

# Trade Wind Intensification and Hurricanes on a Caribbean Beach, Martinique Island: A Comparison of their Morphological Impacts from Field Experiments and Numerical Simulations

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## ABSTRACT

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The impacts of Trade Wind intensification and moderate hurricanes on beach sediment balance have been analysed from a study of time variations of the sediment volume of Bagasse Beach and its shoreface, on the island of Martinique (French West Indies). Field experiments (wave characteristics, longshore current velocity, bathymetric and topographic surveys) conducted at different time scales show a negative dry season sediment budget and a slightly positive annual budget for this microtidal beach. Volumetric variations computed for one day of Trade Wind intensification appear to represent about twice those for one dry season. This analysis reveals that the influence of moderate hurricanes (coastal wave heights less than 2.5 m) on the long-term (2 yr) sediment balance is weak.

In order to compare these high-energy events, numerical simulations have been carried out. Comparison between moderate hurricane conditions and a Trade Wind intensification event shows that the latter is responsible for more important volumetric erosion by about 23%. At a daily scale, moderate hurricanes have a larger power of erosion, 40 m<sup>3</sup> m<sup>-1</sup> day<sup>-1</sup> versus 28 m<sup>3</sup> m<sup>-1</sup> day<sup>-1</sup> for a Trade Wind intensification event. However, hurricane waves last only a few hours to 2 days, while waves generated by Trade Winds last, on average, 3-4 days. This study clearly highlights the importance of Trade Wind intensification events on the short-term (order of days) evolution of this beach.

**ADDITIONAL INDEX WORDS:** *French West Indies, nearshore transport, beach and shoreface evolution, high-energy events, Trade Wind intensification, hurricanes, numerical simulation.*

## INTRODUCTION

On tropical, microtidal coasts, hurricanes are one of the dominant morphodynamic agents that cause erosion. Waves are the principal factors of shoreline retreat and beach erosion, by bringing powerful hydrodynamical forces to the shallow area of a coast (HORIKAWA, 1989). On Martinique Island, French West Indies (Figure 1), the second climatic event responsible for large wave heights is intensification of Trade Winds. The impact of hurricanes is, however, better known than that of Trade Wind intensification events. The morphological impacts of hurricanes and the ensuing structure of the coastal hydrodynamic circulation during such exceptional storms have been studied for the past three decades, essentially along the Louisiana, south-eastern Texas and Florida coasts (MURRAY, 1970; WOODLEY *et al.*, 1981; ROGERS *et al.*, 1982; REJMANEK *et al.*, 1988; BIRKEMEIER *et al.*, 1991; STAUBLE *et al.*, 1991; KATUNA, 1991). Various aspects of the meteorology, climatology, sea-state, storm surge and coastal

morphologic impacts associated with the major hurricanes have been studied, especially with regards to Hurricane Hugo (METEO FRANCE, 1990; TAYLOR and TRAGESTER, 1990; PAGNEY, 1991; STAUBLE, 1990; HUBBARD, 1992) and Andrew (STONE *et al.*, 1993, 1995). More recently, research has been directed toward numerical modelling. STONE *et al.* (1997), for instance, have modelled the wave climate for two future hurricane scenarii on the Louisiana barrier islands.

The Caribbean Islands are very much exposed to hurricanes but, so far, very few studies of the impact of these high-energy events have been carried out. On the Virgin Island of St. Croix, HUBBARD (1992) described the patterns of reef damage and sediment transport following the passage of Hurricane Hugo. The discussion focused on the magnitude of hurricane-related sediment transport and its importance relative to fair-weather processes. On Martinique Island, only the physical characteristics of hurricanes and tropical storms have been studied, mainly those which caused substantial damage and loss of life in the Island. Among these, Hurricane Allen (1980) generated maximum wave heights estimated at 6 m and wave periods of 12 s, and Hurricane David (1979)

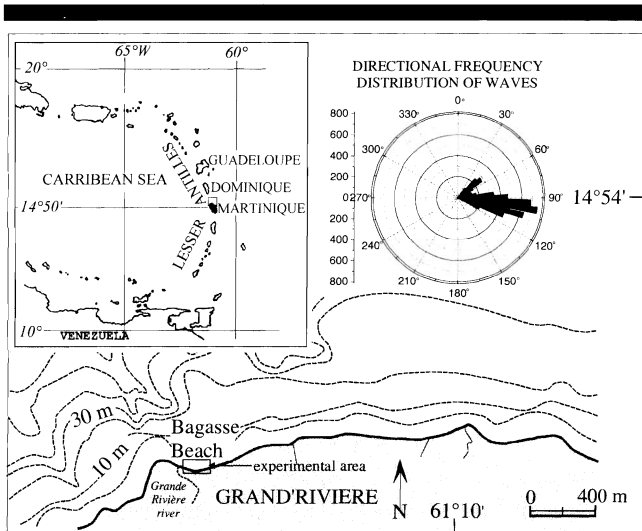


Figure 1. Location map of Martinique Island in the Lesser Antilles and directional frequency of wave distribution between April 1995 and March 1997. The frequency diagram location corresponds to that of the offshore WAVERIDER buoy.

heights of up to 7 m and periods of 15 s (DURAND, 1996). Tropical storms Beulah (1967), Dorothy (1970), Klaus (1990), and Cindy (1993) also caused damages to Martinique Island. However, their geomorphological impact on this volcanic island has hardly been studied.

Similarly, little is known of the impact of intensification of the Trade Winds that blow across the Caribbean Islands. Trade Wind intensification events may generate maximum height waves comparable to those observed during moderate hurricanes (Figure 2). The maximum wave height recorded during the passage of Hurricane Marilyn in September 1995 across Martinique Island was 4.55 m, whereas the wave height attained during an episode of Trade Wind intensification in February, 1996 was 4.09 m (Figure 3). The sedi-

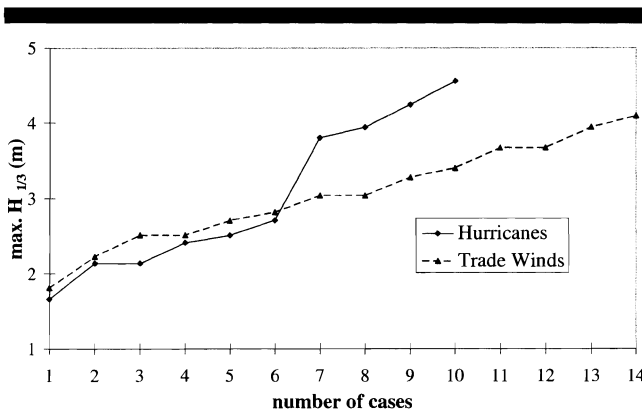


Figure 2. Maximum heights of waves generated by hurricanes and by episodes of intensification of Trade Winds recorded between April 1995 and May 1997. The X axis represents climatic events classified in order of increasing strength.

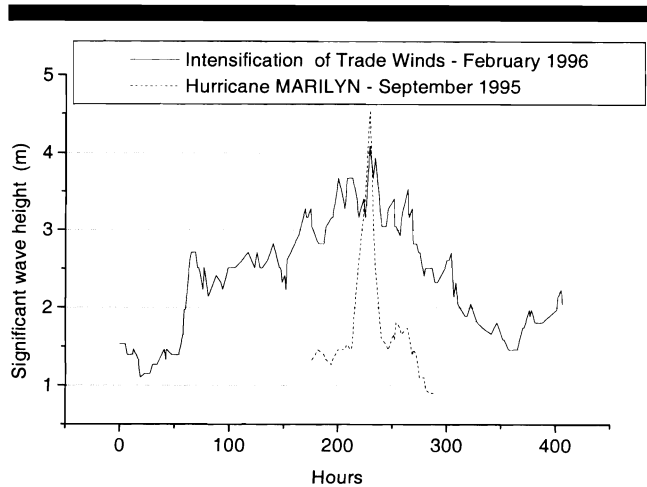


Figure 3. Significant wave height and duration for an episode of Trade Wind intensification (February, 1996) and for Hurricane Marilyn (September, 1995).

mentological impact of such Trade Wind events on the beach and shoreface can be important because of wave height amplification and especially because of the sustained duration of large waves. These events can last several days whereas the passage of a hurricane on the coast generally lasts only a few hours (Figure 4).

In this study, the coastal sediment budget and beach geomorphology impacts of intensification of Trade Winds and of moderate hurricanes have been field studied on a microtidal coast on the northern extremity of Martinique Island (Figure 1). The study site, Bagasse Beach on the Grand'Rivière coast (Figure 1), is located on an alluvial fan open to waves from the Atlantic Ocean, and is bounded by a narrow insular shelf. Beach profiles and field conditions were monitored from 1995 to 1997. This 3-year period was a particularly active in the Caribbean as far as high-energy meteorological events are concerned. Ten offshore passages of hurricanes or tropical storms and fourteen Trade Wind intensification events were

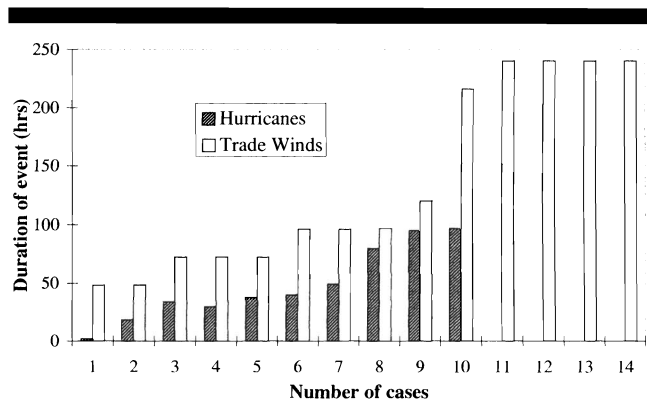


Figure 4. Duration of hurricanes and Trade Wind intensification events recorded between April, 1995 and May, 1997. The X axis represents climatic events classified in order of increasing strength.

recorded. The offshore passages of Hurricanes Iris (26 August, 1995), Luis (5 September, 1995), Marilyn (14 September, 1995) and Bertha (July, 1996) generated high waves that affected the Martinique coast (BLEUSE *et al.*, 1995). These years of active hurricane events provided a unique opportunity to characterise the beach sediment budgets associated with these high-energy events, and at different time scales. Budgets were determined over three time scales: (1) a two year period, (2) one dry season, and (3) at event scale by analysing the impacts of one day of intensification of Trade Winds.

Instrumented experiments including directional wave measurements, sediment sampling on the beach and shoreface, and longshore current measurements with dye releases in the surf zone, were conducted in conjunction with topographic and bathymetric surveys. Morphological changes were estimated from volumetric calculations for each time scale, although shoreface volumes are difficult to quantify for a dynamic subaquatic profile due to permanent wave activity. It is important to note that subaerial beach changes represent only a small fraction of the total volumetric changes across the beach and nearshore system (MORTON *et al.*, 1995). Nevertheless, as demonstrated by AUBREY (1979), storage and release of sand from the subaerial beach should be a primary indicator of shoreface processes, and of the availability of sand in the littoral drift system (MORTON *et al.*, 1995).

The study highlights the relative hierarchy of Trade Wind intensification events and hurricanes of various categories (Saffir-Simpson scale (SIMPSON, 1971)), and at different time scales, on this storm-dominated coast. In the first place, sediment budgets and volumetric calculations deduced from the survey data are presented. Following this, the impacts of a moderate Trade Wind intensification event are compared with those of moderate hurricanes by numerical simulations.

## STUDY AREA

The study area, Grand'Rivière, is a 300 m stretch of curvilinear coast on north Martinique Island, in the middle of the Caribbean Arc (Figure 1). This alluvial fan coast, with low backbeach elevations, comprises two adjacent beaches composed of pyroclastic sediments, and is extremely vulnerable to erosion and flooding during storms. The Grand'Rivière coastline is undergoing rapid retreat, with estimated rates of 0.5 to 1 m yr<sup>-1</sup> between 1950 and 1986 (BOSSER and HERY, 1993). Storms and storm-induced currents are the primary agents responsible for sand transport in the coastal zone. This coast is microtidal and characterized by high wave-energy, with mean wave heights of 1.2 to 1.6 m, and wave periods falling in the 7–9 second range. Tidal range averages less than 0.30 m (S.H.O.M., 1973; KJERFVE, 1981). The prevailing Trade Winds are dominantly northerly to east-southeasterly, and generate waves that come from these directions. Wind-induced changes in water level are commonly larger than those caused by astronomical tides. Falling barometric pressures act to draw up the water surface, producing a rise of approximately 13.6 mm for every 1 mb drop in pressure, *i.e.*, from 0.5 m to 1 m in this area (MAUL *et al.*, 1995; SOGREA, 1992). At Grand'Rivière, the maximum tidal current

speed 2.5 m above the bottom, and at a depth of 70 m, is about 0.32 m s<sup>-1</sup> in the southwesterly direction, and occurs during the ebb (DURAND, 1996). On the upper layer circulation, currents are generally strong in the north of the island (between Martinique and Dominique Islands), around 0.5 m s<sup>-1</sup>, and move in a westerly direction along the north shore (S.H.O.M., 1973). The upper shoreface of Grand'Rivière is a dynamic zone composed largely of medium to fine, well-sorted sands (grain diameter  $D_{50}$  = 0.2 to 0.3 mm), derived from rivers, longshore drift and weathering of the adjacent andesitic rocks.

The experiments were conducted on Bagasse Beach (Figure 1). This narrow beach is limited westward by the Grand'Rivière river mouth, and to the south and the east by rocky volcanic cliffs, up to 80 m high. The coastline faces north-northeast and is exposed to the dominant wave approach direction.

## FIELD EXPERIMENT DESCRIPTION

### Wave Measurements

Wave measurements were obtained from a directional buoy moored by the Technical Services of the Conseil Général of Martinique Island, and operated by METEO FRANCE (the French National Meteorological Services). Wave data were collected almost continuously from April, 1995 to March, 1997. The directional DATAWELL buoy, WAVERIDER, was moored on the insular shelf in 60 meters of water (Figure 1). Wave data were recorded for 20 minutes every three hours, and sent by ARGOS message to a WAREC receiver. The details of the WAREC directional measurement system and the computation of directional wave spectra are described in DATAWELL BV (1993).

### Three parameters were extracted from the recorded data:

- (i) Wave height ( $H_{1/3}$ ), defined as the average height of the one-third highest waves measured over a stated interval of time, usually 20 mn (KOMAR, 1967).  $H_{1/3}$  is defined with a one centimetre resolution. In order to study the storm wave heights, the wave gauge was programmed to automatically record more frequently as soon as wave height exceeded 2.5 meters.
- (ii) Peak wave period ( $T_p$ ), defined as the period associated with the maximum energy in the spectrum; it is the reciprocal of the peak frequency. Wave period is identified from computation of the variance of the energy spectrum with 60 degrees of freedom calculated from a 20 mn record (DATAWELL BV, 1993). The useful frequency band ranges from 1.6 s to 30 s.
- (iii) Wave direction (D). Directional wave measurements obtained by the WAVERIDER buoy are based on the translational principle. The instrument measures translations caused by motion to determine wave direction. Accelerations are measured in the X and Y directions along vertical, north and west axes with 16 degrees of freedom (DATAWELL BV, 1993). Directional resolution is about 1.5°. Angles indicate the direction from which waves are coming.

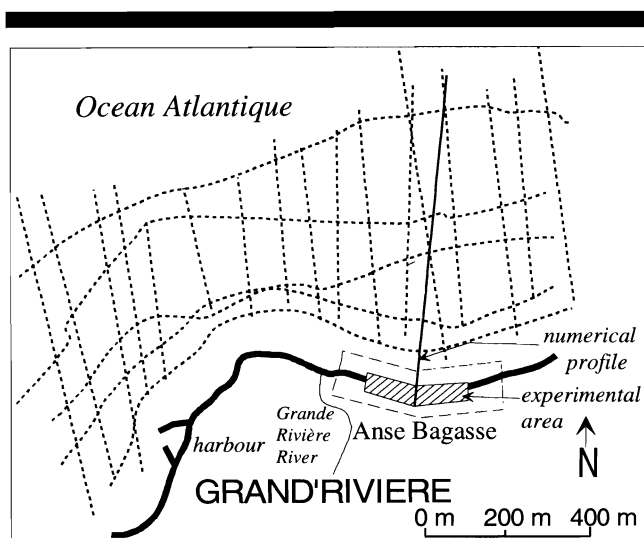


Figure 5. Map showing location of Bagasse Beach, bathymetric and topographic profiles (G.P.S. survey data, Lambert UTM 20) and a profile normal to the coastline used to simulate cross-shore transport with the UNIBEST model (DELFT HYDRAULICS, 1994).

## Currents

Dyes have been used to measure longshore current velocities (LEVOY, 1994). They were injected in the surf zone at different sites along the Grand'Rivière coast and under different wave energy conditions. The dye traces were timed at regular space intervals, thus obtaining the average velocity between two points. Characteristics of mean longshore currents were determined. At all measurement sites, currents were always in a westward direction. During fair-weather conditions, mean current speeds were relatively weak (usually  $<0.6 \text{ m}\cdot\text{s}^{-1}$ ) and during intensification of Trade Winds, mean current velocities increased to about  $1.5 \text{ m}\cdot\text{s}^{-1}$ .

## Topographic and Bathymetric Surveys

Comparison of bathymetric and topographic data for the same region but at different time periods provides a method for calculating net movements of sediment into (accretion) and out of (erosion) a studied area. Bathymetric and topographic profiles over the Grand'Rivière shoreface (between 3 and 20 m water depths) were carried out in July, 1995, October, 1996 and May, 1997, using, respectively, a 500 KHz Tritech echosounder associated with a Trimble DGPS positioning system, and a LEICA electronic station for the beach topography. From one survey to the other, points in the topographic network were referenced to an existing fixed base station. Elevations for each profile were estimated from this base station. Quarterly beach surveys were conducted between July, 1995 and May, 1997. The altimetric uncertainty for network points is about 0.02 m, thus generating a margin of error for volumetric calculations.

Each of these surveys comprised 23 subaquatic profiles and 11 intertidal beach profiles (Figure 5). The intertidal beach survey lines were spaced approximately every 25 m near the

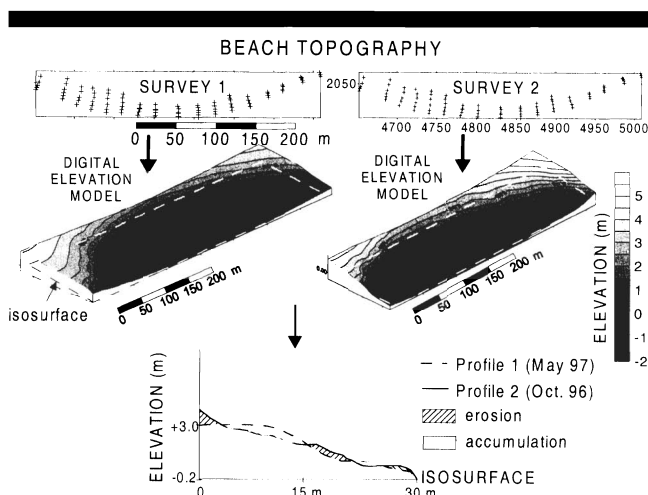


Figure 6. Procedure for calculating beach volumetric changes. Comparison of two different sediment volumes corresponding to two different dates. The bathymetric and topographic data were gridded and contoured on a grid. Each survey corresponds to one Delaunay interpolated grid. Elevation variations between grids enable delimitation of erosion and accumulation areas, and sediment gains and losses. The calculated beach volume lies between the beach slope and the basal isosurface. This isosurface is used as a reference for calculation volume changes from one survey to the other.

fixed instruments, and the subaquatic survey lines every 50 m. The bathymetric data were processed to remove water depth variations due to tidal and wave fluctuations. The positioning error of the navigation data is about 7 m. Therefore, the uncertainty on the water depth measurements is estimated to 0.50 m. The bathymetry of the breaker zone is unknown because large plunging waves rendered conditions hazardous. Consequently, to estimate bottom morphology, *i.e.*, the presence or not of sand bars, we resorted to DEAN'S (1977) empirical formula. He has shown that  $H_b/wT$  is an important parameter for distinguishing barred from non barred profiles (where  $H_b$  is the breaking wave height,  $w$  the fall velocity of sediment, and  $T$  the wave period). At Grand'Rivière, the value of this parameter is greater than 0.85, suggesting a profile without bar morphology.

## Sediment Volume Changes

The morphological impacts of hurricanes and of Trade Wind intensification events have been analysed by comparing the volumes of sediment eroded during two years, during one dry season, and during one day of intensification of Trade Winds. The bathymetric and topographic data were gridded and contoured using the software package SURFER (KECKLER, 1995). For each survey, one interpolated grid was generated (Figure 6). Elevation variations between grids enable the delimitation of erosion and accumulation areas, respectively as volumetric gains and losses of sediments. The calculated beach volumes comprised the three-dimensional area between the beach slope and the basal isosurface of the surveys (Figure 6). This isosurface is the reference for the volumetric calculations for the different surveys. The calculated

volumes are therefore not tantamount to the total sediment volume. The aim was to identify sediment volume variations from one survey to the other. These variations were calculated by subtracting one volume from the other.

Bathymetric changes were also determined by differencing bathymetric grids. Mapping of these variations showed areas of erosion and accretion, or zones considered as stable according to the techniques used for surveying. Beach volume histories also indicate periods when either longshore or cross-shore transport predominates (MORTON *et al.*, 1995). Errors in field experiments and in volume calculations can cumulate, leading to uncertainty of results. Moreover, because of bad weather conditions during the later surveys, only bed level changes larger than 0.50 m were taken into account.

On the beach, volumetric changes were estimated for a defined area. The extremities of the beach were voluntarily excluded from the calculations because of their weak representativeness. The western extremity of the upper part of Bagasse Beach was nourished between the second and the third surveys with riprap, while the eastern extremity is a shingle and cobble beach. Consequently, the active study area was located in the central part of the beach (Figure 5), and covered an area of about 6330 m<sup>2</sup>. The bathymetric surveys covered approximately 1.8 km<sup>2</sup>, and extended about 1 km offshore (Figure 5), to include the outer surfzone and the inner shelf to a depth of about 20 m.

## RESULTS

### Waves

#### Fair-Weather Conditions

The direction and strength of predominant winds affecting Martinique Island have a seasonal distribution. Moderate to strong easterly winds prevail most of the year, resulting in littoral drift to the west, northwest and southwest, depending on coastline orientation. During fair-weather periods between storms, winds blow predominantly from the east or the southeast (54% of waves come from the southeasterly direction), and have low speeds, generally less than 7 m s<sup>-1</sup> (BLEUSE *et al.*, 1995). They generate wave with heights of about 1.2–1.4 m, and periods of 7–8 s. Only 1% of waves were higher than 3 m during the observations. The prevailing winds may undergo seasonal changes. Trade Winds may be temporarily replaced by winds from other directions, as seasonal pressure patterns change. Also, these winds generally break down in the rainy season, especially in October and November (PAGNEY, 1992a).

#### Trade Wind Intensification Conditions

The dry season is characterised by periodic intensification of Trade Winds whose velocities may reach 11 m s<sup>-1</sup> and more, generating unsettled seas from November to May. December and January are particularly unsettled months, because they represent the transition between the rainy and the dry seasons. During these months, gusts of wind and rainstorms generate short-period waves. From December to February, the strong winds shift to the easterly and northeasterly directions, depending on the location of the Inter-

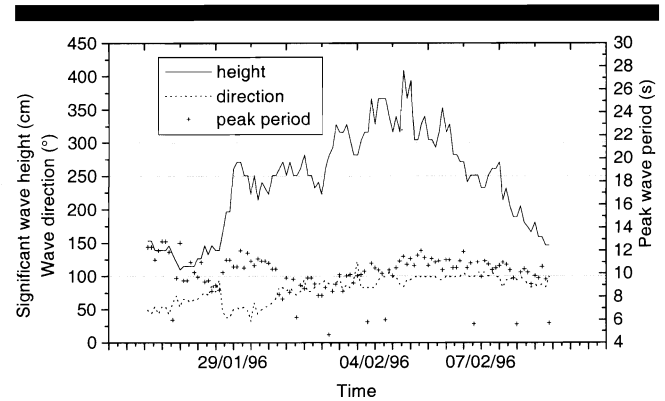


Figure 7. Wave heights, periods and directions measured over the Grand'Rivière shelf during an episode of Trade Wind intensification in February, 1996.

tropical Convergence Zone (PUJOS *et al.*, 1992). Intensification of Trade Winds is determined by migration of the Azores anticyclone which moves with the Intertropical Convergence Zone, resulting in Trade Wind fluctuations (PAGNEY, 1992b). Depending on the location of the anticyclone, Trade Winds, and consequently waves, come from east to east-south-easterly directions, or from the northeasterly direction. Trade Winds blow at 5 to 8 m s<sup>-1</sup> 80% of time, and generate waves of about 1 to 3 m (U.S. NAVAL OCEANOGRAPHIC OFFICE, 1963). Generally, the maximum wave heights generated by Trade Winds are from 2 to 4 m because the wind speeds do not exceed 14 m s<sup>-1</sup>. However, peak wind speeds can reach 19 m s<sup>-1</sup> and can generate significant wave heights of up to 4–4.5 m (DURAND, 1996). In February, 1996, for instance, the maximum wave height attained 4.1 m (Figure 7).

To calculate the number of Trade Wind intensification events, we defined a wave height threshold above 1.5 m, because, at heights above this threshold, beach erosion can be clearly measured (DOLAN *et al.*, 1990). During the study period, the wave records showed that wave heights were over 1.5 m about 30% of the time. Trade Wind intensification events were three times more frequent than hurricanes (Figure 8). We separated the Trade Wind waves (Hs > 1.5 m) in to the two predominant directions. Waves coming from E to ESE, observed between January and March, are more frequent than those from NE which occur from October to January (Figure 9). During the exceptional months of February, 1996 and 1997, respectively 14 and 18% of waves were larger than 3 m, whereas during the other months of the year, this height was exceeded less than 4% of the time.

#### Hurricane Conditions

Hurricanes and tropical storms occur during the rainy season, from June to October. Hurricanes reaching the Caribbean Islands are generated by disturbances of African or East Atlantic origin that travel from east to west over the Atlantic Ocean. These disturbances may be reinforced by instability associated with the Trade Winds (PAGNEY, 1992b). Hurricanes strike inside an area of about 180 km around Marti-

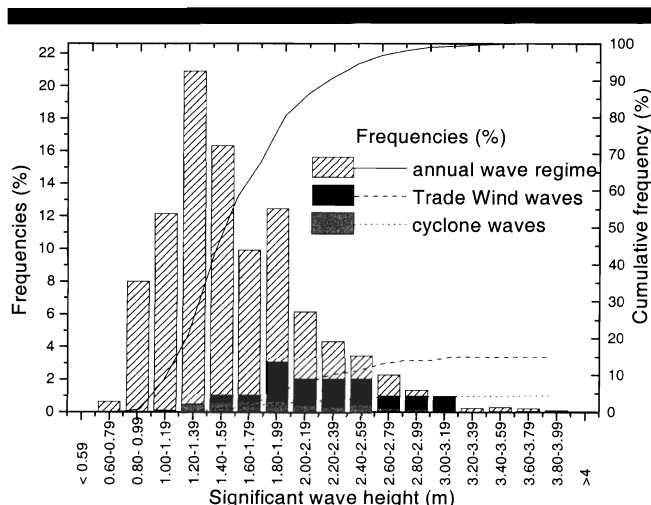


Figure 8. Wave height frequencies for the annual wave regime, for waves generated by intensification of Trade Winds and for waves generated by hurricanes. The x axis represents significant wave height (m), the left-hand y axis frequencies (%) and the right-hand y axis cumulative frequencies (%).

nique Island (PAGNEY, 1992b) approximately once every four years, mainly in August and September. However, although the hurricanes or degraded tropical storm do not always strike the island directly, they generate swells that can travel thousand of kilometres before dissipating their energy on the coast (COCK, 1995). The surge resulting from these storms commonly adds 0.3–1 m to the normal tidal level along the Martinique coastline. A hurricane-generated surge may raise the ocean surface by more than 2.5 m above normal tidal level, as with Hurricane Hugo on Guadeloupe Island in 1989 (BLEUSE *et al.*, 1995). DEANE *et al.* (1973) calculated maximum significant wave heights of 8 m and periods of 13–16 s generated by hurricanes in the eastern Caribbean. Waves of this kind can strike the Martinique coast once every 15 years and wave heights larger than 3 m can occur once every 5 years (DURAND, 1996). Generally, hurricanes and tropical storms generate high waves over short durations (order of a few hours), separated by long spells of low wave energy. It is therefore important to study these dynamic effects in relation to storm duration and frequency over time. The years 1995 and 1996 were exceptional by the frequency of the strong storms. Indeed, several high-energy meteorological events generated significant wave heights greater than 3 m. For example, Figure 10 shows the frequency of hurricanes and tropical storms (Felix, Iris, Luis, and Marilyn) in August and September, 1995 that generated large significant wave heights. In 1996, waves generated by cyclones occurred in July (Hurricane Bertha), in August (Hurricanes Edouard and Fran) and in September (Hurricane Hortense), and had significant heights of 2 to 4 m. Hurricane Bertha has been selected for numerical simulations in a later section of the paper. It was a category 1 hurricane whose track passed to the north of the Caribbean islands.

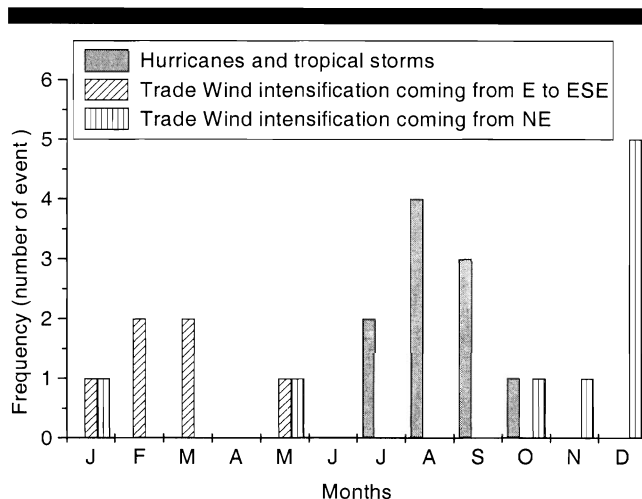


Figure 9. Monthly frequency of hurricanes and episodes of intensification of Trade Winds episodes on northern Martinique Island between April 1995 and March 1997.

### Morphological Changes

#### Sediment Budget for One Day of Trade Wind Intensification

Surveys were conducted on Bagasse Beach just before and after a one day-long (October 23 and 24, 1996) intensification of Trade Winds that generated significant wave heights of about 1.5 m. The eroded volume of sand was about 2400 m<sup>3</sup>, with an accuracy estimated at about 20%. Figure 11A shows important erosion on the eastern part of the beach and minor accumulation on the western part. Offshore sediment movements were therefore predominant, with minor longshore drift to the west. Vulnerability of the eastern part of the beach to erosion is partly a function of antecedent beach state. Indeed, as mentioned earlier, this part of the beach is composed of cobbles and shingle eroded from the cliff faces which are directly exposed to high waves. With the return of

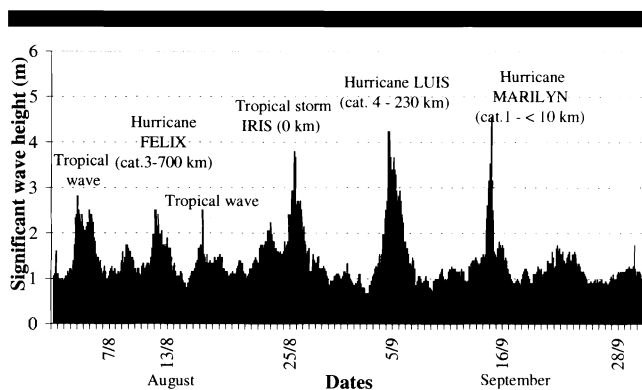


Figure 10. Example of two particularly active hurricane months, August–September, 1995, when the north of Martinique Island was affected by four episodes of hurricane waves with heights over 2.5 m. These waves came from distant hurricanes or from hurricanes that swept along the northeast coast of Martinique.

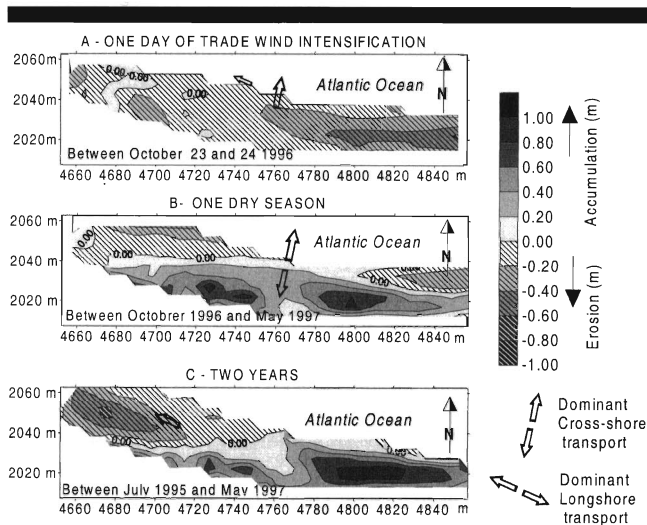


Figure 11. Beach level changes on the experimental area of Bagasse Beach for three different time scales. Fig.11A represents eroded and accumulated area during one day of intensification of Trade Winds event, Fig.11B during one dry season, and Fig.11C during two years.

fair-weather conditions, a variable proportion of this material may again move onshore. The amount of sediment returned to the beach depends on the maximum depth from which waves can transport sediment landward under these constructive fair-weather conditions, compared to the maximum depth to which sediments can be transported seaward under erosive storm conditions (HEQUETTE and HILL, 1993).

The eroded volume measured for one day is significant, but the erosive capacity would probably not be the same for two or three successive days of intensification of Trade Winds. The estimated maximum of eroded material is around  $2400 \text{ m}^3/24 \text{ hrs}$  maintained over 84 hrs. This represents an upper estimate of  $8400 \text{ m}^3$  of sediments. During the dry season covered by our study, an average of 5 intensification events took place, representing a total estimated loss of sediment of about  $42\,000 \text{ m}^3$ .

These results show that the dry season is a high wave-energy season due to periodic Trade Wind intensification events that create wave conditions for the erosion of up to  $2400 \text{ m}^3 \text{ day}^{-1}$  of sediments from Bagasse Beach. This clearly highlights the importance of Trade Wind intensification events on the short-term (order of days) evolution of this beach.

### Dry Season Sediment Budget

At the scale of one dry season, five large wave events occurred in response to Trade Wind intensification. The waves propagating came from the northeast. Over this period (October, 96–May, 97), the total sediment budget of the experimental area of Bagasse Beach was negative by about  $1100 \text{ m}^3$ . This value represents an average lowering of the beach surface of around 0.2 m. Erosion of the lower foreshore attained about 0.5 m (Figure 11B). Part of the eroded sediment was deposited on the upper foreshore, where maximum ac-

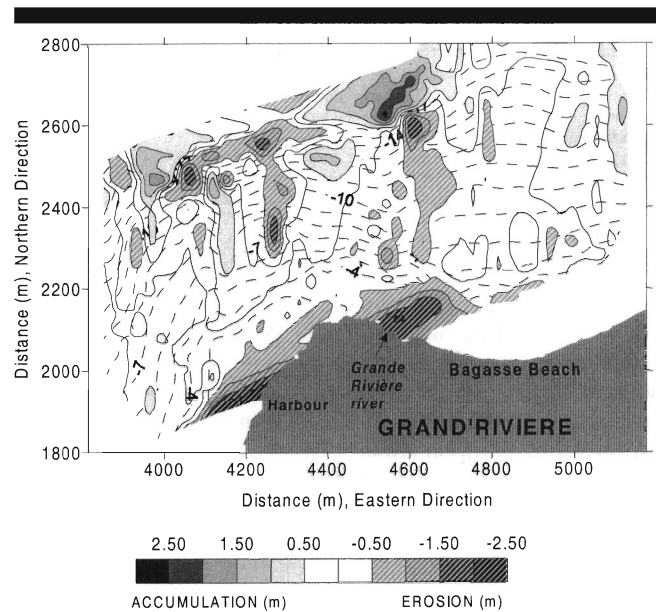


Figure 12. Bathymetric changes on the inner shelf of the Grand'Rivière coast (July 1995–October 1996). Because of bad weather conditions during the last surveys, only bed level changes larger than 0.50 m have been taken into account. The white zone corresponds to this uncertainty.

cretion reached 0.90 m. Erosional and depositional zones were arranged parallel to the coastline, showing a cross-shore displacement of sediment. Onshore movements explain beach accretion during fair-weather conditions, then offshore sand movements during Trade Wind intensification events induce a negative budget at a scale of a dry season. Surge conditions at the coast during these events probably induced steady offshore currents explaining offshore sediment dispersal and deposition on the inner shelf. Indeed, over the same period, bathymetric data from depths of 6 to 15 m showed changes in elevation that exceeded 0.5 m (Figure 12). The alluvial fan was eroded on the eastern part of the beach and about 1.8 m of sediments was eroded from the bed of the nearby Grand'Rivière river (Figure 1). Profiles located on the eastern part of the shoreface showed hardly any change. In spite of the morphological changes on the experimental beach, calculations of the global sediment volume between October and May revealed no significant variations, indicating overall equilibrium between beach sediment erosion and accumulation on the inner shelf.

To summarise, the survey data show that the volume of sediment eroded on the foreshore during one day of intensification of Trade Winds is about twice the total dry season loss of sediment measured between October, 1996 and May, 1997.

### Two-Year Sediment Budget

The total sediment budget on the experimental area of Bagasse Beach was slightly positive (by around  $500 \text{ m}^3$ ) between July, 1995 and May, 1997, a period covering two rainy seasons and two dry seasons. However, the 1995 and 1996 cy-

Table 1. *Sediment budget of Bagasse Beach at different time scales.*

	Sediment budget (m <sup>3</sup> )
One day of intensification (Trade Winds)	-2400
One dry season	-1100
Two years	+500

clone seasons were active ones, with the passage of no less than 8 hurricanes and tropical storms that generated large waves. Several episodes of Trade Wind intensification also occurred. It should be stressed however that the hurricanes were of rather moderate energy. One that passed very close to Martinique Island was classified as a category 1 hurricane on the Saffir-Simpson scale.

Whereas the dry season sediment budget was clearly negative, the annual sediment budget was positive (Table 1). Furthermore, during storm conditions, part of the eroded beach sediment was transported offshore and deposited onto the shoreface. When calm conditions occur, the orientation of the wave crests induce a longshore transport and sand move to the beach, specially during rainy seasons (except during short term events of high energy wave conditions). The data show accumulation on the eastern part of the beach, where the bed level increased to a maximum elevation of 0.8 m (Figure 11C). This accumulation is due to onshore sand movements during rainy season. Erosion on the western part of the beach reflects the last storm effects that affected the Bagasse Bay. The overall data show that accretion was most important during the rainy season outside hurricane events. However, the sediment budget during the two rainy seasons is not directly known. An estimate of the sediment budget during one rainy season has been obtained from the results for two years and for two dry seasons. This budget is estimated to be positive by about 1350 m<sup>3</sup> on the experimental area of Bagasse Beach.

In conclusion, the survey data show that the sediment budgets for two years and during the dry and rainy seasons are well balanced, whereas at the scale of one event of intensification of Trade Winds, the budget is clearly negative. We infer from this that there an important onshore movement of sand takes place during fair-weather conditions, in dry and rainy season, and that, storms, Trade Wind intensification, hurricanes, provoke beach erosion during short periods.

## NUMERICAL SIMULATIONS

In order to gain a better knowledge of the sedimentological impact of moderate hurricanes and Trade Wind intensification events, we carried out numerical simulations of sediment budgets. We used models to estimate sediment volumes eroded by Trade Wind events lasting more than three days. The results were then compared with those of a numerical simulation of a moderate hurricane event generating the same coastal wave heights. We used the numerical model HISWA (Hindcast Shallow Water Waves), developed by DELFT HYDRAULICS (1995), to describe the propagation of waves coming both from a distant hurricane and from an episode of intensification of Trade Winds. Wave propagation was sim-

ulated between the wave buoy located offshore over 60 m-deep water and the coast. Associated sediment transport was simulated using UNIBEST (Beach Sediment Transport) models (DELFT HYDRAULICS, 1994) along a topographic and a bathymetric profile located in the centre of Bagasse Beach (Figure 5).

## Numerical Models

From the incident waves and bathymetric data, HISWA computes wave heights and directions at shallow water depths. As described by HOLTHUIJSEN *et al.* (1988), the model is based on the wave action equation. HISWA solves the equilibrium equation of the total energy of the system. External processes that may modify this energy (surf, friction on the bottom) are introduced in the model using semi-empirical functions (VOGEL *et al.*, 1988; DEN ADEL *et al.*, 1990; SCLAVO *et al.*, 1996). The wave records at the Grand'Rivière DATAWELL buoy provided the incident data for wave propagation analysis. A detailed presentation of HISWA can be found in HOLTHUIJSEN *et al.* (1988) and DELFT HYDRAULICS (1995).

The x-axis of the computational grid is taken roughly along the direction of wave propagation and the y-axis is normal to the x-axis. The computation progresses step by step in the x-direction. The bottom topography is represented by a depth array of 175 × 100 grid points, with a spacing of 100 m. Wave characteristics (heights, periods and directions) recorded at Grand'Rivière buoy were used as boundary conditions for the model which then simulates the propagation of waves on the inner shelf. The physical parameters used in the HISWA model are default friction parameters ( $cf_w = 0.01$  and  $cf_c = 0.005$ ). Two different grid orientations were used by nesting, in order to obtain better correspondence between reality and simulations.

The HISWA model has been tested by VOGEL *et al.* (1988), and numerous applications have been successfully carried out in different environments (*e.g.*, DINGEMANS, 1987; DEN ADEL *et al.*, 1990; and more recently SCLAVO *et al.*, 1996).

The UNIBEST (DELFT HYDRAULICS, 1994) model simulates cross-shore transport along a profile normal to the coastline (STEETZEL, 1993). The results generated by HISWA (*e.g.*, wave heights, directions and periods at the 10 m isobath) were used as boundary conditions for the UNIBEST model. The time scale is comprised between 1 h and 48 h, which corresponds to extreme hydraulic and storm conditions. Using pre-storm profile and hydrodynamic conditions, UNIBEST computes evolution of the cross-shore profile, storm surge levels, significant wave heights and longshore currents during the storm. The length of the studied profile, including the subaerial beach, the shoreface and the inner-shelf, was 1200 m. UNIBEST simulates over a maximum of 48 hours but tests have been made to simulate Trade Wind intensification during 84 hours. The results of simulation after 48 hours were used as initial conditions for the following 36 hours. The chosen time step was 5 hours for a total duration of 84 hours. In the UNIBEST model, we used the following parameter inputs: viscosity ( $0.83 \cdot 10^{-6} \text{ m}^2 \text{ s}^{-1}$ ), median grain diameter (204 μm) and fall velocity ( $0.029 \text{ m s}^{-1}$ ).

Table 2. Comparison of measured and simulated (HISWA and UNIBEST) significant wave heights and directions at Grand'Rivière, Martinique Island. Simulations were carried out using HISWA and UNIBEST models.

Date	Offshore Incident Wave (°)	Coastal Incident Wave (°)		Wave Height (m)			
		Measured	Simulated*	Measured (-10 m)	Simulated (-10 m)*	Measured (-3 m)	Simulated **(-3 m)
July 1995	100	35	30	<1	0.95	0.80	0.75
Oct. 1996	50	30	26	1.45	1.10	1.85	1.70
May 1997	99	35	30	2.50	2.35	1.60	1.50

\* HISWA

\*\* UNIBEST

### Comparison with Field Measurements

The survey data have been used to calibrate and validate the HISWA model (Table 2). The table displays, for the three experimental conditions, the input wave parameters measured by the offshore buoy. The accuracy of the calculated wave heights has been estimated to an error of 24% in comparison to field data. Tests on physical parameters were conducted with the HISWA model. It appeared that water level variations had an insignificant influence on significant wave height and direction up to a depth of 5 m, *i.e.* a variation of 0.1° in direction, and 0.001 m in height for an elevation of 0.10 m of the water level. Tests realised on the bottom friction parameters ( $cf_w$  and  $cf_c$ ) showed that these parameters were no sensitive to depth variations up to 5 m. Above a depth of 5 m, wave height attenuation appeared for  $cf_w$  greater than 0.015.

Tests on variations of significant wave heights relative to wave directions showed that the greater the wave heights, the greater the attenuation on the inner shelf. Thus, between depths of 20 and 5 m, for waves coming from an easterly direction, with significant heights between 1 and 3 m, the attenuation across the inner shelf was about 10%. For significant wave heights of 4 m, attenuation was about 14%, and for 8 m, about 24%. For waves coming from east-southeast, attenuation was larger because of strong refraction over the inner shelf. Waves coming from the northeast were less attenuated and are, in consequence, more dangerous.

The survey data have been used to validate the UNIBEST

model (Table 3) by comparing measured and calculated longshore current velocities. The three experimental conditions are depicted in the table, and in each case, the tidal current is represented by one of two characteristic stages: high tide and low tide. The mean accuracy of the calculated longshore velocity is estimated at  $\pm 20\%$  with the UNIBEST model (Table 3).

### Events Selected for Simulation

Two simulations were carried out using moderate-energy categories for both Trade Wind intensification events and hurricanes, and, for purposes of comparison, a third simulation was carried out on fair-weather conditions. The selected events were: (1) a moderate Trade Wind intensification event based on the October 1996 survey data and (2) a moderate hurricane based on data on hurricane Bertha data. The characteristics of these input events are shown in Table 4. Surge levels were calculated only from barometric pressure (MAUL *et al.*, 1995). It must be stressed that the curvilinear configuration of the Grand'Rivière coastline does not favour storm surge level amplification.

Hurricane Bertha had a pressure of 988 mb in its centre, and generated maximum significant wave heights of 3.95 m and periods of 10–12 s. These values were used as boundary conditions. Hurricane Bertha induced waves that came from a northeasterly to east-southeasterly direction, and that lost about 40% of their height by refraction over the inner shelf. Thus, significant wave heights were less than 2.40 m over the inner shelf. The surge level calculated for Bertha is 0.30 m, a value confirmed by field observations of METEORFRANCE (BLEUSE *et al.*, 1995).

During the Trade Wind intensification of October, 1996, significant wave heights reached 2.7 m on the outer shelf and about 2.3 m over the inner shelf. This event lasted about 3½ days. These various events are compared below.

### Moderate Hurricane and Moderate Intensification of Trade Winds

The results of simulations show that waves generated by Hurricane Bertha would erode Bagasse Beach to the tune of  $38 \text{ m}^3 \text{ m}^{-1} \text{ day}^{-1}$ , which is more than the erosion of about  $28 \text{ m}^3 \text{ m}^{-1} \text{ day}^{-1}$  simulated for the intensification of Trade Winds. Field experiments (one day of intensification of Trade Winds) show an erosion of about  $7 \text{ m}^3 \text{ m}^{-1} \text{ day}^{-1}$  on the experimental area of Bagasse Beach, representing approximately one third of the calculated total profile volume

Table 3. Comparison between measured longshore velocity and longshore velocity calculated by the UNIBEST model.

Climatic Conditions	Tidal State	Measured Longshore Velocity (ms <sup>-1</sup> )	Longshore Velocity Computed (UNIBEST) (ms <sup>-1</sup> )
July 1995			
case 1	high tide	0.42	0.40
case 2	low tide	0.67	0.60
October 1996			
case 1	high tide	0.29	0.18
case 2	low tide	0.40	0.31
May 1997			
case 1	low tide	0.40	0.30
case 2	low low tide	0.27	0.20

Table 4. *Hydrodynamic conditions used for numerical simulations.*

Climatic Conditions	Parameters Based on	Offshore Hs (m)	Nearshore Hs (m)	Tp (s)	Average Storm Surge (m)*
Fair-weather conditions	April–May 1995	from 0.70 to 1.70	0.54	7–12	/
Moderate hurricane	Hurricane Bertha (July 1996)	from 1.50 to 3.94	from 0.82 to 2.40	8–14	0.30
Moderate Trade Wind intensification	23–27 October 1996	from 1.50 to 2.70	from 0.90 to 2.30	8–18	0.10

\* above the local reference datum (−0.54 m), storm surges are limited because of the narrow shelf and deep water surrounding Grand'Rivière.

given by the simulation. Also, model predictions seem consistent with field experiments at the daily scale. This is not the case when field experiments and numerical simulation are compared for one dry season. The simulation shows that the model overestimates erosion. From the experiment data, the total loss of sediment was estimated at 42 000 m<sup>3</sup> on the experimental area for an average of 5 intensification events. Numerical simulations for the same period predicted about 80 000 m<sup>3</sup> of sediment. Also, at the seasonal scale, numerical simulation overestimated field measurements by a factor of 2. It is significant to note that the results (Table 5) show that one storm is capable of transporting more sand offshore in one day (30 m<sup>3</sup> m<sup>−1</sup> day<sup>−1</sup>) than fair-weather processes can move onshore in 3 or more days (9 m<sup>3</sup> m<sup>−1</sup> day<sup>−1</sup>).

The respective durations of moderate hurricanes and of Trade Wind events must be taken into account. These are 48 hours for the first, and 84 hours for the second. The global eroded volumes over the total duration of the event were 76 m<sup>3</sup> m<sup>−1</sup> for the hurricane event and 98 m<sup>3</sup> m<sup>−1</sup> for the Trade Wind event. This analysis reveals that beach erosion is more important for a moderate Trade Wind intensification event by about 23%. Consequently, the eroded volume is more important at the end of a moderate Trade Wind intensification event than during a moderate hurricane (Figure 13).

**DISCUSSION**

The experiments reported in this paper show that moderate hurricanes have a small influence on the seasonal sediment budget balance of Bagasse Beach. These observations

Table 5. *Numerical sediment-transport rates under various energy erosion regimes at Bagasse Beach, Grand'Rivière, Martinique Island (based on table 1).*

Condition	Daily Transport (m <sup>3</sup> m <sup>−1</sup> day <sup>−1</sup> )	Integrated Transport On Duration Of Event (m <sup>3</sup> m <sup>−1</sup> )
Fair-weather	9	/
Moderate hurricane (cat. 1)**	38	76
Moderate Trade Wind intensification event	28	98

\* Calculated frequency based on wave conditions measured at Grand'Rivière wave gage from April 1995 to March 1997.

\*\* cat. 1: category 1 storm on the Saffir-Simpson scale (Simpson, 1971).

are consistent with those of MEARNS *et al.* (1988) who studied the impact of an intense storm on the shelf of Onslow Bay, North Carolina. In September 1984, Hurricane Diana (category 3) generated significant wave heights and periods that

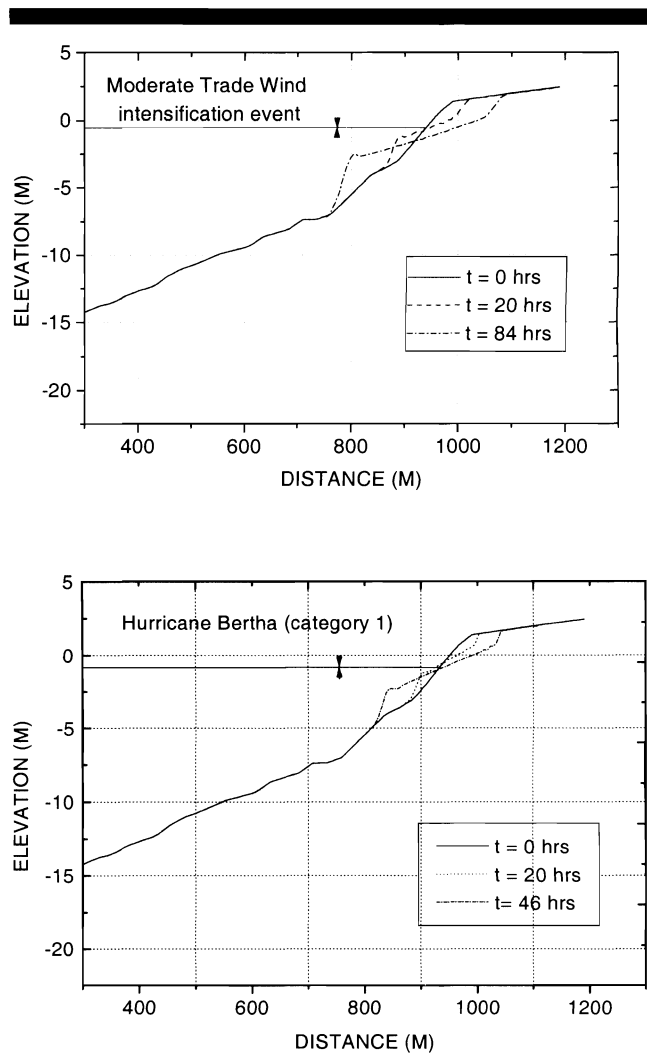


Figure 13. Numerical simulation of the evolution of the profile of the Grand'Rivière coast during an event of moderate Trade Wind intensification and for a moderate hurricane (Hurricane Bertha).

reached 4.5 m and 6–7 s during its passage over the bay, and horizontal water velocities of  $125 \text{ cm.s}^{-1}$  at the sea floor. Surveys conducted three months after the passage of Diana revealed no measurable sea-floor changes. MEARNNS *et al.* (1988) attributed the relatively resistant nature of the shelf surface to a paucity of loose sediment available for transport, and to cohesiveness of the outcropping Miocene sediments. Their conclusion was that the storm-dominated nature of this shelf surface reflected primarily its sediment starved nature and shelf equilibrium with the ambient, high-energy setting (MEARNNS *et al.*, 1988). In the same vein, BOSS (1993) made a reconnaissance survey before and after Hurricane Andrew (August 1992) in order to evaluate the impact of this cyclone on the carbonate platform of the northern Great Bahamas Bank. Andrew is one of the most energetic hurricanes to have crossed the North Atlantic. It moved over the Great Bahamas Bank as a category 3 hurricane. Bathymetric comparisons before and after this hurricane indicated no significant changes. BOSS (1993) demonstrated the importance of specific dynamic aspects of hurricanes (*e.g.*, varying intensity, strength, size, forward speed, duration) which influence their geologic potential, even over relatively short track distances. Therefore the relatively rapid passage, in about 3 hours, of a weakened Hurricane Andrew across the Great Bahamas Bank prevented the establishment of substantial unidirectional flows capable of modifying sediment bodies, whereas the limited radial extent of hurricane-strength winds (<50 km from the eye) restricted potential changes in bathymetry to the area (BOSS, 1993).

Although they lack fine precision, the eroded volumes we have estimated for Bagasse Beach at different time scales provide an alternative quantitative basis for estimating the dry and rainy season sediment budgets of this tropical beach, and for evaluating the daily impact of Trade Wind intensification events as well as that of moderate hurricanes. It must be noted that the field experiments integrated sediment budgets (erosion and accretion), while the numerical simulations integrated only erosion and cross-shore transport (longshore transport was not included).

The simulations show that only  $9 \text{ m}^3 \text{ m}^{-1} \text{ day}^{-1}$  of sediments move over Bagasse beach and its shoreface during fair-weather conditions. During moderate intensifications of Trade Winds, which occur several times a year, this rate increases to  $28 \text{ m}^3 \text{ m}^{-1} \text{ day}^{-1}$ . Storm induced sediment transport far exceeds these values. During a moderate hurricane, about  $38 \text{ m}^3 \text{ m}^{-1} \text{ day}^{-1}$  of sand can be removed over a maximum period of 48 hours. Results for one day of moderate intensification of Trade Winds are consistent with fields experiments, which show a one-day removal of  $7 \text{ m}^3 \text{ m}^{-1} \text{ day}^{-1}$  of sand on the experimental area. This is not far from erosion rate of  $9 \text{ m}^3 \text{ m}^{-1} \text{ day}^{-1}$  predicted by the model.

Simulations for extreme intensities have also been conducted, but sediment transport due to hurricanes were over-estimated compared to other studies as BIRKEMEIER *et al.* (1991), DINGLER and REISS (1995) or STONE and FINKL (1995). So these results have not been published by lack of data validation. But it seems that such events will have long term consequences on the Grand'Rivière coast unlike intensification of Trade Wind events.

Our study has proposed relative values that enable comparison between moderate hurricanes and moderate Trade Wind intensification events. More advanced field experiments that include full access to the breaker zone probably should be envisaged, in order to improve the resolution of both the field experiments and the numerical simulations. It should be then possible to organize the high-energy climatic events that contribute to the morphodynamic evolution of Bagasse beach into a hierarchy comprising different time scales.

## CONCLUSION

The Grand'Rivière shoreface on Martinique Island in the Caribbean is an example of a wave-dominated coast where morphological changes, induced by moderate to high-energy climatic events, are decisive factors that regulate the short-time coastal sediment budget. By analysing volumetric changes on the beach and its shoreface, time variations of the sediment budget in this tropical area during erosive wave conditions have especially been synthesised.

Fields experiments (wave characteristics, longshore current velocities, bathymetric and topographic surveys) have shown the importance of daily sediment budget trends during a Trade Wind intensification event versus seasonal and annual budgets not involving extreme hurricanes. Our results show that volume variations measured for one day of intensification of Trade Winds represent about twice the volume variations measured for one dry season. In the experimental area of Bagasse Beach ( $6330 \text{ m}^2$ ), the estimated maximum is  $2400 \text{ m}^3 \text{ day}^{-1}$  over an 84 hour period. This represents  $8400 \text{ m}^3$  of sediments eroded during one event of intensification of Trade Winds. During the dry season covered by the study, an average of 5 intensification events took place, representing a potential and global loss of sediment estimated at  $42\,000 \text{ m}^3$  on the experimental beach area. At the scale of one dry season, the total sediment budget determined from topographic surveys over the experimental area of Bagasse Beach is however negative only by about  $1100 \text{ m}^3$ , and at the annual scale, the total sediment budget is well balanced (about  $+500 \text{ m}^3$ ). Thus, in spite of numerous moderate to high-energy climatic events, fair-weather conditions balance sediment losses at the annual scale. Indeed, 1995 and 1996 were active cyclone years, with the passage of 10 moderate hurricanes and tropical storms that generated large wave heights (maximum, 4.55 m), in addition to several episodes of intensification of Trade Winds. In consequence, the most important accretion occurs during the rainy season outside hurricane events. This is confirmed by field observations which show silting up of the harbour during this season. These experiments show that moderate hurricanes do not have a determining influence on the seasonal sediment budget balance of Bagasse Beach.

In order to gain better knowledge of the morphodynamic impacts of moderate hurricanes and of episodes of intensification of Trade Winds, we carried out a number of numerical simulations. Comparison between moderate hurricane events and episodes of Trade Wind intensification shows that volumetric retreat is more important for a moderate Trade Wind intensification event by about 23%. Moderate hurricanes have a greater power of erosion, of the order of  $38 \text{ m}^3 \text{ m}^{-1}$

day<sup>-1</sup>, versus 28 m<sup>3</sup> m<sup>-1</sup> day<sup>-1</sup> for a Trade Wind intensification event. However, hurricane-generated waves are active for only a few hours to two days, while Trade Wind waves last several days (3–4 days on average). A finding of particular significance from those experiments is that one of these storms is capable of transporting more sand offshore in one day than fair-weather processes can move onshore in 3 or more days. The sediment balance of Bagasse Beach therefore depends on the frequency of these high-energy events responsible for erosion. For moderate events, the integrated sediment transport volumes appear to be larger for Trade Wind intensification events than for hurricane events by about 25%.

Trade Wind intensification events are determinant to predict short-term evolution of the beach but their influence to the long term evolution seems to be negligible contrary to extreme hurricanes. To predict coastal evolution in tropical regions, the long term modelling approach (several years) needs to focus on extreme hurricane events.

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