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Beaches Seasonal and Paroxysmal Morphosedimentary Dynamics: Results of 10 years Martinique Coastal Observation Network

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ABSTRACT

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Coastlines are vulnerable to the effects of climate change and sea-level rise as well as modifications in the wave climate and, in particular, increased storminess. The coastal areas of islands form part of this scenario and the Martinique shoreline illustrates this intensification of shoreline retreat and coastal erosion. In the context of this critical situation, a coastal observation network was set up in 2010 to monitor the evolution of the coast of Martinique. This network includes 28 beaches along the coast of Martinique and is based on studies of shoreline evolution using aerial photographs and topographic surveys of 71 cross-shore transects. The main aim of this network is to characterize the modal and seasonal dynamics of these vulnerable beaches and to estimate their resilience capacity and trends in the context of the increasing frequency of hurricanes. Analysis of the measurements over the last ten years highlights a general acceleration of the shoreline retreat. Furthermore, in terms of seasonal coastal evolution processes, the results clearly show the weak effect of the longshore sediment transport component on the open beaches of Martinique Island. However, a predominant cross-shore sediment transport component is observed on smaler bay beaches, which represent the most numerous beach type on the island (including several pocket beaches). On the short-term scale, the results of hydrodynamic and morphodynamic measurements highlight variable and intensive beach dynamic responses with a determining role played by shoreface parameters and coral-lagoon complexes. While cyclones have a significant impact on reducing the slope of beach profiles, our measurements reveal a significant resilience of eroded beaches owing to constructive swell. We also demonstrate that the hurricane season is not the season with the strongest morphosedimentary impacts. This almost ten-year-old observation network, provides an overview of shoreline evolution on Martinique and is an efficient management tool for the Lesser Antilles coastal environments.

ADDITIONAL INDEX WORDS: *Survey network, beaches, morphodynamics, paroxysms, resilience, Martinique*.

INTRODUCTION

In the present-day context of global change marked by the rise in sea level and the increase intensity of high energy weather-marine events such as cyclones in the tropical regions (IPCC, 2014), observations are required to improve our understanding of processes and the response of the environment faced with unknown factors. Tropical beaches are among the first areas to suffer the consequences of the increase of erosion processes. (Zhang *et al.*, 2004). On Martinique, these beaches are fragile, being made up of thin sedimentary prisms. The sediment source-areas are limited in size (sandy coral-reef terraces and lagoons in the case of white organo-calcareous sands; inland catchments in the case of beaches made up of black volcanic sands) (Lloyd, Perkins, and Kerr, 1987; Saffache, 1998). The sedimentary volumes available for reworking are very limited (Dolique and Charpentier, 2014a). Moreover, beaches in the Antilles have a fundamental role as regards the ecosystem, natural heritage and economic activities that has to be protected (Angeon and Saffache, 2008; Dehome and Saffache, 2008). Therefore, it is

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necessary to set up observation networks to acquire a better understanding of the present-day dynamics and future evolution of beaches, aiming to improve the management of these fragile environments. An observation network known as ALERT (Littoral pAroxysms, Evolution and Resilience of Tropical coastlines) was created in 2001 (Littoral pAroxysms, Evolution and Resilience of Tropical coastlines) (www.alert,sitew.eu). This network implements means for measurement and observation of the coast faced with extreme events (Dolique, Jeanson, and Besson, 2007), and is present in Guyana, French Polynesia, Mayotte, on the Scattered Islands in the Indian Ocean, in Vietnam and now in the Antilles (Martinique, Guadeloupe and Saint Martin) founded by the INTERREG CARIBSAT project (Jeanson, Dolique, and Anthony 2010; Jeanson, Dolique, and Anthony, 2014).

The objective of this research action is to implement a network for the monitoring of coastal environments (especially beaches, but also mangrove forest fronts) subject to weather-marine hazards (cyclones, storms, cyclonic swells, etc.). This network allows scientists and decision-makers to better understand the evolution of environments under stress and investigate the processes of possible resilience (progressive return to an earlier situation). Since June 2015, the monitoring of beaches in the Schoelcher municipality (Madame, Madiana and Collat Bays) has been integrated into SNO-DYNALIT, a French national monitoring network certified by the CNRS, which, in the long term, manages the acquisition and harmonization of meteorological data concerning the dynamics of 36 French coastal sites.

The protocol of this observation network is based on 3 spatio-temporal scales:

- State of the coastline and comparison of its evolution over half a century, using historical documents (aerial photographs and maps)
- Modal and paroxysmal dynamics of beaches, using topographical data, over an observation period of 10 years
- Detailed analysis of the morphosedimentary behaviour of test beaches in response to forcing parameters.

The implemented observation network is made up of 71 transverse topographic profiles located on 28 beaches showing significant dynamics. The objective is to determine the baseline state for the morphology of these beaches, taking into account their modal evolution. Measurements are repeated following the occurrence of a strong weather-marine hazard: (tropical wave, storm, cyclone, cyclonic swell, etc.) to characterize their impact on the beach. Finally, measurements are carried out with short time steps (once to several times a week) on specific profiles to identify the processes and resilience capacity (existence or non-existence of a natural return to a previous morphological situation). The running of this network has been ensured by a local coordination partnership (University of the Antilles, IRD) in charge of a team made up of different laboratories (see acknowledgements). The project has enabled the setting up of international collaboration on the topic of coastline dynamics in the Lesser Antilles (see acknowledgements).

STUDY AREA

Martinique is located in the Lesser Antilles (Figure 1). It is bordered in the east by the Atlantic Ocean and in the west by the Caribbean Sea. The highest point on the island of Martinique is the volcanic neck of Mont Pelée, which rises to 1,397 m above sea level. The climate is tropical humid with alternating seasons, showing a local influence due to the island location. A relatively cool and dry season (December to May), which can be divided into two periods: (i) from December to February, characterized by sustained north-easterly trade winds and long swell, (ii) the "carême" period from February to April, characterized by dry weather. The climate also comprises a hot and humid season (from June to November), characterized by a peak period of cyclones in September-October. The 350-km-long coastline is varied, consisting of volcanic cliffs alternating with small bays and coves with sandy or sandy-muddy sediment. A few mangroves forests colonize the heads of some of the bays, especially in the southern part of the island. The beaches are reduced in length (50 m to 4 km) and in width (less than 20 m in general), made up of limited volumes of sandy sediment (Jeanson et al, 2016). The tidal range is microtidal (0.2 to 0.7 m). The southern part of the island facing the Atlantic is bordered by coral reefs, with a 25-km-long main barrier and numerous fringing reefs, 200 to 500 m wide. As part of this study, 28 beaches were observed over the whole coastline of the island. Four "testbed/pilot study" sites were selected according to some characteristics (Figure 1):

(i) Schoelcher beaches (pocket-sized beaches in an urban environment, with one beach subject to direct anthropogenic influence, with swell on the Caribbean seaboard);
(ii) Diamant beach (4 km long, subject to longshore drift and rip currents);
(iii) Cap Chevalier beaches (pocket-size beaches typical of the lagoonal triad: reef - sea-grass bed – coral sand beach);
(iv) Carbet beach (characterized by a river mouth and a steep shoreface, with Caribbean swell).

EQUIPMENT AND METHODS

The topographic network is based on precisely geo-referenced benchmarks used to carry out the topographic measurements of beach profiles and the DTM. 71 profiles were surveyed on 28 beaches between 2008 and 2018. The objective was to determine the states of modal behaviour of the beaches, and eventually characterize their capacity of resistance to a high-intensity hazard and the associated resilience processes. The DTM were measure using a *Leica GS15* differential GNSS. The data from the headends were recorded in UTM 20 coordinates on the WGS 84 ellipsoid. A *Leica TS06* laser theodolite was used to monitor the beach profiles. These profiles allowed us to train students of the University of the Antilles to topographic measurements by theodolite. As a result, these students were able to carry out regular reiteration of the measurements and feed the data base over a period of ten years.

The coastline evolution was analysed comparing a serie of IGN (National Geographic Institute) ortho-photos from 1951 to 2017. As far as possible, the shorelines defined here are indicated by waterlines along the land-water interface; In microtidal context

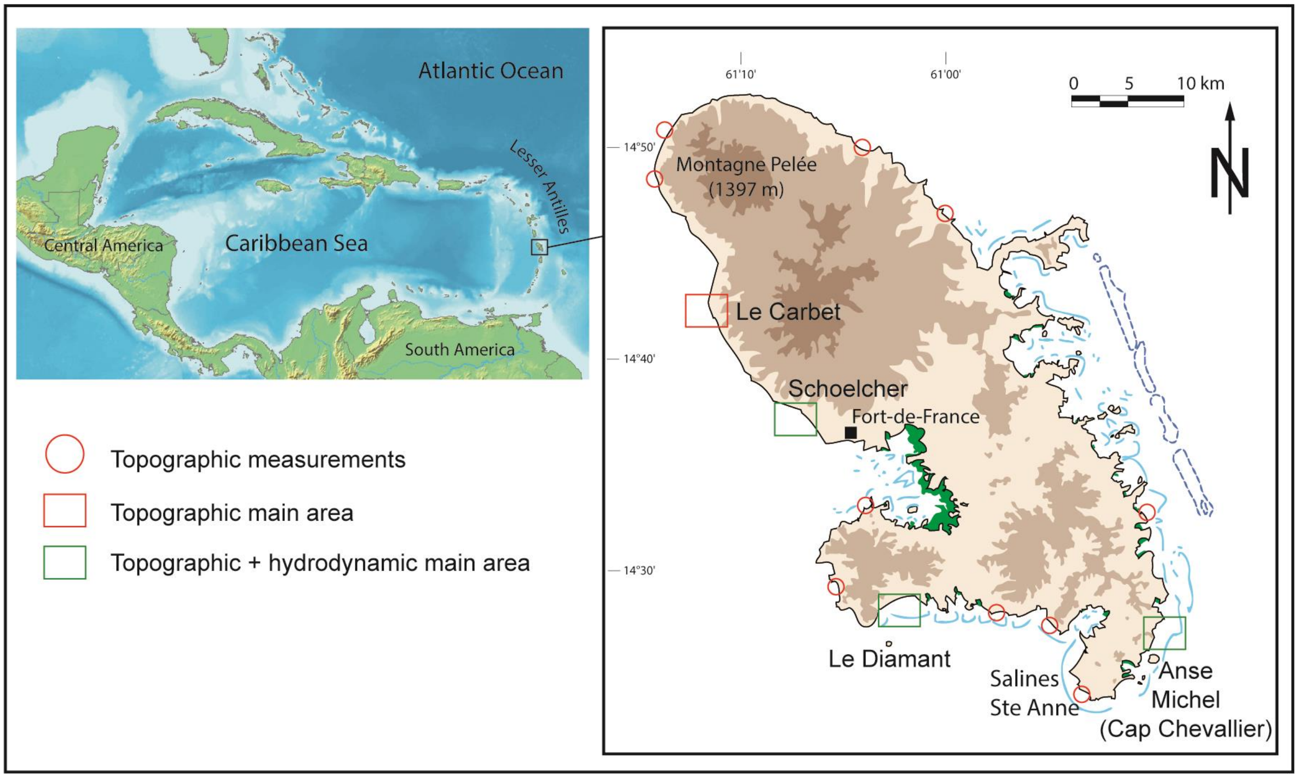

Figure 1. Location map of the study area.

(range 0.4 m) and during calm weather conditions, these shoreline shows a low variability, On some other sites, the vegetation-sediment boundary was chose as shoreline. In the Antilles, psammophilous plants of the *Ipomoea* type bordering natural beaches usually provide a good shoreline indicator. The waterlines were digitised and treated under DSAS (Thieler and al., 2009), then more recently under MobiTC (CEREMA). *In-situ* hydro-sedimentary experiments (meteorological, current and wave measurements, sedimentary traps, etc.) were carried out in 2011, 2013 and 2015 on the sites of Anse Michel, Schoelcher and Le Diamant, to characterize the forcing and swell-dissipation capacities, as well as the associated sedimentary transport. A DAVIS Weather Monitor 2 station was used to record meteorological parameter. The anemometer and the weather vane were fixed onto a 6-m-high mast, which was positioned on the first-floor terrace of the lifeguard station on Le Diamant Beach. This open location, away from any direct obstacles, allowed the optimal recording of winds from all directions. However, the hills to the north are an obstacle for the north-easterly winds. The console of the station containing the barometer was located in the lifeguard station itself. A SENTINEL 1200 Hz current-meter/swell gauge (ADCP: *Acoustic Doppler Current Profiler*) placed on the “master profile” for topographic monitoring at the Le Diamant site was used to measure the energy and parameters of the incoming swell in the system under study (*boundary layer characteristics*). This enabled to monitor the evolution of the swell characteristics up to the foreshore via measurements by pressure sensors located along the master profile. an array of NKE (SP2T) pressure sensors were also deployed. Since these sensors have small dimensions (120 mm x 25 mm), they do not require cumbersome logistic means for their installation. With a precision of 3 cm and a resolution is 0.3 cm, the sensors can be used down to a maximum depth of 30 m. In total, six sensors were used, fixed to metal rods so they could be installed on the sandy seabed or coral reefs. Finally, Kraus-type traps (Kraus 1987; Rosatti and Kraus, 1989) were used to sample sedimentary particles according to four cardinal directions during a tidal cycle. The deployment of these traps allows measurement of the transport of sediments in suspension, saltation and reptation. The traps are made up of 63 µm-mesh nets which are fixed to a standardized metallic mouth. The first two nets are oriented parallel to the coast (trending NW-SE, but referred to here as the N-S axis for simplification), while the other two are perpendicular to the shoreline. This arrangement enables determination of the principal sedimentary fluxes on a beach: longshore (longitudinal to the beach) and cross shore (transverse to the beach). Each trap was positioned on the immediate shoreface, near the swash zone. The chosen duration for trap deployment was 24 hours, with an emptying of the nets every six hours. The collected sand was then dried, weighed and samples were sent to the sedimentology laboratory of the UMR 7330 CEREGE for grain size analysis.

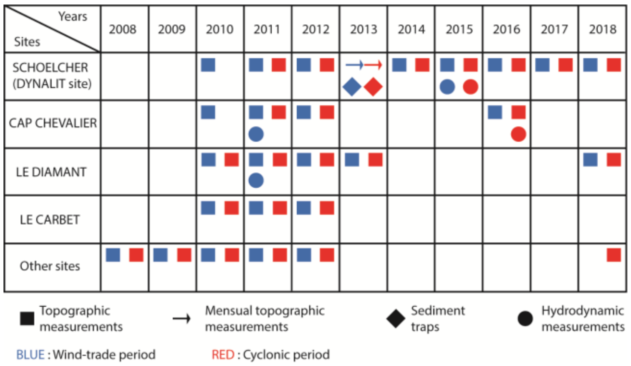

Figure 2. Location and chronology of the measurements.

ANALYSIS OF NETWORK OBSERVATIONS

Coastal Analysis

Coastline evolution analysis was carried out for the sites of Le Carbet, Schoelcher, Le Diamant, Salines de Ste Anne and Ste Marie, using aerial vertical photographs, from 1951 to 2017. The results demonstrate a low erosion tendency in the long term, but not very significant in the medium to short term. On the longest coves, we can clearly identify sedimentary cells. However, the beaches show erosion dynamics in more recent years, with slight but constant shoreline retreat (between 0.3 to 0.6 per year). On the cove of Salines de Sainte Anne, a sedimentary circulation cell is detected between 1951 and 1982. The littoral drift is clearly from east to west. From 1982, erosion spreads over the entire beach and the rate of erosion is higher. The same trend is observed on Anse Michel beach, with an exacerbation of shoreline dynamic trends from 1992 onwards. The mangrove forest front remains stable, with some vegetation even advancing towards the sea. The pocket beaches are relatively stable, even though markedly erosion in the medium term (under 0.1 $m.y^{-1}$ in 10 to 20 years), but show non-negligible variability in the short term (over 0.3 $m.y^{-1}$; 1 year; 5 years). The dynamics of the Martinique beaches are essentially expressed by transverse sand transport, with massive export of sand towards the shoreface in paroxysmal situations and a relatively rapid return of this sand in modal situations. The end-result of these alternations in transverse movements is negative sand budget in the medium and long term, with sands remaining permanently trapped on the shoreface, especially in the north-Caribbean municipalities where the shoreface slope is steep. The longitudinal cell trends of the longest beaches, clearly observable between 1950 and 1980 (Figure 3), tend to be replaced by these transversal dynamics over the last decades.

Topographic Analysis

The topographic analyses are based on a dense network of surveyed profiles (71 profiles carried out on a total of 28 beaches).

The measurements are essentially concentrated on four sites: Schoelcher, Le Diamant, Le Carbet and Cap Chevalier (Anse Michel in Sainte Anne). On these four sites, the objective is to understand the modal and seasonal morphosedimentary evolution so their functioning can be characterized in four different geographical contexts. Special attention is paid to the rates and volumes of longshore and cross- shore sediment transport imposed by modal forcings (especially swell). In the other sites, the topographic profiles represent an initial state baseline from which it is possible to implement a repetition of measurements in the case of major weather-marine events, to determine the impact of storms and characterize the resilience mechanisms. The beaches of the municipality of Schoelcher (Anse Madame, Anse Collat and Anse Madiana) were chosen for regular topographic surveys because of their dimensions, in conformity with the modal dimensions of coves on Martinique (200 to 400 m long) (Figure 4) - large enough to detect significant longitudinal and transverse trends. Some topographic profiles carried out after 2008, along with others surveyed on a regular basis (monthly) since 2013, have all been integrated into the national data base SNO-DYNALIT since 2015. Digital terrain models are also established twice a year (May: end of the dry season; December: end of the cyclone season). Analysis of the whole topographic dataset shows that Anse Madiana is evolving according to two patterns: (i) transverse sand transfers driven by short paroxysmal phases; (ii) a modal SE-NW longshore sand transfer, which does not exclude temporary alternating cross shore transport directions. It is noteworthy that Anse Madame displays a particular evolution. First of all, as confirmed by the analyses of aerial photographs, this beach in the long term shows a modal dominant NW-SE oriented longshore drift, which contrasts with the other modal drifts in this sector of Schoelcher beaches (SE-NW). This situation is linked to the presence of a major anthropogenic structure: the “Place des Arawaks”. This structure creates a rotation of the modal swell due to diffraction. The obliqueness of the swell at the upwash is therefore modified, creating a drift towards the SE. In paroxysmal situations, when the swell is surging (tropical waves, long swell wave trains, sometimes of cyclonic origin), this modification due to diffraction is less clear and the sediment transport resumes its SE-NW direction. During 2013, this beach underwent longitudinal sedimentary fluctuations caused by variations in the swell system (beach rotation), corresponding to two diffractive NW-SE phases and one paroxysmal SE-NW phase (figure 4). The Anse Collat beach exhibits a clear NW-oriented longshore drift. The effects of weather-marine events of greater intensity can also be observed, characterized by an erosion scar and a sand slide towards the immediate adjoining shoreface (Dolique and Charpentier, 2014a, 2014b). The sedimentary material is then reworked by the modal agitation. The redistribution of sand over the whole profile is more efficient during the efficient swell regime (trade-wind period). The results of our measurements demonstrate that, in the short term (month to year), these beaches evolve rapidly and with cross-shore alternating phases of transport direction. In the medium term, their morphology is driven by longshore drift (longitudinal transfers), which is admittedly weak but morphologically efficient (Dolique and Charpentier, 2014b; Josso, 2015).

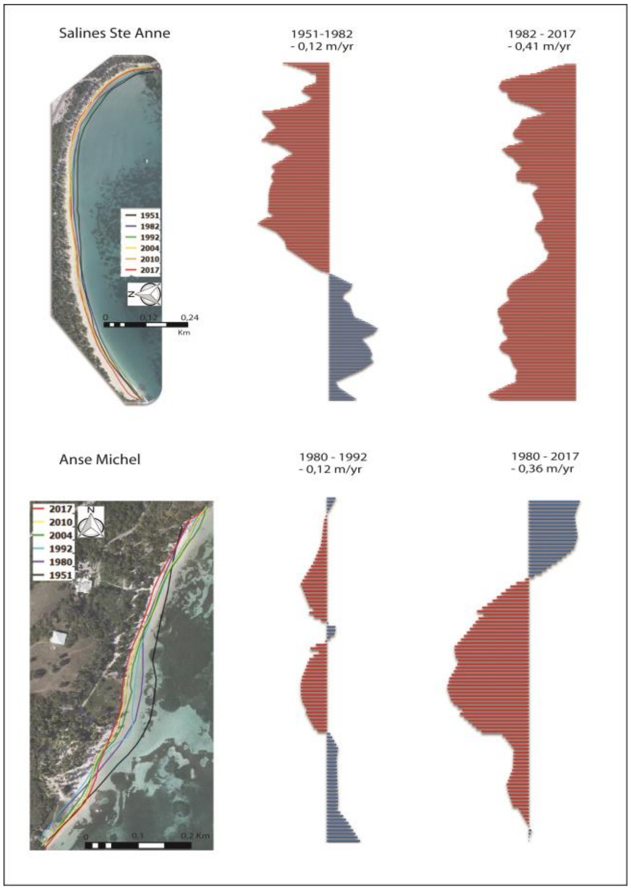

Figure 3. coastline analysis and trends (Salines – Anse Michel, Ste Anne; aerial photographs).

The observations carried out on these beaches lead us to define several tendencies:

(i) The Schoelcher beaches undergo cross-shore alternations of sedimentary transport (phases of erosion with downward movement of the sand in the profile, which quite often alternate with phases of accretion accompanied by shoreward movement of the sand in the profile). The phases of erosion are often linked with short but highly intense weather-marine events (cyclonic swells, swells generated by trade winds or tropical waves). These phases can occur during any season of the year, but are often more frequent in the period associated with trade winds (December to March) and more intense in cyclonic periods. The phases of accretion occur during periods of moderate agitation, when swells are strong enough to be constructive, but not strong enough to be destructive. As a result, the material moves upwards on the profile and, in the case of the strongest waves, accretion can reach the top of the beach.

(ii) The longshore drift has a clearly identified SE-NW orientation, based on observations of aerial photographs as well as topographic measurements. On Martinique, the longitudinal sediment transport is often marked by alternating phases (the sedimentary material moving back and forth) according to the seasonal direction of the swell. But, in the long term, the dominant drift is SE-NW on this part of the Martinique coast; the Atlantic trade-wind swell is subject to diffraction in the south of the island through the Saint Lucia Channel, as well as refraction at the entrance of the Fort-de-France Bay.

(iii) Anse Madame is an exception to the pattern described above. Indeed, the "Place des Arawaks" is an anthropogenic structure on the seafront which modifies the path of the swell wave train by diffraction, creating a NW-SE drift expressed by the accumulation of a sedimentary prism against the seafront and simultaneous erosion to the NW, with the walls being attacked by the waves. In cases of stronger phases of agitation, this diffraction is less efficient and the sediment transport returns to its natural SE-NW path.

(iv) The morphology of the beaches shows regular seasonal variations in longitudinal sediment transport. These variations are more random and irregular in the case of transverse transport. In the dry season (February to June) the agitation conditions are weak and the modal trade winds are light. The waves have no effect whatsoever on the global morphology of the beach. The sand moves within the profile (transversely and longitudinally) only during paroxysmal phases (sudden, intense and rapid increase in agitation of the water surface, with higher and stronger waves). This situation generally causes an erosion of the beach profile with slipping of the material towards the nearby shoreface. These paroxysmal phases can occur throughout the year, even though they are more frequent in the trade winds season (December to March) and more intense in the cyclone season (June to November). The recovery of the beach profile occurs during periods of moderate turbulence, with reconstructive swells redistributing the shoreface berm sediments over the whole of the profile, thus leading to growth of the beach.

Sedimentary Trends

To determine the dominant fluxes of sediment transport under modal conditions, we carried out trapping experiments to measure particle fluxes near the seabed under representative hydrodynamic conditions. For this purpose, the Kraus trapping technique (Kraus, 1987; Rosatti and Kraus 1989) was implemented. Two campaigns were carried out on two sites: the first at the end of the dry season (June 2013) and the second at the end of the cyclone season and the beginning of the period of sustained trade winds (December 2013). The two sites selected here are Anse Madiana and Anse Collat. The volumes collected in "Kraus streamer traps", positioned in relation to the longshore – cross-shore cardinal directions, were analysed and weighed to acquire data for the understanding of sedimentary transport and its spatial pattern.

The results (Figure 5) demonstrate a clear preponderance of cross-shore fluxes at the expense of longshore fluxes. This situation is typical of the fluxes observed on small beaches of this type (pocket beaches, cove beaches, enclosed beaches…) particularly in the short term, corresponding to a situation where sediment transport is controlled by swash movements. (Dean, 1991; Dolique and Anthony, 2005; Héquette *et al.*, 2001;

Seymour and Castel, 1989). During the hurricane regime (measurements of June 2013), swells transported sand to the top of the beach (84.18% of the total trapped volume), whereas during the trade winds (December 2013 measurements), the waves carried the sand towards the coast (72.77% of the total trapped volume). In periods of weak trade winds, a constructive swell generates a positive orbital current. This means that the modal transport of sand is oriented to the coast and that the beach rebuilds its stock of sand from the stocks located in the shoreface. During the trade winds season (period of increased force of trade winds from the beginning of December to the end of March), or in paroxysmal situations (tropical waves, storms, cyclones, cyclonic swell, etc.) the swell is surging, with a significantly increased wave height, creating a high-energy swash; the orbital currents of the waves are termed "negative" (Hequette, 2001) and carry large quantities of sand from the beach towards the shoreface, thus causing beach erosion (often temporary in the short term). Longshore fluxes are generated by modal currents resulting from swash dynamics when the swell is oblique to the shoreline (longshore drift). These fluxes are less clearly expressed in terms of trapped volumes, but nevertheless show a transport direction on both beaches and for both periods which is in conformity with the modal longshore drift already observed previously by topographic measurements and the analysis of aerial photographs (Figure 3). The measurements also show a reversal of the direction of the dominant sediment flux linked to seasonality. When the trade winds are light, a constructive swell generates a positive orbital current. This means that the modal transport of sand is directed towards the coast and the beach is nourished with sand derived from sedimentary bodies on the immediate shoreface. The Madiana and Collat beaches show mainly transverse sedimentary transport, leading to seasonal exchanges of sand in the profile (Dolique and Charpentier, 2014a). During periods of light trade winds (and more globally under agitation conditions ranging from modal to calm), the constructive swell progressively brings up the sand from bodies in the immediate shoreface to the emergent surf zone, where it is then redistributed throughout the profile by the highest waves (run-up). In the well-marked trade winds season (from December to March), the more energetic swells carry sand from the beach towards the immediate shoreface, where it is deposited below the surf zone in temporary sink which serves to re-nourish the beach during the next constructive season. Here, the longshore drift is poorly identified towards the NW sector. The resulting deposits are accumulated over a longer time scale than the observation period in the framework of this study. In spite of the small volumes trapped here, the SE-NW longshore drift is not negligible, as observed during the sedimentological study. This trend can also be reversed over the period of a year, but the final result remains SE-NW (Dolique and Charpentier, 2014a).

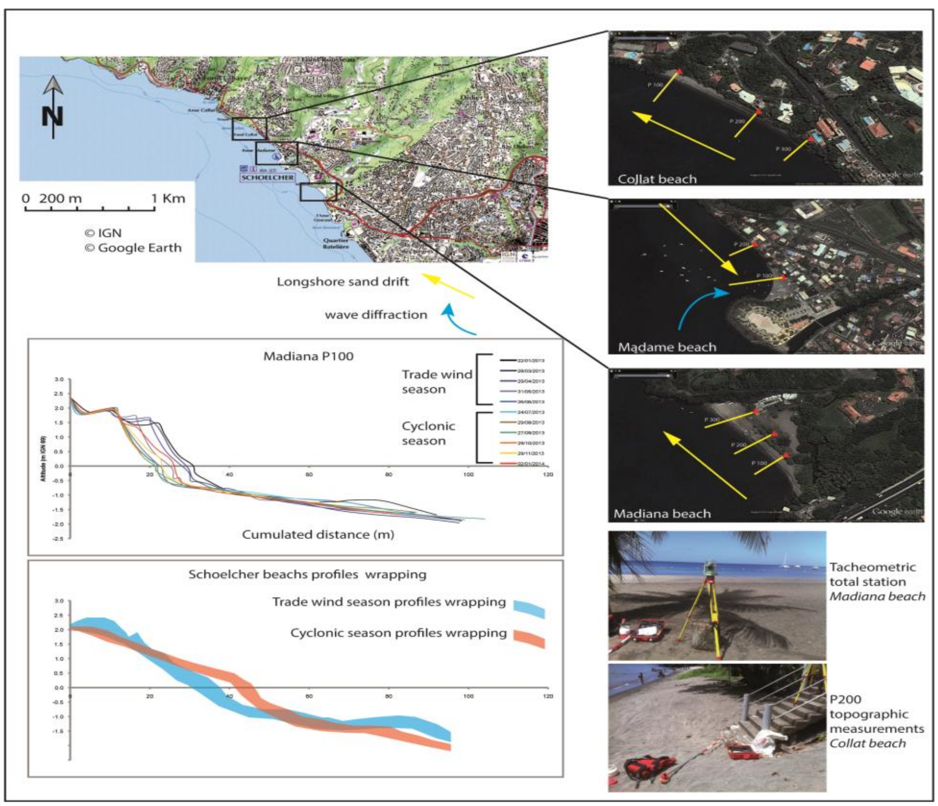

Figure 4. Topographic measurements and trends (Schoelcher).

Oceanic and Shoreface Parameters

A field campaign to install morphodynamic instrumentation was carried out in November and December 2011 by a scientific consortium of four different universities. This involved deploying an array of instruments (meteorological, wave-gauges, current and micro-topographic sensors, sedimentary monitoring, etc.) to investigate the role of local forcings and the modalities of energy transfer at the entrance of the beach system, in two different shoreface contexts: Anse Michel at Cape Chevalier and Anse du Diamant, which represent a coral lagoon and an open bay, respectively. At Anse du Diamant, the instruments were set up in front of the lifeguard station, in the axis of a topographic profile, to investigate the influence of meteorological parameters, especially the wind, on the water mass and the behaviour of the swell during its propagation. swell measurements were carried out at several points (offshore at Saint Lucia buoy, on the shore and in the surf zone). The role of nearshore currents also needed to be analysed.

At Anse Michel, the objective was to see how the energy of the swell is dissipated along a reef-lagoon-beach line.The ADCP was deployed at a mooring offshore from the reference profile on the 25 November and recovered on 3 December 2011. The deployment as well as the recovery of the instrument at the end of the measurement period was carried out at Anses d'Arlet by a fishing boat from Petite Anse, aided by two divers from the Martinique Marine Environment Observatory (OMMM). The mean recorded significant wave height of the swell (Hs) is of the order of 0.35 m, reaching a maximum of 0.72 m when SW winds are blowing at around 8 m.s-1. Generally, this series of measurements reveals a very clear correlation between the wind speed and the significant wave height of the swell measured at around 5.5 m depth. The Hs increases systematically as soon as the average wind speed exceeds 5 m.s-1 (Figure 6). However, the increase in Hs is not proportional to the wind speed, but shows different responses to winds having the same speed but with different directions. This clearly demonstrates the impact of different ambient winds, whose prevailing directions (notably winds slightly oblique to the coast line) have a strong influence on the Hs. The direction of the swell remains relatively stable, propagating towards the SSE, whatever the speed and direction of the ambient winds. The significant period of the swell, measured during this campaign, fluctuates between 4 and 9 s, with a mean value of around 7 s. This type of swell is sensitive to the variations of speed and direction of the wind and can momentarily be replaced by wind waves (with periods of about 4 s) during breezes. The speed and direction of the swell show a clear sensitivity to variations in meteorological conditions. A maximum wave speed of around 0.15 m.s-1 is recorded for the average swell when SE winds are blowing at more than 8 m.s-1. However, The absence of a wave speed peak can be noted when the SE wind is blowing at more than 12 m.s-1 (in contrast with the Hs peak associated with this event). Thus, it can be supposed that the height of the water column plays a role in determining whether or not wind shear has an impact on wave speed. In fact, when the average water depth exceeds 5.5 m, the impact of the height of the water column remains negligible. As a result, the response of the wave speed to wind speed follows a succession of relatively long wind events and is not associated with wind events of short fetch. This can be observed on the two measured peaks in wave speed following a succession of three wind peaks between 26 and 28 November 2011. The analysis of a tide under relatively modal weather conditions allows us to define the bi-directional character of tidal currents at Diamant in the absence of a meteorological forcing induced by the winds. The flood tide current is more stable, flowing towards the East and South sectors, while the ebb tide is less stable with a diffuse flow mainly towards the NW and NE. However, the flood tide current runs faster than the ebb tide (Figure 6). The instruments were deployed so as to capture the evolution as well as the spatial and temporal differences in the conditions of agitation on the two studied sites. The measuring instruments were deployed at the Anse Diamant site between 24 November and 3 December 2011, close to the lifeguard station. The pressure sensors were positioned along the axis of the topographic profile. The first sensor was placed in the surf zone at the level of a sand bar and at an average depth of about 1 m. The second sensor was placed further offshore at about 100 m from the beach at an average depth of 5.2 m.

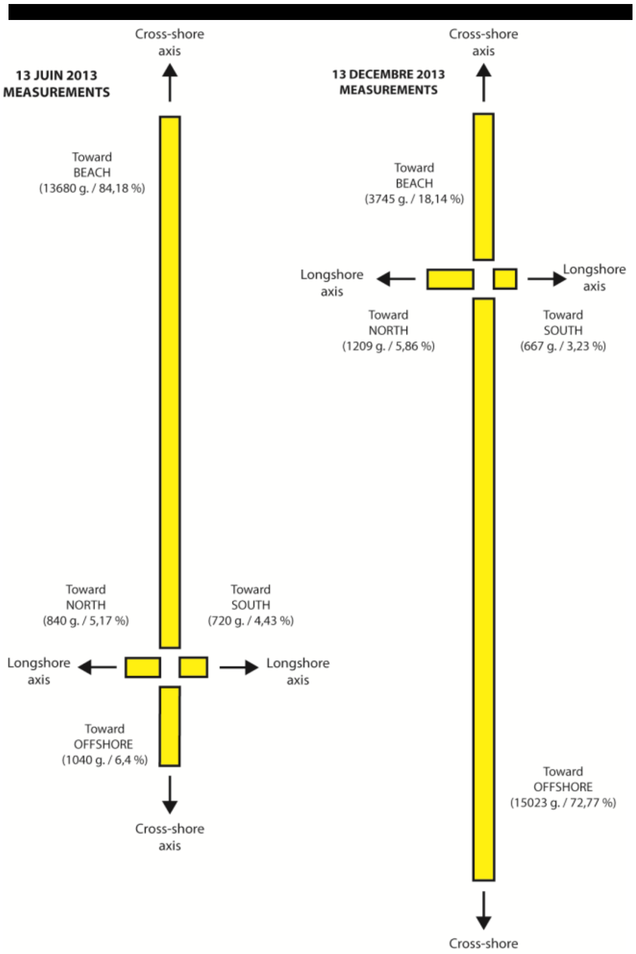

Figure 5. Longshore and cross-shore fluxes (Schoelcher).

The recorded spectral peak periods tend to increase between the beginning and the end of the campaign according to the meteorological conditions encountered, showing values of the order of 4 to 9 s. These peak periods are often longer at the level of the sensor at the bottom of the beach, evidently due to the reflection of waves on the beach. Figure 6 shows the swell spectra associated with a selection of measurements representative of calm and agitated weather conditions. In calm weather, the swell spectrum shows a succession of peaks (between 0.10 and 0.20 Hz, i.e. 5 and 10 s), evidently corresponding to the swell created by trade winds in the Martinique region and in the Atlantic. It is noteworthy that the spectral energy is higher at the sensor placed at the bottom of the beach than offshore, especially for low frequencies near 0.10 Hz. In conditions of stronger agitation, the swell spectrum shows a large increase in energy and a marked peak of 0.16 Hz (6s) offshore. This peak is linked to short- period waves generated by squalls near the island. We also observe that the swell spectrum recorded by the offshore sensor shows a wider range of frequencies, with higher energy at low frequencies compared with the sensor on the coast. Three pressure sensors were deployed on the Anse Michel site between 25 November and 3 December 2011. These pressure sensors were positioned along the axis of a topographic profile. The first sensor was placed at the bottom of the beach in a sandy zone at an average depth of about 0.3 m. The second pressure sensor was positioned on the inshore side of the coral reef, at about 250 m from the beach at an average depth of 1.65 m. It was placed just behind the coral reef flat on a sandy zone colonized by a sparse phanerogam sea-grass bed. Finally, the third pressure sensor was deployed on the oceanward side of the coral reef on the outer slope at a depth of 1.35 m. For the pressure sensor situated on the outer side of the reef, the significant wave height of the swell varies between 0.6 and 0.9 m. At this site, there is no apparent link between the significant wave height of the swell and the tidal cycle, thus suggesting that the recorded waves actually represent incoming oceanic waves (Figure 6). On the contrary, for the two other sensors positioned behind the reef barrier, wave heights are very strongly influenced by variations in water level, even if these are very limited in the microtidal environment of Martinique. The sensor behind the coral reef flat records wave heights in the range of 0.22 to 0.32 pressure sensor m at high tide and 0.07 to 0.12 m at low tide. For the sensor at the bottom of the beach, maximum heights vary from 0.15 to 0.25 m at high tide, while recorded wave heights are close to zero during low tides. The difference of significant wave height measured between the outer slope of the reef and the inshore zone highlights a major reduction in wave energy during propagation towards the coast (Jeanson et al, 2016). Analysis of the peak periods reveals a wide variability of results depending on the instruments. The peak periods of waves recorded on the outer side of the coral reef vary between 8 and 9 s, which corresponds to the swell generated by trade winds on the Atlantic. At the back of the reef, peak periods are much more variable. Even if the predominant waves are always observed with periods of 8 to 9 s, at low tide the peak periods are much longer (between 30 and 90 s). This is because of the filtering of waves and the transfer of energy from high frequencies towards low frequencies during low water levels on the reef flat. This phenomenon is even more clearly expressed at the bottom of the beach where the peak periods range almost exclusively from 30 to 90 s and where infragravity waves are predominant. This can also be clearly seen from the analysis of swell spectra, which shows, as well as wave energy reduction, a modification of the spectrum caused by the reef structure (Jeanson et al, 2016). Measurements at the Diamant site clearly demonstrate a strong dependence of local meteorological conditions on the structure of swell spectra and energies which control the forcing of beaches. Energy is essentially distributed by wind-waves generated by coastal winds. Some more distant frequencies, originating from Atlantic waves, are able to reach the beaches during paroxysmal events (Figure 6, Le Diamant). Measurements at Anse Michel show the crucial role played by the reef barrier in dissipating the energy of incoming swell, and the importance of lagoonal sea-grass beds in the dispersion of long-period infragravity swells (Figure 6, Anse Michel).

Paroxysmal Forcing (example from hurricane Tomas)

Hurricane Tomas passed across the south of the Lesser Antilles on 30 and 31 October 2010. It generated strong winds on Martinique, but especially strong swells offshore (over 7m troughs in the Saint Lucia Channel (Météo-France web data), and caused huge breakers on the beaches in the south of the island, removing considerable quantities of sand. At Diamant, for example, our measurements make it possible to quantify the erosion over several sectors of the beach. Regular measurements have been subsequently carried out to provide a better knowledge of how sand progressively returns to the top of the beach (resilience).

The comparison of topographic profiles shows a linear retreat of the beach ranging from 5 to 13 m and a vertical downwasting of about 1 to 1,5 m (Figure 7). The greater part of the sand is carried towards the shoreface, about 10 m away from the strand line, creating a breaker bar. The rate of resilience was characterized by volumetric measurements made on specific points of the profiles. An initial large mass of sand returns rapidly during the first 20 days (Figure 7). Even though the resilience process is slower, it takes place at an irregular pace depending on the variations in swell height. Finally, the paroxysmal episode results in a loss of sand volume in the sedimentary budget. This loss is not totally compensated for in the long term.

SYNTHESIS OF NETWORK OBSERVATIONS

Short-term and Immediate Processes

The results of topographic observations, especially after storms or high energy conditions, shows that on an instantaneous time-scale, Martinique beaches evolve along a cross-shore axis.

In a modal situation, on beaches with a sea-grass bed in the lagoon, swells combined with a low tidal range bring drifts of vegetal material coming from the seagrass shoreface**.** When a high-intensity weather-marine phenomenon occurs, the swash carries the sand away very rapidly towards the shoreface due to an asymmetry in favour of the backwash; the beach profile becomes steeper and a bar appears in the near subtidal zone (Dean, 1991; Greenwood and Osborne, 1991; Pilkey *et al.*, 1993). The run-up also projects sand towards the top of the beach, forming an upper beach berm (Figure 8 short term situation). When modal conditions return, or during paroxysms of lesser intensity, more constructive swells move the sand up the beach, but more rapidly than previously thought (Bigot, 2015; BRGM, 2014; Coicaud, 2015; Dolique and Charpentier, 2014b; Josso, 2015; Reine dit Reinette, 2014). Here, we are dealing with the notion of triggering levels at the water/sediment interface, but the in fluence of this factor is so far unknown and would warrant further exploration in the framework of future studies.

Our measurements carried out during cyclone Tomas (2010), along with more empirical observations following cyclones Irma and Maria (2017), show that the retreat, even the levelling down of the beaches, does not necessarily have catastrophic consequences over time, insofar as there is a rapid return to an initial state (resilience) (Figure 8; short term situation). However, this resilience remains incomplete; part of the sand, displaced towards greater depths, cannot be moved back, which over time influences the sedimentary budget which becomes negative.

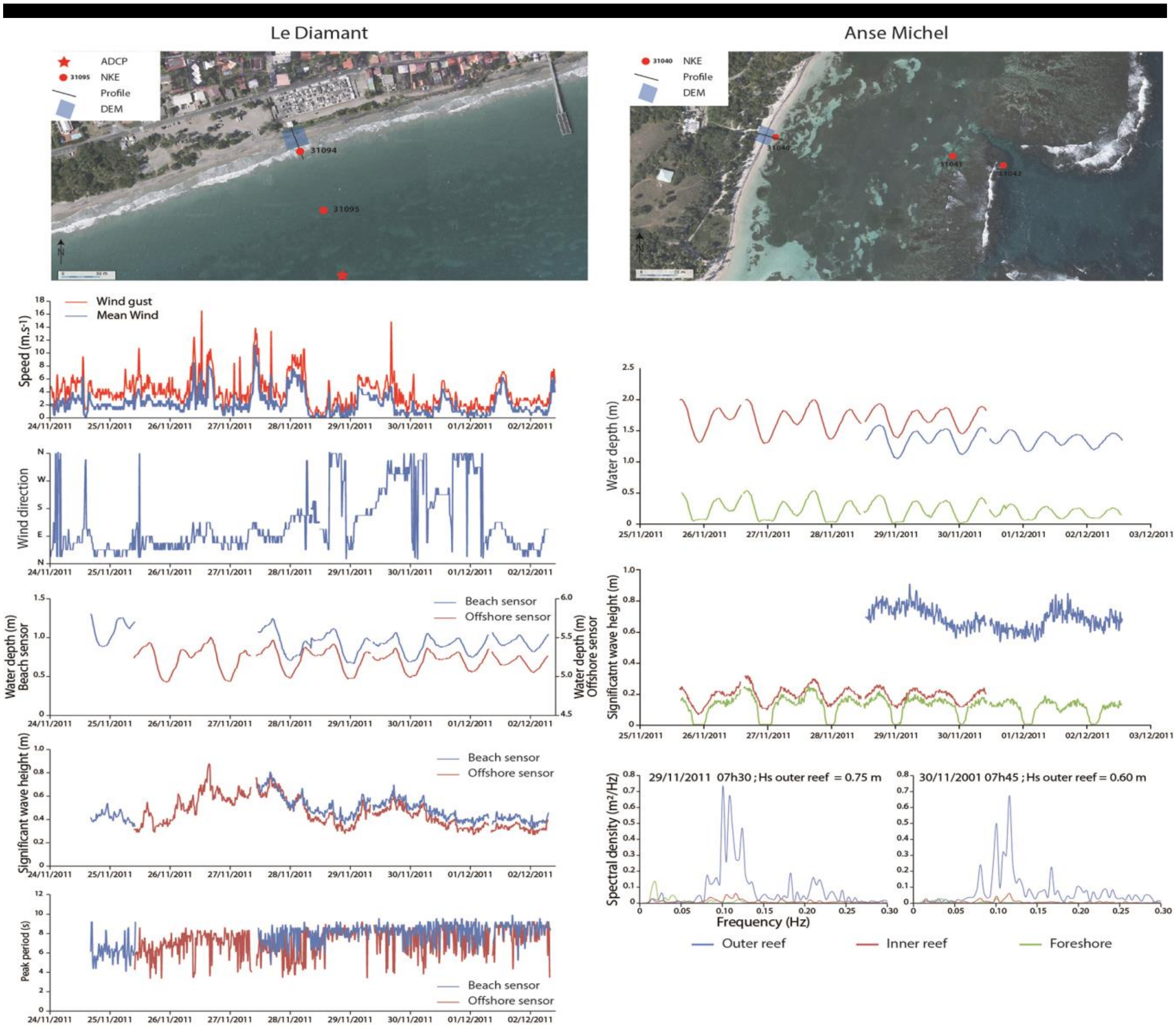

Figure 6. Hydrodynamic measurements (Le Diamant and Anse Michel).

Intra-annual Seasonal Trends

On the intra-annual scale, beaches show weakly developed longitudinal sedimentary dynamics (but which can sometimes still be observed) and strong transverse dynamics under the influence of weather-marine paroxysms. Beach evolution is controlled by variations, either random or seasonal, of the agitation conditions (wave height, orientation of swell fronts). Transverse variations of the beach profile are linked to phases of agitation having essentially seasonal frequencies. In the light of our results, it appears that the most active period for beach evolution is not the cyclone period (June to November), but rather the period of strengthening trade winds between December and February (Dolique and Charpentier, 2014b). In fact, during this period, short phases of agitation, linked to waves generated by stronger trade winds, lead to cross-shore transfers of the sand towards the shoreface (Figure 8 medium scale).

Numerous studies have shown the significant impacts of tropical storms and hurricanes on the evolution of beaches (Bourrouilh-Le Jan, Beck, and Gorsline, 2007; Ciavola and Coco, 2018; Nagarajan, Khamaru, and De Witt, 2019; Fritz et *al.*, 2007; Sallenger *et al.*, 2006; Wang and Horwitz 2006; Zaho, 2018). Therefore, it is often accepted that the morphologically most active period is the hurricane season. Our observations show that the cyclonic season (when the north-easterly trade wind system is weaker, in favour of south-easterly air flow) is associated with surf conditions that are more conducive to a progressive upshore movement of the berm sand, from the shoreface towards the beach (Figure 8 medium scale).

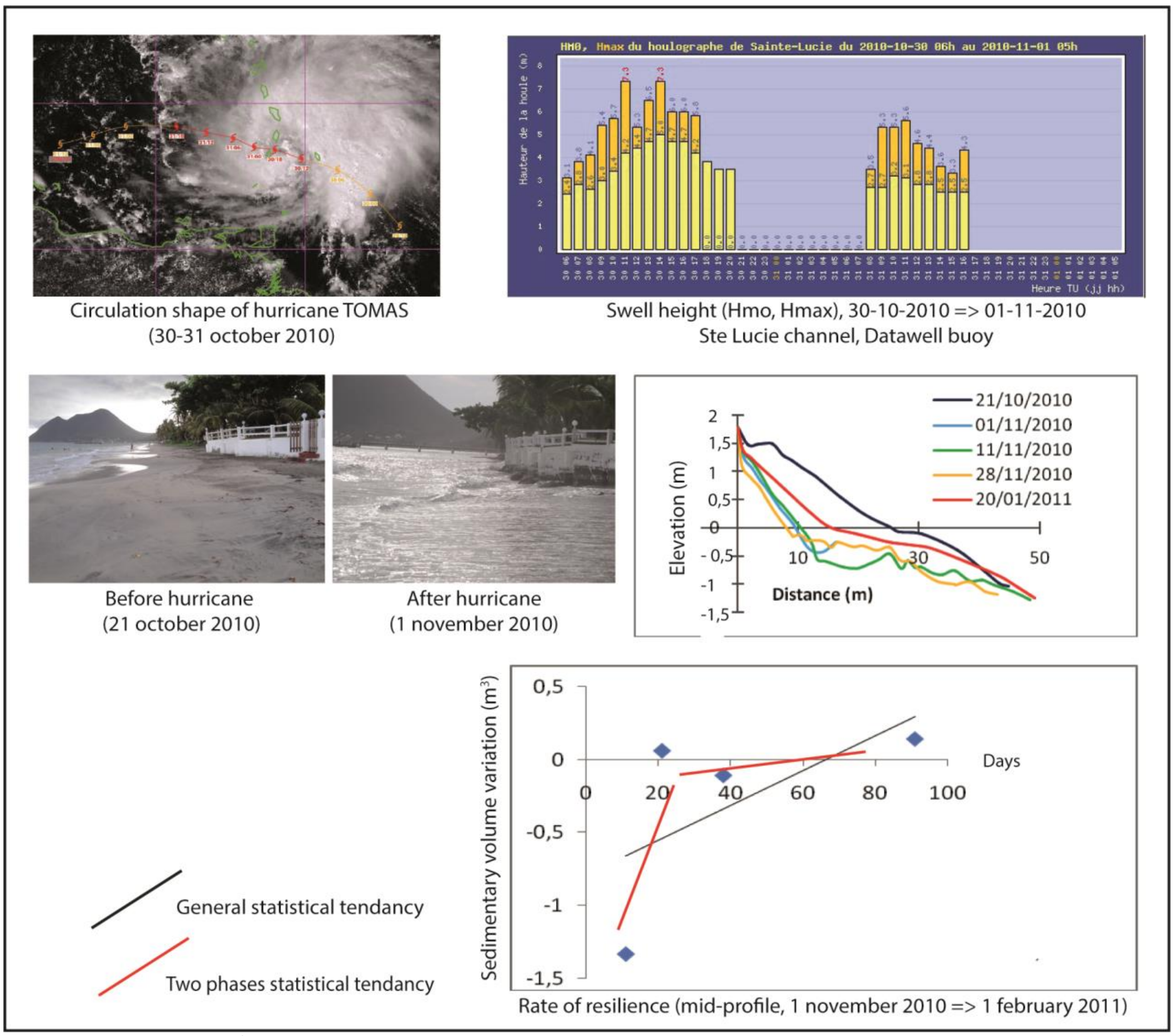

Figure 7. Impact and resilience of hurricane TOMAS (October – November 2010).

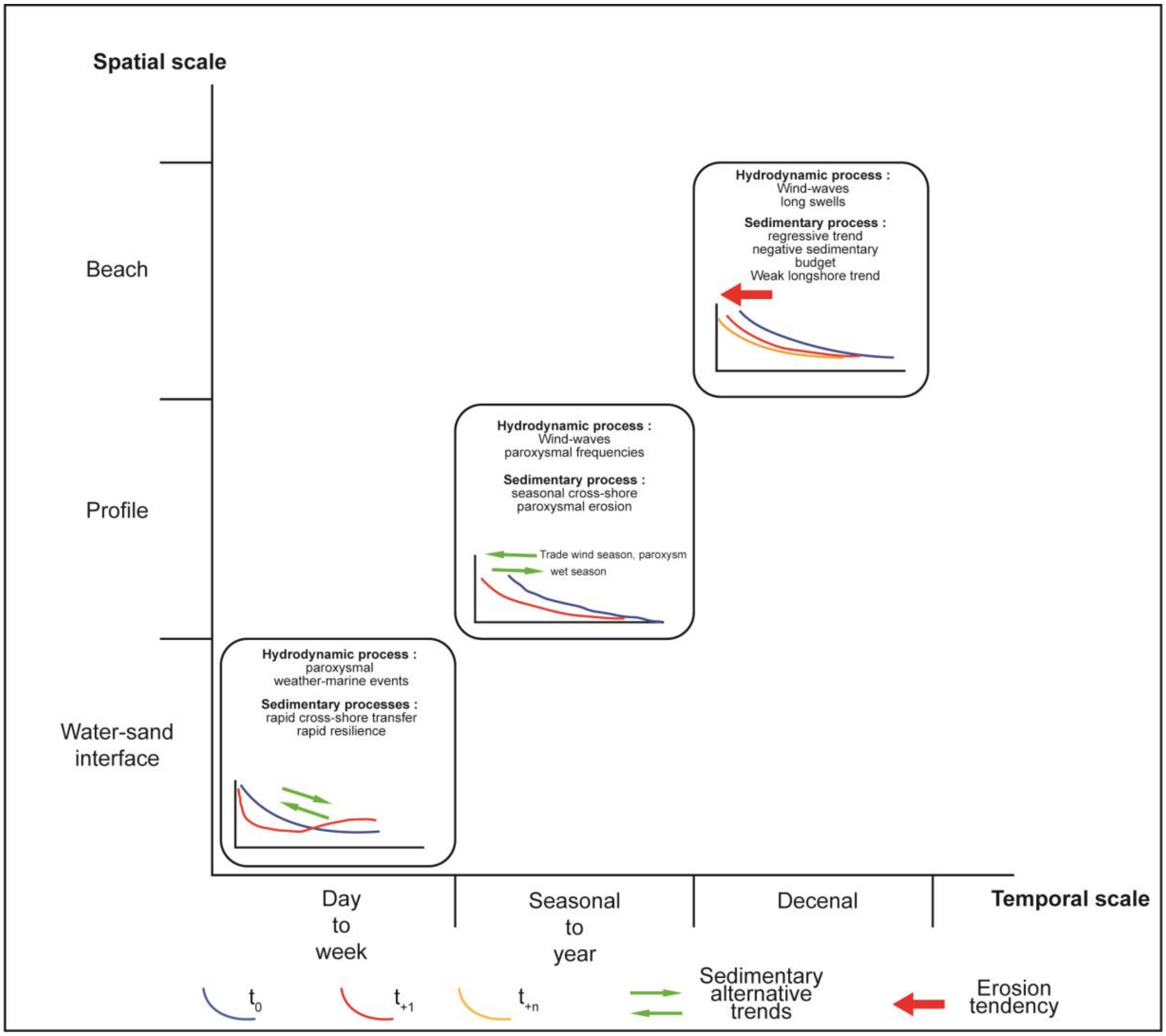

Figure 8. Spatio-temporal coastal dynamics in Martinique: synthesis. (This figure shows the interlocking of spatio-temporal scale governing the evolution processes of Martinique beaches).

On the other hand, retreat of the profile will be rapid if a random cyclonic event such as a hurricane occurs during this period, either offshore or near the island, generating a paroxysmal swell of exceptional magnitude.

In the longer term, and on a multi-annual scale, this alternation of cross-shore sedimentary dynamics causes a progressive loss of beach sand in favour of the shoreface (reduction in the overall volume per linear metre, calculated on the Schoelcher profiles, (Figure 4). This means that, in the long term, the beaches show a trend towards erosion, as previously observed on the scale of the last half century (Saffache and Desse, 1999).

Long-term Trends

At the scale of the whole island, majority of beaches show erosive dynamics which confirms their overall fragility. However, this evolution remains barely perceptible over a period of about 70 years. This appears to be in contrast with certain coves and mangrove fronts, where there is a trend towards accretion (Saffache and Desse, 1999). BRGM (2013) showed that the evolutions were weak in the short term. The observations of Monnier (1825), as well as the studies of Saffache (1998) have shown that the Martinique beaches has progressively lost part of their surface area, especially in sandy coves. The reasons for this fragility are numerous and can be linked to anthropogenic activities at different times which exacerbate the natural reduction in the volumes of sedimentary bodies after the latest Quaternary marine transgression: removal of sand for the construction industry or developments sited too close to beaches (Saffache, 1998), thus preventing natural exchange with sand bodies at the back of the beach; uprooting of psammophile plants, such as *Ipomoea pescaprae,* which fix the sand, and their replacement by coconut palms (*Cocos nucifera*) with a lower fixing potential;

replacement of black or grey volcanic sand with white coral sand for the needs of the tourism industry or progressive degradation of coral reefs by urban sewage (Saffache, 1998). These parameters have had a negative impact on the sedimentary budget of the beaches.

Over the last 30 years, this coastal retreat seems to have accelerated. On the 2 sites presented here and representative of the Martinican coves, the analysis of aerial photographs shows an increase in the amount of shoreline retreat. Some beaches, formerly marked by a morphology due to longshore drift (where sectors in erosion contrast with sectors in accretion, such as at Diamant or Salines de Sainte Anne), now show a shoreline that is entirely in erosion, leading to a progressive smoothing out of differences in beach width. From our observations, it is still too early to judge the reasons for this current acceleration in erosion. The reduced volume of sand bodies, especially on coral reef shores, is evidently to be evoked.

The morphodynamics of beaches can be divided into different sectors according to their geometry, especially the factors of exposure to dynamic agents: beaches open to direct trade wind swells (i.e. Le Diamant), beaches protected by a coral barrier (i.e. Anse Michel), beaches at the back of coves or bays (i.e. Ste Anne), beaches with a steep shoreface (i.e. Le Carbet), etc (Figure 1). These factors also suggest the important role of temporal (seasonal) conditions of exposure of these beaches to swell systems. Oceanic influences appear to be complex with combinations of short frequencies (wind waves) and longer frequencies (gravity waves, infragravity and cyclonic-infragravity waves).

The enhancement of this erosive trend can be linked to an increase in weather-marine forcings in the framework of global climate change (IPCC, 2014), which are both observed and expected, and which concerns modal as well as paroxysmal dynamics.

CONCLUSION

Over the last ten years (2008-2018) numerous measurements and observations have been carried out on the dynamics of Martinique beaches, through various research projects (the most important being INTERREG IV CARIBSAT) and a workshop set up by the French national coast observation network (SNO-DYNALIT). The main results of this observation network indicate spatio-temporal trends that are both identifiable and constant.

On an instantaneous scale (day to week), an increase in the swell system induce a readjustment of the topographic profile, with some sediment transport towards the top of the beach.

However, most of the sediment transport is towards the bottom of the beach and the shoreface, where it leads to the formation of a bar. On the return of modal hydrodynamic conditions, so-called constructive swell moves the sediment up the beach at a relatively rapid rate.

At annual scale (season to year), strong paroxysms lead to profile erosion, while moderate paroxysms lead to beach recovery through accretion. However, erosive profiles are not only observed during the cyclone season, when beaches are expected to be subject to higher energy conditions. The most marked retreat can be observed during the trade winds season (December to March), while the cyclone season offers optimal conditions for a return to a more stable and balanced initial state. However, in these situations of alternating circulation within a profile, the volume of sediment carried up the beach does not always correspond to the volume moving downslope. In the long term, this is damaging for the sedimentary budget.

At a longer time-scale (decade to century), this progressive loss of sedimentary material clearly contributes to enhance the regressive tendency of beaches, which has been accelerating over a period of around 70 years. This slow but global downwasting exacerbates a situation already heavily impacted by past anthropogenic activities, and which will become potentially worse in the future by the expected intensification of weather-marine dynamic agents in the context of global climate change**.**

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