Recovery 1st September, 2007 (m^3/m)
Site 1	0.26	1.01
Site 2	-3.02	1.08
Site 3	-4.24	2.22
Site 5	-3.75	-0.50
Site 6	1.64	2.38
Site 8B	-2.37	2.82
Site 9B	0.75	2.27

Following the hurricane event, by 1st September 2007, the sites that eroded during the hurricane started to recover by recording positive beach volume changes. Site 5 only recorded negative volume changes during this event, as the shoreward migration of a bar continued after the hurricane where the location of the bar's trough on the beachface caused erosion. Sites 1, 6 and 9B experienced greater accretion in the recovery period due to continued sediment discharge from the rivers following the hurricane event (Table 2).

6.3 Relationship between Storms and Bar Migration

The passage of Hurricane Dean to the north of the island made an imprint on the beach profiles at Cocos Bay. The stronger swell waves generated by this event were able to force faster landward bar migrations, which aided in the accretion observed at some sites. At other sites, the position of the trough was evidenced by erosion on the profiles. The river flooding that occurred during the event may also have been responsible for the accretion observed at adjacent sites (sites 1 upper foreshore, sites 6 and 9B lower foreshore) due to sediment influx into the coastal system.

Under normal wave conditions, bar migrations that occurred from spring to neap tide took approximately 6 days to migrate a distance of 5 m (0.83 m/day) Site 6 experienced the most dramatic changes observed over the entire study period where the storm waves from Hurricane Dean were able to cause the landwards migration of an offshore bar by 50 m in 18 days (2.78 m/day) from 1st – 19th August 2007 (Figure 13). After the storm waves dissipated, the offshore bar continued migrating landwards though at a significantly slower rate; a distance of only 10 m in 13 days (0.77 m/day) from 19th August – 1st September 2007. In the previous year, from the 24th August to the 1st September 2006, Tropical Storm Ernesto passed through the Caribbean Sea just north of Grenada A similar trend was observed at site 6 with the passage of Tropical Storm Ernesto from 9th August to 8th September 2006, where the profile underwent substantial accretion due to landwards bar migration (Figure 13).

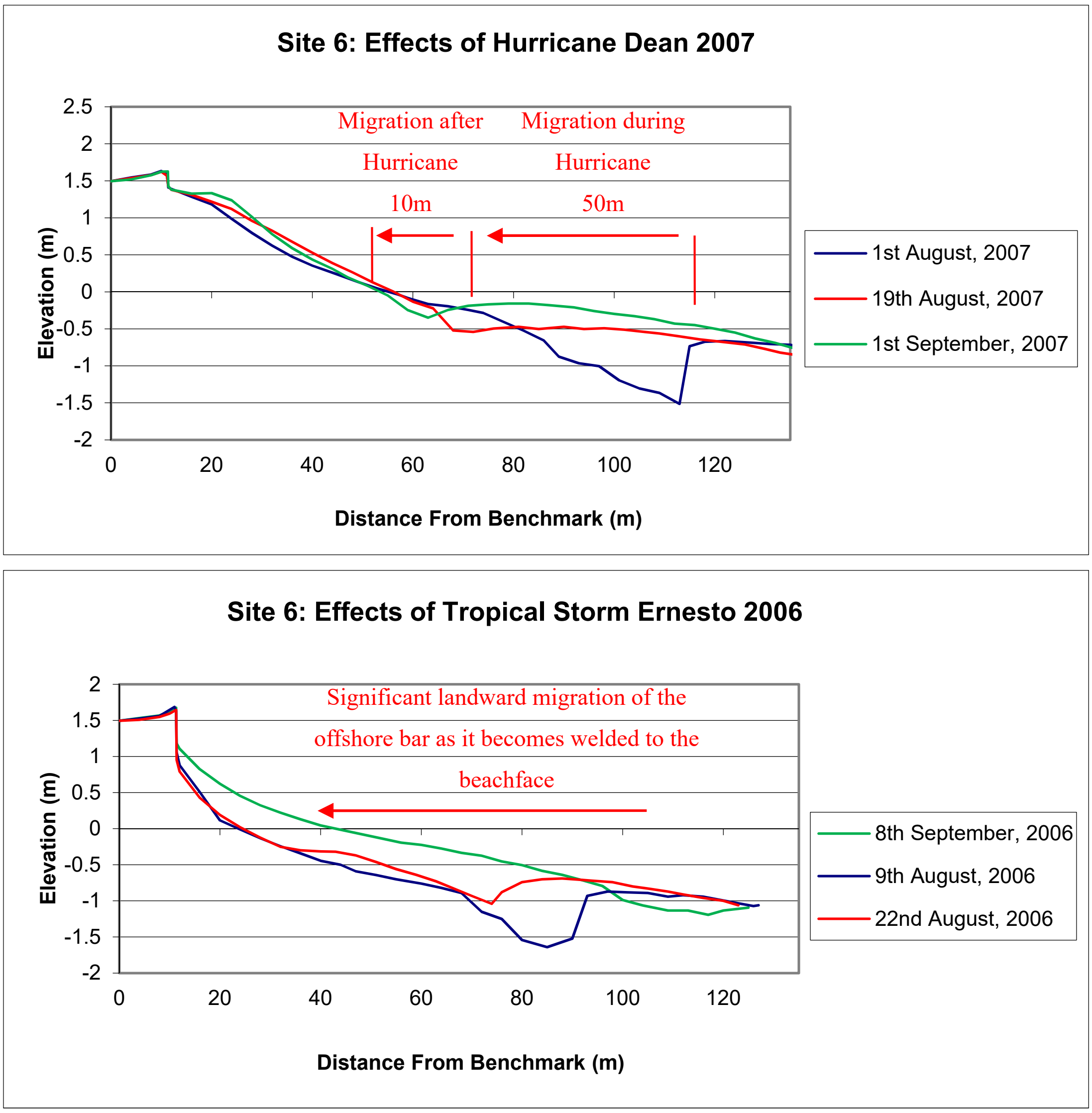


Figure 13. Enhanced bar migrations driven by storm activity

6.4 Sediment Response

King (1972) suggested that the causal link between sediment size and beach gradient lies in the percolation rates associated with different sediment sizes. The percolation rate will be greater in coarser-grained sediment. Krumbein and Graybill (1965) demonstrated that poor sorting resulted in less percolation and steeper profiles compared with well-sorted sediments of the same mean grain size. The sediment had variable responses to the hurricane event. In the upper foreshore, only sites 8B and 9B showed much variation to the event as the changes observed in the sediment from coarse to fine were a reflection of whether shells were buried or removed to the lower foreshore. In the lower foreshore, site 1 sediments changed to include a new mix of sediments which was supplied from the L'Ebranche River following the event. At sites 8B and 9B, their lower foreshore sediment changes were again as a result of the burial or accretion of shells. The surf zone sediments at sites 8B and 9B were not affected by the passage of the hurricane, as the same relative amounts of shells present before the event were also present following the hurricane. At Cocos Bay, coarser sediments (Bascom 1951) and poor sorting (Krumbein and Graybill 1965) produced steeper profiles.

In terms of sediment characteristics in response to morphological change, the most stable sites were sites 2, 3, 5, and 6 (i.e.; although their morphology changed, their sediment characteristics remained relatively unchanged). Sites 3, 5 and 6 were also the sites that appeared to be in a state of equilibrium over the entire study period. Most sediment changes occurred on the lower foreshore at the northern (site 1) and southern section (sites 8B and 9B) of the bay. To the north of the bay, the sediment changes were as a result of new sediment being deposited by the river following the hurricane, whereas to the south, the changes due to burial or exposure of shells.

Using Pearson's Correlation, there was a correlation between mean grain-size (phi) and the sorting of those sediments at a 0.01 significance level. Therefore as mean grain-sizes increases (as phi values decrease), sediments became less well sorted. There was also a moderate correlation between the mean beach angles and the sorting of the sediments at a 0.05 significance level; where a reduction in sorting resulted in steeper beach angles. A linear regression test on the sediment data and mean beach angles showed that the significant predictor of mean beach angle was sorting, at a confidence level of 95%. This means that as sorting decreases, beachface gradients increases because of slower percolation rates (Krumbein and Graybill 1965) and as sorting improves, beachface gradients decreases.

6.5 Future Implications

The 2005 Atlantic Hurricane Season was the most active in recorded history, with 28 storms, including 15 hurricanes; 7 of which were major hurricanes. The 2006 season was fairly inactive compared to the 2005 season. There was total of 10 storms, with 5 hurricanes; 2 of which were major hurricanes. In 2007, the season was fairly active with 15 storms, including 6 hurricanes; 2 of which were major hurricanes. While there have been no steady increases in the hurricane activity since 2005, most climate scientists agree that storm activity will increase gradually in the coming decades due to global warming (Anderson et al., 2010; IPCC 2007). Projected increased hurricane activity also increases the likelihood of a hurricane making landfall in Trinidad. IPCC predictions for sea level rise due to global warming poses similar threats to the area (Boer et al., 2001). Williams (2013) listed the implications for global warming and sea level rise as increased rate of landward migration of the barrier, decreased barrier width and elevation of barrier and sand dunes, increased frequency of storm overwash, increased frequency of barrier breaching and inlet formation and widening and segmentation of the barrier. Increased sea level rise of 5 mm/yr for the next 100 years and projected increased cyclonic activity in the region, would exacerbate the existing coastal erosion problems at this bay, which may lead to breaching of the barrier beach. Breaching of this barrier beach has implications for the ecology of the Nariva Swamp which provides habitat for numerous threatened species including the West Indian Manatee (Trichechus manatus) – currently registered as vulnerable under the IUCN Red List (Deutsch 2008).

7. Conclusions

The passage of Hurricane Dean has demonstrated that the sites along the bay respond differently to high energy events. Although the hurricane did not make landfall, it provided a unique opportunity to study the effects of the swells generated on the coastal system of an Atlantic Ocean exposed coastline. While the effects on smaller pocket beaches in the Caribbean have been well documented, this study provided some insight into the response of an open bay, high energy dissipative beach system just south of the main hurricane belt. It should also be noted that results presented are based on observations of just under 2 years of data collection from December 2005 to September 2007. This data was able to provide information on the state of the beach system prior to the passage of Hurricane Dean. While a longer dataset of hurricane passages would undoubtedly make the following conclusions more robust, the analysis has provided some understanding into the beach dynamics driven by the passage of an extreme event.

The sites that recorded negative volume changes during the hurricane event (either due to the battering of waves or trough development) started to recover after the hurricane. However, the sites located adjacent to the outflow of the three rivers (L'Ebranche, Nariva and Ortoire Rivers), experienced positive beach volume changes due to the input of new sediment from the river discharge that occurred during the event. It is important to note that the response of the beach to this high energy event varied spatially. The morphological response, whether erosion or accretion, was determined by the state of the beach prior to the event, and the morphological features present. Across the bay, this event was able to enhance bar formation and migration particularly in the surf zone and to a lesser extent on the lower foreshore. Where bars were present prior to the event, the hurricane forced faster landward bar migration which led to accretion either on the lower foreshore or upper foreshore regions as the bar became welded to the beachface. Landward bar migration (e.g. from the surf zone) was also responsible for some erosion recorded, particularly on the lower foreshore regions, as the troughs of the bars were areas that were topographically lower. In cases where bars did not exist, the hurricane was able to hasten the formation of bars, which subsequently generally dissipated in the recovery period, as the beach returned to its equilibrium profile. These findings are invaluable and could form the benchmark for other related studies in a region where global climate models forecast a future with increased and enhanced tropical cyclonic activity.

References

Andel, V. (1967). The Orinoco Delta. *Journal of Sedimentary Petrology, 37*(2), 297-310.

Anderson, J., Milliken, K., Wallace, D., Rodriguez, A., & Simms, A. (2010). Coastal impact underestimated from rapid sea-level rise. Eos. *Transactions American Geophysical Union, 91*(23), 205–206, http://dx.doi.org/10.1029/2010EO230001

Bacon, P. R., Kenny, J., Alkins, M., Mootoosingh, S., Ramcharan. E., & Seeberan. G. (1979). *Nariva Swamp Development Project: Studies on the biological resources of Nariva Swamp, Trinidad*. Occasional Papers 4. St. Augustine, Trinidad: University of the West Indies.

Barker, D., & Miller, D. (1990). Hurricane Gilbert: Anthropomorphizing a natural disaster. *Area, 22*(2), 107-116.

Bascom, W. N. (1951). The relationship between sand size and beach face slope. *Transactions of the American Geophysical Union,* 32, 866-874.

Bertrand, D., O'Brien-Delpesh, C., Gerald, L., & Romano, H. (1992). Coastlines of Trinidad and Tobago. A Coastal Stability Perspective. Institute of Marine Affairs, Hilltop Lane, Chaguaramas.

Bleuse, P., Soulan, A., Frayssinet, P., & Bleuse, N. (1995). 1995 l'annee de tous les cyclones, METEO France Ed., 39.

Blott, S. J., & K. Pye. (2001). GRADISTAT: A grain size distribution and statistics package for the analysis of unconsolidated sediment. *Earth Surface Processes and Landforms*, *26*(11), 1237-1248

Boer, J. G., Stouffer, R. J., Dix, M., Noda, A., Senior, C. A., Raper, S., & Yap, K. S. (2001). IPCC Third Assessment Report - Climate Change 2001, Chpt. 9. Projections of Climate Change.

Carter, R. W. G. (1991). *Coastal Environments*, Academic Press Ltd., London.

Coch, N. K. (1995). *Geohazards Natural and Human*, Prentice Hall, Englewood Cliffs, New Jersey, 481p.

Darsan, J. (2005). A comparative study of the coastal geomorphology of Cocos Bay and Las Cuevas Bay, Trinidad. *Caribbean Geography, 14*(2), 116-132.

Darsan, J. (2012). An analysis of the coastal geomorphology and evolution of Cocos Bay, Trinidad. Unpublished PhD Thesis, University of the West Indies, St Augustine.

Darsan, J., Ramnath, S., & Alexis, C. (2012). *Status of beaches and bays in Trinidad 2004-2008, Technical Report.* Institute of Marine Affairs, Hilltop Lane, Chaguaramas, pp 214.

Darsan, J., Asmath, H., & Jehu, A. (2013). Flood-risk Mapping for Storm Surge and Tsunami at Cocos Bay (Manzanilla), Trinidad. *Journal of Coastal Conservation, 17*(3), 679-689 http://link.springer.com/article/10.1007/s11852-013-0276-x

Dyer, K. R. (1986). *Coastal and Estuaries Sediment Dynamics.* New York: John Wiley and Sons.

Dean, C., Thom, M., & Edmunds, H. (1973). Eastern Caribbean coastal investigations (1970-1973). *British Development Division in the Caribbean, 11*, pp 79.

Deutsch, C. J., Self-Sullivan, C., & Mignucci-Giannoni, A. (2008). *Trichechus manatus*. In: IUCN 2012. IUCN Red List of Threatened Species. Version 2012.2. Retrieved February 26, 2013 from www.iucnredlist.org

Durand, F. (1996). Hydrodynamique sedimentaire sur le plateau insulaire de la Martinque, These Universite de Bordeauz, 1, 214.

Environmental Management Authority. (2001). *Background paper: Climate change vulnerability assessment for Nariva Swamp*. Port of Spain.

Eyre, L. A. (1989). Hurricane Gilbert: Caribbean record breaker. *Weather, 44*, 160-64.

Folk, R. L., & Ward, W. C. (1957). Brazos river basin: A study in the significance of grain size parameter. *Journal of Sedimentary Petrology, 27,* 3-27.

Farris, A. S., & List, J. H. (2007). Shoreline Change as a Proxy for Subaerial Beach Volume Change. *Journal of Coastal Research, 23*(3), 740-748.

Gardner, T. A., Cote, I. M., Gill, J. A., Grant, A., & Watkinson, A. R. (2005). Hurricanes and Caribbean coral reefs: impacts, recovery patterns, and role in long-term decline. *Ecology, 86*(1), 174-184.

Georges, C. (1983). A coastal classification for Trinidad. Institute of Marine Affairs, Hilltop Lane, Chaguaramas.

Goudie, A., Anderson, M., Burt, T., Lewin, J., Richards, K., Whally, B., & Worsely, P. (1990). Geomorphological

Techniques. Routledge, p.570.

Hardisty, J. (1990). *Beaches: Form and process.* London: Unwin Hyman.

IPCC (Intergovernmental Panel on Climate Change) (2007). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom: Cambridge University Press, p. 996.

King, C. A. M. (1972). *Beaches and coasts*. London: Edward Arnold (Publishers) Ltd.

Komar, P. D. (1976). *Beach processes and sedimentation*. New Jersey: Prentice Hall.

Krumbein, W. C., & Graybill, F. A. (1965). *An introduction to statistical methods in geology*. New York: McGraw Hill.

Michener, W. K., Blood, E. R., Bildstein, K. L., Brinson, M. M., & Gardner, L. R. (1997). Climate change, hurricanes and tropical storms and rising sea level in coastal wetlands. *Ecological Applications, 7*(3), 770-801.

National Data Buoy Centre. (2007). Reports from the National Data Buoy Center's Stations During the Passage of Hurricane Dean 13-23rd August, 2007. Retrieved June 26, 2014, from http://www.ndbc.noaa.gov/hurricanes/2007/dean/

National Hurricane Center (2008). Tropical Cyclone Report, Hurricane Dean 13-23rd August, 2007. Retrieved August 26, 2008, from http://www.nhc.noaa.gov/ms-word/TCR-AL042007_Dean.doc

Pagney, F. (1992). Les Antilles francaises, des iles sous triple hypotheque: sismique, volcanique et cyclonique. *Historiens-Geographes, 335,* 361-377.

Reeve, D., Chadwick, A., & Fleming, C. (2004). *Coastal Engineering: Processes, Theory and Design Practice*: Spon Press, p. 461.

Schneider, C. (1981). The Littoral Environment Observation (LEO) Data Collection Programme. Vicksburg, Mississippi: U.S. Army Engineering Research Centre, Coastal Engineering Technical Aid No. 85-5.

Singh, B. (1997). Climate-related global changes in the southern Caribbean: Trinidad and Tobago. *Global and Planetery Change, 15*, 93-111.

Trinidad & Tobago Meterological Service (2007). The impact of the 2007 Hurricane Season Operations for T&T". Synoptic Branch Piarco International Airport, Piarco, Trinidad. Retrieved August 18, 2008, from http://www.wmo.int/pages/prog/www/tcp/Meetings/HC30/documents/TrinidadandTobago.pdf

Williams, P. (2000) Station descriptions for cross-sections along the east coast of Trinidad. In NEDECO and Delft Hydraulics (2000). *Feasibility Study and Detailed Design for Coastal Protection Works, Trinidad.* Trinidad: Government of Trinidad and Tobago Ministry of Works and Transportation Drainage Division.

Williams, S. J. (2013). Sea-level rise implications for coastal regions. *Journal of Coastal Research Special Issue, 63*, 184-186.

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