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Storm Impact Scale for Barrier Islands

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ABSTRACT

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A new scale is proposed that categorizes impacts to natural barrier islands resulting from tropical and extra-tropical storms. The proposed scale is fundamentally different than existing storm-related scales in that the coupling between forcing processes and the geometry of the coast is explicitly included. Four regimes, representing different levels of impact, are defined. Within each regime, patterns and relative magnitudes of net erosion and accretion are argued to be unique. The borders between regimes represent thresholds defining where processes and magnitudes of impacts change dramatically.

Impact level 1 is the 'swash' regime describing a storm where runup is confined to the foreshore. The foreshore typically erodes during the storm and recovers following the storm; hence, there is no net change. *Impact level 2* is the 'collision' regime describing a storm where the wave runup exceeds the threshold of the base of the foredune ridge. Swash impacts the dune forcing net erosion. *Impact level 3* is the 'overwash' regime describing a storm where wave runup overtops the berm or, if present, the foredune ridge. The associated net landward sand transport contributes to net migration of the barrier landward. *Impact level 4* is the 'inundation' regime describing a storm where the storm surge is sufficient to completely and continuously submerge the barrier island. Sand undergoes net landward transport over the barrier island; limited evidence suggests the quantities and distance of transport are much greater than what occurs during the 'overwash' regime.

ADDITIONAL INDEX WORDS: *Tropical storms, extra-tropical storms, swash, sand transport.*

INTRODUCTION

The impact of a storm on a barrier island is dependent not only on the magnitude of storm forced parameters, such as storm surge, waves and wave runup, but is also dependent upon the geometry, particularly the vertical dimension, of the barrier island at landfall. By considering the magnitude of storm parameters relative to coastal dimensions, a new scale is developed that categorizes storm-induced patterns and magnitudes of net erosion and accretion on barrier islands. This proposed scale is fundamentally different than existing storm related scales, such as Saffir-Simpson for hurricanes and Dolan-Davis for extra-tropical 'northeasters' which are based on storm, and storm-forced, parameters such as wind speed and wave height (SAFFIR, 1977; SIMPSON, 1971; DOLAN and DAVIS, 1992, 1994). These existing scales, although quite useful in categorizing the strength of an approaching storm, have limited skill in scaling the ensuing geologic impacts to different coastal environments.

Consider, for example, two barrier islands that represent end members of relief among the barriers that comprise nearly all of the United States' mid- and southeast Atlantic and Gulf of Mexico coasts. The Isles Dernieres in coastal Louisiana are extremely lowlying rising only 1.5 m above mean sea level (MSL) whereas, the Outer Banks of North Carolina at Duck have a foredune ridge that is 5 times higher (Figures 1 and 2). As a consequence, the Isles Dernieres are overwashed by the combination of storm surge and wave runup during typical cold fronts several, or more, times per year (RICHIE and PENLAND, 1985, 1988). In contrast, a similar winter storm on the Atlantic seaboard would not generate conditions sufficient to overwash the foredune ridge at Duck (For example, see beach profile changes at Duck for a typical winter storm in SALLENGER, *et al.,* 1985). In fact, even though exposed to several hurricanes and numerous severe extratropical storms, the Duck area has not experienced extensive overwash for 36 years, *i.e.* not since the Ash Wednesday Storm of March 1962, one of the most severe storms to strike the Eastern Seaboard in recorded history (STEWART, 1962; DOLAN and DAVIS, 1992, 1994).

The variable impacts observed at the Isles Dernieres and Duck are explicitly accounted for in the proposed scale which is based on the elevation of storm wave runup relative to the elevation of critical geomorphic features on barrier islands. Four regimes are defined. Within each, net sand-transport directions and processes are argued to be unique. The borders between regimes represent thresholds where processes and magnitudes of impacts change dramatically. The proposed scale applies to natural barrier islands subjected to both tropical and extra-tropical storms, and provides a new framework to forecast the impact of a storm prior to its landfall.

First, we discuss methods for estimating storm wave runup and define critical measures of barrier island topography. Second, we discuss how the elevation of runup relative to the elevations of a barrier island can be used to establish a

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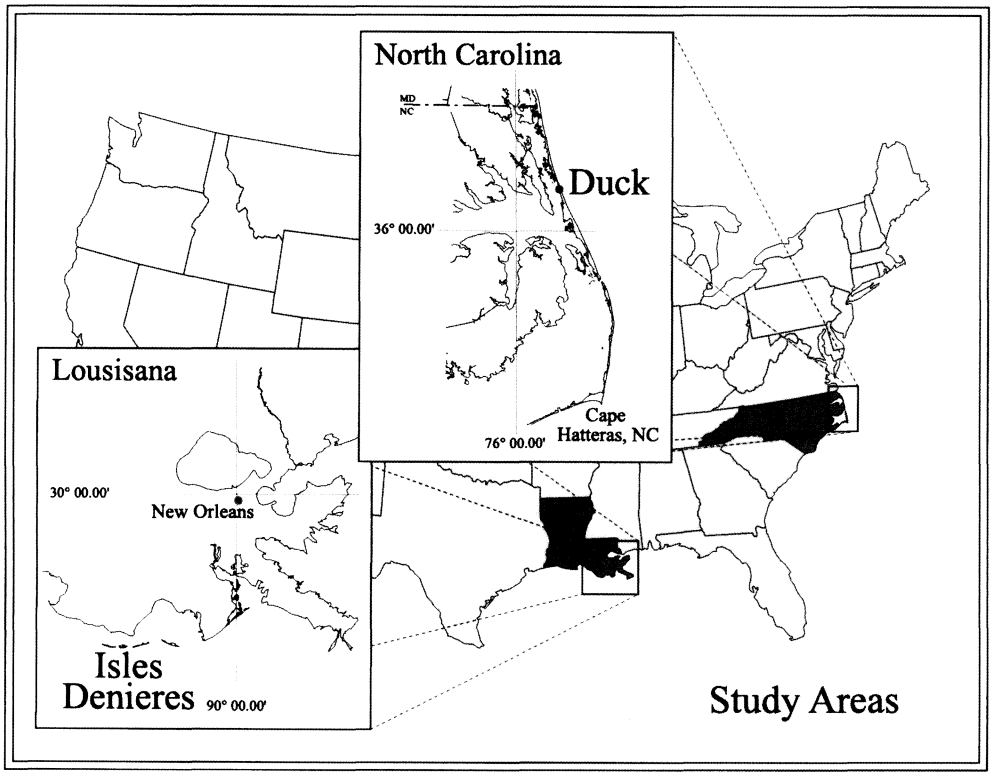

Figure 1. Locations of the compared study sites: Duck, NC and Isles Dernieres, LA.

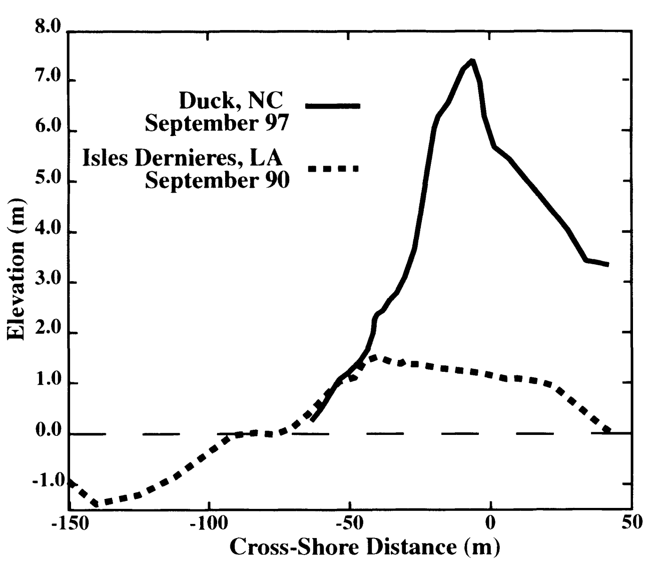

Figure 2. Comparison of a beach profile from the Outer Banks of North Carolina at Duck to a profile from coastal Louisiana at the Isles Dernieres. (Locations are shown in Fig. 1). At the Isles Dernieres, no foredune ridge was present hence D_{HIGH} (see Fig. 3) was evaluated as the elevation of the berm crest, approximately 1.5 m. In contrast, at Duck, a well developed foredune ridge was present whose elevation was five times greater than the berm at Isles Dernieres.

unique scaling for storm impacts. Next, in the discussion section, we discuss how the scaling might be used to interpret storm impacts both between barriers and along barrier islands of variable topography.

DEFINITION OF PARAMETERS

Consider the part of a barrier island that is subaerial under non-storm conditions and how it changes during storms through water-borne sand transport perpendicular to the shoreline. Take R_{HIGH} and R_{LOW} to be representative high and low elevations of the landward margin of swash relative to a fixed vertical datum (Figure 3). (The fixed datum should be lower than the R and D parameters defined here.) R_{HIGH} and R_{LOW} include the elevation due to astronomical tides and storm surge as well as the vertical height of wave runup. R_{LOW} represents the elevation below which the beach is continuously subaqueous.

In this paper, R_{HIGH} and R_{LOW} are calculated with empirical relationships (using data in Table 1). Using data from Duck, North Carolina, HOLMAN (1986) found the 2% exceedence of runup, which includes both swash height and wave setup, as

$$R_{2\%} = H_o(0.83\xi_o + 0.2) \quad (1)$$

The Iribarren number $\xi_o = \beta/(H_o/L_o)^{1/2}$ where β is local beach slope, H_o is deep water significant wave height, and L_o is deep water wavelength. Hence, a representative 'high' runup elevation, that is the 2% exceedence runup elevation is

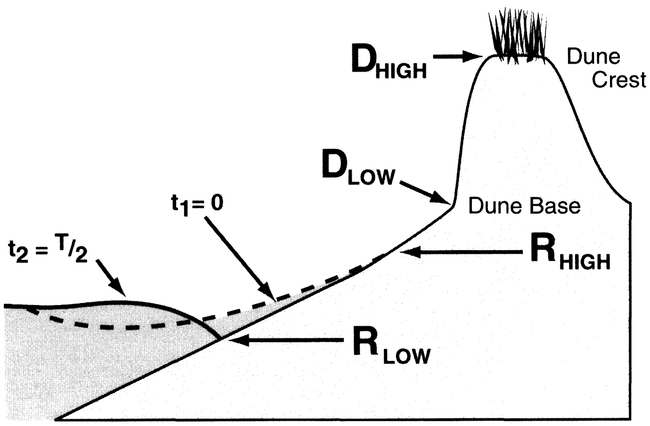

Figure 3. Definition sketch describing variables used in scaling the impact of storms on barrier islands.

$$R_{HIGH} = R_{2\%} + \eta_{mean} \quad (2)$$

where η_{mean} is mean sea level obtained, for example, from a tide gauge and includes both astonomical tides and storm surge. The 2% exceedence swash amplitude has been found by HOLMAN (1986) to be

$$S_{2\%} = H_o(0.85\xi_o + 0.06) \quad (3)$$

Hence, a representative 'low' runup elevation below which the beach is, for the most part, continuously subaqueous is

$$R_{LOW} = R_{HIGH} - S_{2\%} \quad (4)$$

Take D_{HIGH} to be the elevation, relative to the fixed datum, of the highest part of the 'first line of defense' of the barrier beach, *i.e.* the elevation of the foredune ridge (illustrated in Figure 3) or, if a foredune is not present, the elevation of the crest of the beach berm. (See, for example, the berm profile of the Isles Dernieres in Figure 2.) On beaches where there is a foredune ridge, D_{LOW} is the elevation of the base of the dune (Fig. 3). For the geometry discussed here, in the absence of a foredune ridge $D_{LOW} = D_{HIGH}$.

PROPOSED SCALE

By considering how both R_{HIGH} and R_{LOW} vary relative to D_{HIGH} and D_{LOW}, a series of storm impact regimes can be objectively defined (Figure 4A; Table 2).

Swash Regime

First, the 'swash regime' is the condition, during a storm, where swash is confined to the foreshore of the beach seaward of the dune or berm crest and R_{HIGH}/D_{HIGH} is less than the critical threshold defined by

$$R_{HIGH}/D_{HIGH} = D_{LOW}/D_{HIGH} \quad (5)$$

(Figure 4A; Table 2). Under these storm conditions, it is well known that the beach foreshore erodes and sand is transported offshore where it is deposited, only to be returned to the beach following the storm under more quiescent conditions over weeks or months (*e.g.* SHEPARD, 1950; BASCOM, 1953). Hence, when time averaged over the complete storm-erosion/post-storm-recovery period, such a response is the manifestation of a cross-shore transport system where there is no net change to the beach. The typical winter storm at Duck (discussed above) falls in the 'swash regime' with the expected storm erosion of the foreshore and complete post-storm recovery (Figure 4B).

Collision Regime

On beaches where there is a foredune ridge, as R_{HIGH} increases, runup will eventually collide with the base of the dune forcing dune erosion (SHIH and KOMAR, 1994; SHIH *et al.*, 1994; RUGGIERO *et al.*, 1996). This 'collision regime' occurs when the critical threshold of Equation 5 is exceeded (Figure 4A; Table 2). The eroded sand is transported offshore (or longshore) and, in contrast to the 'swash regime', does not typically return to re-establish the dune. Hence, in general,

Table 1. *Estimated values of variables used in calculations shown in Figure 4B.*

Storm	Location	D_{HIGH}[1]	D_{LOW}[1]	Ho	T	Surge + Tide[1]
Hurricane Andrew, 8/25–26/92	Isles Dernieres, LA	1.5	1.5	9.1[2]	10.7[2]	2.2[3]
Typical winter storm	Isles Dernieres, LA	1.5	1.5	2.5[4]	7[4]	0.8[5]
Ash Wednesday storm, 3/5–8/1962	Duck, NC	7.3	3.4	9.1[6]	12.0[7]	2.7[8]
Typical winter storm	Duck, NC	7.3	3.4	2.5[4]	7[4]	1.2[5]

[1] Elevations are referenced to mean sea level. For Isles Dernieres, D was estimated from the profile in Figure 1 whereas for Duck, measures of D are averages taken from 58 cross-shore profiles 20 m apart derived from airborne scanning laser telemetry acquired in September 1997; [2] DiMarco et al. (1995); [3] Halford (1995); [4] Characteristics of a typical winter storm similar to that examined in Sallenger et al (1985) at Duck; [5] Assumed storm surge of typical storm at both locations was 0.6 m (although for the same forcing Isles Dernieres may be somewhat greater because of the more gentle offshore slope). Assumed storm hit at mean higher high water (MHHW) at both locations, hence 'Surge + Tide' at Duck is higher because of the larger tidal range. [6] Dolan and Davis (1992); [7] Using wave height and duration from Dolan and Davis (1992), estimated T from deep water wind wave generation relationships. [8] Dolan and Davis (1994) reported a 'maximum' surge for class 5 northeasters of 2.2 m. This was added to the elevation of MHHW. The latter is an underestimate since the storm occurred during perigean tides.

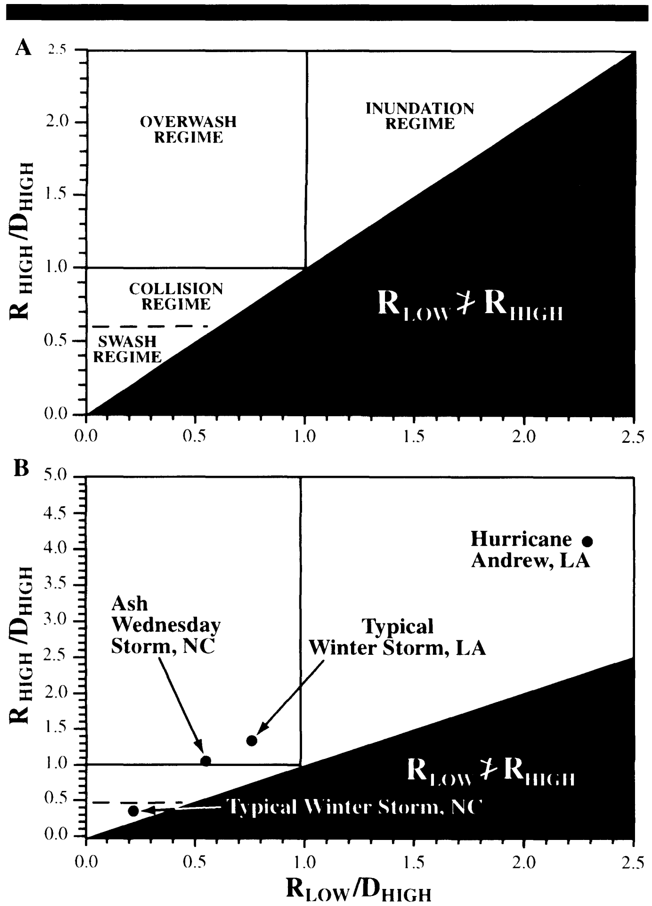

Figure 4. A. Delineation of four different regimes important to categorizing storm impacts on barrier islands. Note that R_{LOW} cannot be greater than R_{HIGH}, hence the indeterminate part of the plot. The threshold between 'swash' and 'collision' regimes is dashed because it's value $R_{HIGH}/D_{HIGH} = D_{LOW}/D_{HIGH}$ is dependent on specific beach dimensions whereas all other thresholds are unique. For the purposes of these plots, the threshold dividing 'swash' and 'collision' regimes calculated from the profile from Duck (Fig. 1) is plotted. B. Characteristics of storms discussed in this paper are plotted using available information. The data used are provided in Table 1.

for a storm where the threshold expressed in Equation 5 is exceeded, the foredune ridge undergoes net erosion. In addition to net erosion of the dune, the foreshore of the beach likely undergoes the same types of changes considered as part of the 'swash regime'.

Overwash Regime

As R_{HIGH} continues to increase, overwash, or overtopping of the dune or berm crest, occurs when $R_{HIGH} > D_{HIGH}$, hence the critical threshold

$$R_{HIGH}/D_{HIGH} = 1 \quad (6)$$

defines the difference between the 'collision regime' ($R_{HIGH}/D_{HIGH} < 1$) and an 'overwash regime' ($R_{HIGH}/D_{HIGH} > 1$) (Figure 4A; Table 2). Note that in the absence of a dune ridge, $D_{HIGH} = D_{LOW}$ and Equation 5 = Equation 6. Hence, under these conditions, there is no 'collision regime' and Equation 6 defines the difference between the 'swash regime' and an 'overwash regime'.

As discussed above, the lowlying Isles Dernieres are easily overwashed and fall into the 'overwash regime' even for a typical winter storm (Figure 4B). In contrast, the same winter storm impacting Duck is classified as 'swash regime'. Note also that the Ash Wednesday storm impact at Duck scales as the 'overwash regime', the same as the typical storm at Isles Dernieres.

In the overwash regime, as runup overtops the dune (or berm crest), water can flow landward at speeds measured in excess of 2 m/s decelerating with distance landward (FISHER *et al.,* 1974; HOLLAND *et al.,* 1991). This gradient in flow leads to erosion of the dune (or foreshore) and deposition farther landward. For a minor event at the Isles Denieres, sand deposited by overwash extends landward of the dune crest typically tens of meters. During the Ash Wednesday storm on the Outer Banks of North Carolina, overwash deposits extended landward hundreds of meters (DOLAN and HAYDEN, 1981). Observations by LEATHERMAN (1979) at Assateague Island, Maryland, Virginia indicate roughly the same range of landward penetration of overwash.

The sand that undergoes net landward transport over the dune crest as part of the 'overwash regime' is not readily returned seaward to the beach under post-storm conditions. Hence, when time averaged within a fixed spatial frame of reference, this overwash leads to migration of the barrier beach landward (LEATHERMAN, 1979). Of course, other processes, *e.g.* eolian transport, can be locally important and return overwashed sand to the beach foreshore mitigating barrier migration (LEATHERMAN, 1979; DINGLER *et al.,* 1992). However, in general, the overwash process contributes to a barrier island's net landward migration.

Inundation Regime

When the storm-induced sea level rise is sufficient to completely submerge a barrier island, the flows over the barrier are no longer simple overwash. Rather, the once subaerial part of the barrier island becomes impacted directly by surfzone processes. The threshold for this 'inundation regime' is

$$R_{LOW}/D_{HIGH} = 1 \quad (7)$$

(Figure 4A; Table 2). Whereas the overwash process seems at least conceptually understood, when beaches become completely subaqueous during a severe storm the processes are not so clear. One example for the impact of a storm in the 'inundation regime' is that of Hurricane Andrew on the Isles Dernieres (Figure 4B). Before and after beach profiles and aerial photographs show that, in contrast to the 'overwash regime', in many places on the Isles Dernieres the beaches were completely denuded of sand leaving a marsh outcrop behind (DINGLER and REISS, 1995). Evidence suggests that the eroded sand underwent a net landward transport. For example, a spit, several kilometers long was nearly completely eroded away (PENLAND *et al., in press*). In post-Andrew photography, a sand body that appeared to be a remnant of the eroded spit could be detected a kilometer landward. Similar changes have been observed in comparisons of bathym-

Table 2. *Storm Impact Scale for Barrier Islands.*

Impact Level	Range of R_{HIGH}/D_{HIGH} and R_{LOW}/D_{HIGH}	Regimes and Predictions of Beach Changes
1	R_{HIGH}/D_{HIGH} = 0 to D_{LOW}/D_{HIGH}	SWASH REGIME: • Runup is confined to the foreshore of the beach. • During storms, the foreshore typically erodes and sand is transported offshore. • Following the storm, sand is transported onshore gradually, over weeks to months. Hence, the eroded sand is replaced and there is little net change to the beach.
2*	R_{HIGH}/D_{HIGH} = D_{LOW}/D_{HIGH} to 1	COLLISION REGIME: • Runup collides with the base of the foredune ridge (if no foredune is present see note, *, below). • The collision forces sand to be eroded from the dune and transported offshore (&/or longshore). • Eroded dune sand is not readily returned to the dune, hence there is net erosion (relative to Impact Level 1).
3	$R_{HIGH}/D_{HIGH} > 1$ and $R_{LOW}/D_{HIGH} < 1$	OVERWASH REGIME: • Runup exceeds the elevation of the 'first line of defense', either dune ridge or, if dune is not present, the berm crest. • Sand is transported landward (tens to hundreds of meters) contributing to the net migration of the barrier beach landward (i.e. there is net erosion of the beach foreshore & net deposition landward of dune).
4	$R_{HIGH}/D_{HIGH} > 1$ and $R_{LOW}/D_{HIGH} > 1$	INUNDATION REGIME: • Elevation of the base of swash motion, R_{LOW}, exceeds the elevation of the 'first line of defense', D_{HIGH}, hence the entire beach/foredune ridge system is continuously subaqueous; • Limited observations suggest that massive net onshore transport occurs with landward migration of sand bodies on the order of 1 km.

* If no dune ridge is present, $D_{LOW} = D_{HIGH}$, and there is no Impact Level 2. Hence, as R_{HIGH}/D_{HIGH} increases from zero, a beach with no dune ridge will first experience the 'swash regime' followed in sequence by the 'overwash' and 'inundation regimes'.

etry in the vicinity of Isles Dernieres obtained prior to and following the impact of Hurricane Andrew (LIST *et al.,* 1997). Hence, this limited database suggests massive onshore transport of sand at scales on the order of a kilometer, an order of magnitude greater than scales observed for the 'overwash regime'.

To refine and expand this characterization of the 'inundation regime', more observations are needed. Research might best be focused on barriers with small D_{HIGH} where the threshold in Equation 7 is more likely to be exceeded relative to a location like Duck where Equation 7 has not been exceeded in recorded history.

IMPACT LEVELS

Associated with each of the four regimes discussed above is an impact level that increases from 1 to 4 with increasing R_{HIGH}/D_{HIGH} (Table 2). Where the storm forcing and coastal geometry are known, this proposed scale can be used to categorize and forecast potential impacts identified with each regime. As a practical consideration, forecasts made as a storm approaches the coast would be based upon the prestorm coastal geometry yet, in reality, the geometry can change during a storm which could in turn change the impact level. Hence, forecasts would be relevant to the initial impact of a storm, when geometry has not changed appreciably, and are valid as the storm progresses, as long as D_{HIGH} does not change to the extent that a new threshold is exceeded. If a new threshold is exceeded, as a result of a storm of long duration or a geometry conducive to complete dune erosion (*e.g.* a narrow dune ridge), the result will be an increased impact level. For example, if an Impact Level 2 storm persists to the extent that the dune is completely eroded away, D_{HIGH} will decrease such that the threshold in Equation 6 is exceeded initiating the 'overwash regime' of Impact Level 3.

DISCUSSION

Given sufficiently accurate and densely spaced topographic data, the proposed scale should be useful in describing variable impacts that would occur to a barrier island where D_{HIGH} varies considerably along its extent. For example, it is common to find a barrier island with large foredune ridges on one part of the island and with small D_{HIGH} on other another part. Whereas the large dunes may, for a given storm, limit the impact regime to 'swash' or 'collision', the low areas may locally enter the 'inundation regime' where temporary inlets form. It is well known that temporary inlets that open during storms are associated with significant landward transport and development of sand bodies commonly referred to as flood-tidal delta deposits (PIERCE, 1969; GODFREY and GODFREY, 1973; LEATHERMAN, 1979). The magnitude and cross-shore scale of this transport is much greater than overwash and is similar to what is discussed above for the 'inundation regime' except that it occurs locally rather than extensively along the barrier's length. A number of investigators have argued that the landward sediment transport associated with inlet formation during storms contributes more than overwash to the net migration of barrier islands landward (PIERCE, 1969; GODFREY and GODFREY, 1973; LEATHERMAN, 1979).

In order to implement the use of the proposed scale, estimates must be made of D. Accurate and densely spaced topographic data over regional scales to estimate D_{HIGH} and D_{LOW} are rare and difficult to acquire. Recently, however, airborne scanning laser altimetry has been used to map the topography of coasts and other terrain over regional scales with vertical accuracies of 10 cm and outstanding spatial coverage (*e.g.* KRABILL *et al.,* 1995; SALLENGER *et al.,* 1999). In fact, much of the mid-Atlantic coast of the U.S. has now been mapped with laser altimetry. See initial results of NASA, NOAA, USGS cooperative mapping of beaches at:

http://coastal.er.usgs.gov/hurricanes/

As more data like these become available, our ability to determine D_{HIGH} and D_{LOW} will facilitate the application of the proposed scale to categorizing and forecasting storm impacts to barrier island coasts.

SUMMARY

A new scale is proposed describing the impact of storms on barrier islands. The new scale differs from previous scales by explicitly including the topography of the coast relative to forcing processes. Four impact regimes are defined each representing a unique suite of processes and of magnitudes of impact. The scale can be used to describe, and potentially forecast, the relative impact of a storm as it approaches a particular reach of coast.

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