

A monitoring network for assessing the impact of extreme marine meteorological events on tropical beaches

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ABSTRACT

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Since 2003, a monitoring network of the dynamics of sandy beaches has been in operation in three tropical sites: Martinique (French West Indies), Tahiti and Moorea (French Polynesia) and Mayotte (Mozambique Channel). The objective of this network is to measure the impact of extreme weather-related marine events (storms, cyclones, strong swells, surges...) on beaches with varied structural settings and sedimentary environments. The methodology consists in the installation of observatories on the dynamics of sandy beaches in different morphological and sedimentary contexts. A "state zero" is established from a combination of satellite imagery, low altitude digital imagery and topographic and hydrodynamic measurements. These measurements are reiterated after an extreme event in order to apprehend the importance of morphological change, impact dampening and recovery. The monitoring is then continued over regular intervals with the aim of determining rates of morphological and sediment budget recovery until equilibrium is restored.

This experimental network design will subsequently be extended to other tropical beaches located on the propagation paths of cyclones.

ADDITIONAL INDEX WORDS: *Storms, tropical sandy beaches, morphodynamics, topographic data, remote sensing, coastal recovery.*

INTRODUCTION

The environmental changes currently experienced by the earth are now clearly established, especially as regards temperature and sea-level rise and their effects in terms of significant increases in the frequency and intensity of extreme weather events (IPCC, 2001, TITUS, 2005). Many coastal zones will be facing a generalised intensification of erosion, combined with an increase in flooding frequency, salt water contamination of coastal freshwater resources and, in the long term, the disappearance of low islands, wetlands and mangroves (HOLLIGAN and DE BOOIS, 1993). The sea-level rise and the projected evolution of extreme climatic phenomena will have (and already have) very significant effects on coastal ecosystems and, in particular, on their morpho-sedimentary environments. Coastal erosion is already a generalised phenomenon in the world (70 % of the world's coasts are in erosion, BIRD, 1985). Erosion will become more common and erosion rates will increase. These phenomena are a major challenge to coastal zone managers as they affect areas occupied by more than 60 % of the world's population (SMALL *et al.*, 2000). In addition, it would also seem that tropical coasts are liable to be more affected by extreme marine meteorological events than temperate and cold-climate coasts (IPCC, 2001), notably cyclones and their effects in terms of increases in swell energy. While there is debate as to the extent and distribution of areas liable to be

affected by cyclones, there is agreement on a high probability (66 to 90%) of more intensive cyclonic activity due to global change. Wind velocity and precipitation peaks and averages will also become more intense (IPCC, 2001). In extra-tropical latitudes, the IPCC predicts fewer but more intense storms because of accentuated low-pressure fields due to higher temperatures and strong evaporation. These conditions will result in enhanced swell energy and propagation of higher-energy waves from temperate depression areas to tropical coasts (WIGLEY and RAPPER, 2001, TITUS, 2005). Apart from the erosion of tropical beaches (FINKL, 1994), these changes will have significant effects on mangroves and coral reefs, even though there is uncertainty as to the capacity of these formations to adapt and respond to these impacts (PASKOFF, 2000). The most fragile environments will be low coasts, notably those with extensive tidal flats, as well as sandy coasts characterised by fragile sediment budgets. Particularly exposed are tropical island states (NICHOLS and LEATHERMAN, 1995; LEATHERMAN, 1997).

Table 1: Field sites and significant features of the sites

Field sites	Specific spots	Morpho-sedimentary environments	Weather – marine forcing	Problems
Caribbean sea	Tartane Bay, Martinique, French West Indies	Small north-exposed sandy beach, coralo-volcanic sand, narrow lagoon, weak sediment supply	Strong cyclonic events Atlantic storms	Weak coral sediment supply, important suburban settlements Tourist infrastructure
	Grande Anse Macabou, Martinique, French West Indies	Small east-exposed sandy beach coralo-volcanic sand-limited reef weak sediment supply		Weak coral sediment supply, low coast, Back swamps
Pacific ocean	Punaauia beach, Tahiti, French Polynesia	Open west-exposed beach Coarse-grained coral sand Damaged lagoon reefs	North-west Cyclones and storms, strong southern swell, surges, sea-level rise (and associated parameters)	Cross-shore beach dynamics, lagoon surrounding volcanic island and high island beach erosion, important suburban settlements Tourist infrastructure
	Tiahura, Moorea, French Polynesia	North-exposed lagoon Regular bathymetry Cay dynamics Fine coral sand		sediment dynamics influenced by lagoon
Indian ocean	Trevani beach, Mayotte, Comores archipelago	North-exposed sandy beach coralo-terrigenous sand Wide lagoon	Cyclones and storm from the north Southern swell energy concentration on crossing coral reef.	Continuation of the survey network already initiated. Mixed sediment dynamics (fine + coarse sediments) Important tourist infrastructure behind the beach
	Dapani beach, Mayotte, Comores archipelago	South-exposed half-open bay mixed mangrove – lagoon environment and morphodynamic interactions coralo-terrigenous sand sand ridges in upper beach mangrove erosion wide lagoon		Continuation of the survey network already initiated. Urban pressure. Beach-mangrove interactions Consequences of mangrove erosion on fisheries

The aim of the project reported in this paper is to set up a system of observatories on the dynamics of sandy tropical beaches in various settings and exposed to extreme meteorological tropical events.

The project will focus on observing, monitoring and characterising rates of shoreline change at various scales, as well as threshold levels, adaptation sensitivity, feedback and recovery under various influences (sediment and vegetation interactions, human impacts ...) in the face of extreme meteorological events (cyclones, tropical storms, surges, strong swells...).

The underlying scientific objective will be to characterise and quantify the capacity of beaches, selected according to their specific environments, to react to pressure from extreme meteorological events.

STUDY AREAS

The field sites were selected on the basis of varied morpho-sedimentary and hydrodynamic contexts (Table 1). The problems

they face are also different. Three main sites were retained, respectively in the Caribbean Sea, the Indian Ocean and the Pacific Ocean. Within these main sites, numerous specific spots were selected according to their sediment budget situation, their exposure to waves and their management problems.

METHODS

The methodology involves the installation of a sustainable network of regular observations and measurements, with the aim of analysing and apprehending the dynamics of the monitored sites.

A reference state, referred to as “state zero”, serves as a starting point. Measurements (sediments, hydrodynamics and weather conditions) are immediately carried out following each extreme event in order to determine the impact on this reference state. Measurements are then continued at a determined frequency in order to estimate the resilience of the coastal system.

Table 2: Methodology

Sites	Topographic survey	Hydrodynamic and sediment measurements	Images	Integrated management tools
Caribbean (Martinique)	Currently underway with 6 profiles on 2 beaches	A series of current and wave measurements in the north of the island + deployment of an offshore wave buoy.	High spatial and temporal resolution images by SEAS station (SPOT + ENVISAT). Reference image acquired on September 18, 2006. Priority programming of image acquisition in the event of cyclone. Post-cyclone image analysis.	Geographical Information System "Cyclone Impact" currently under development.
French Polynesia (Tahiti, Moorea)	22 profiles on 6 beaches. Established in April 2003. First reiteration in November 2003 (seasonal variations)	Bathymetric measurements on Tiahura lagoon, Moorea.	3 time series (77-88-2001) of vertical numerical images (Punaauia beach). Study of water colour in relation to bathymetry (Moorea).	To be implemented. Numerical data available.
Indian Ocean (Mayotte)	22 profiles on 10 observed sites. Installation in September 2005. Reiteration in February 2006. Reiteration envisaged in February 2007 and June 2007.	3 hydrodynamic profiles envisaged. Mayotte lagoon, June 2007. Dense wave and current measurements envisaged on Dapani beach.	Full sets of 5 series of aerial photographs (1949-69-89-97-2003)	In progress. PhD thesis and contracts.

The temporal and spatial scales of the observations are varied and complementary (table 2). GPS-georeferenced topographic data has been obtained on all the sites. High resolution topographic profiles have then carried out with an infra-red electronic station. For the sites in French Polynesia and Mayotte, the profiles were reiterated in order to characterize seasonal morpho-sedimentary trends. The monitoring network is used as a tool for collecting information on longshore and cross-shore beach dynamics and for the establishment of an initial "geomorphic zero state" of observation. Series of comprehensive measurements will be carried out from time to time in order to characterize the dynamics of the water/sediment interface in different contexts involving complex sediment mixtures (coral sands from French Polynesia; mixed carbonates and volcanic sands from Martinique; mixed carbonates and terrigenous detritic sands from Mayotte). Fine-scale topographic measurements aimed at obtaining digital elevation models (DEMs) at each low tide will also be carried out together with measurements of wave and current parameters from deployments of electromagnetic and acoustic instruments (S4, Dobie wave gauges, ADVs, ADCPs), and of substrate behaviour (ALTUS surface monitoring gauges, Kraus sediment traps, fluorescent tracers). A comparison of the results obtained will be carried out with existing models on sediment transport on beaches with homogeneous sediments.

On the Caribbean site (Martinique island), an observatory based on a methodology of monitoring of cyclone effects on coastal environments is currently being set up with SPOT and ENVISAT satellite images provided by the "SEAS station" in French Guyana (an image reception station for satellite-assisted environmental monitoring). A reference image is acquired in order to obtain a "zero state" of the coastal environment (beach characteristics, state of the lagoons, vegetation density...). Images with high spatial-temporal resolution can be acquired immediately through the "SEAS" station after an extreme event such as a cyclone in order to determine the impact of the event.

RESULTS

In French Polynesia, the reiteration of the 22 profiles from 6 beaches has thrown light on the beach sediment dynamics especially following a strong windy event which whipped up heavy swell from the southwest on 29th April, 2003. The observations highlight the behaviour of coral beaches surrounding a volcanic island environment under conditions of high wave energy. In Punaauia, for example, on the island of Tahiti the topographic analysis made it possible to highlight the fundamental part played by outcrops of beachrock on the beach sediment dynamics (JEANSON, 2004).

In stormy conditions, the swells break on the upper sandy beach and the backwash, canalised by the beachrock, is evacuated through passes and evacuates sand towards the lagoon. Under modal conditions, recovery is only partial because the sand that is gradually brought back towards the beach by constructive swell is blocked by the beachrock. This thus perturbs the cross-shore sediment dynamics, causing in the long-term a sediment deficit on the upper-beach and inducing chronic erosion problems.

These outcrops of beachrock are also irregular along the coastline and thus induce differential longshore organisation of the sediment distribution (DOLIQUE *et al.*, 2004). On Papenoo-Taharuu beach in Tahiti, the role of the lagoon on beach swash drainage and its effect on the beach sediment budget during storm events is clearly brought out by the monitoring. The recovery rate of a volcanic sand spit drained by this lagoon was also calculated (JEANSON, 2004).

Algorithms relating water colour to bathymetry have helped in the setting up of tools for monitoring the bathymetry and dynamics of the sandy lagoon of Tiahura, in Moorea (DOLIQUE *et al.*, 2005).

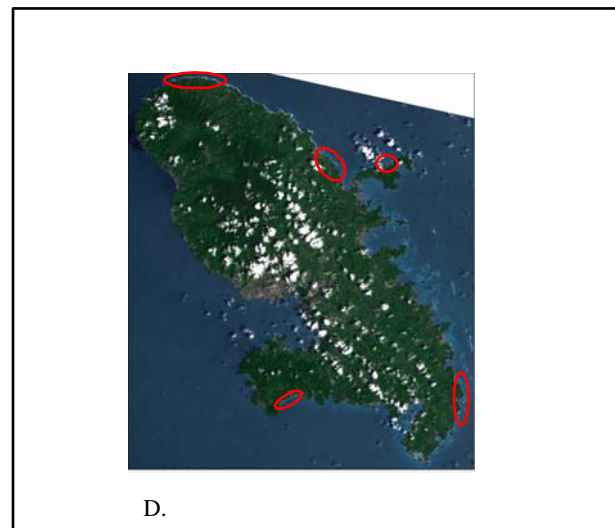
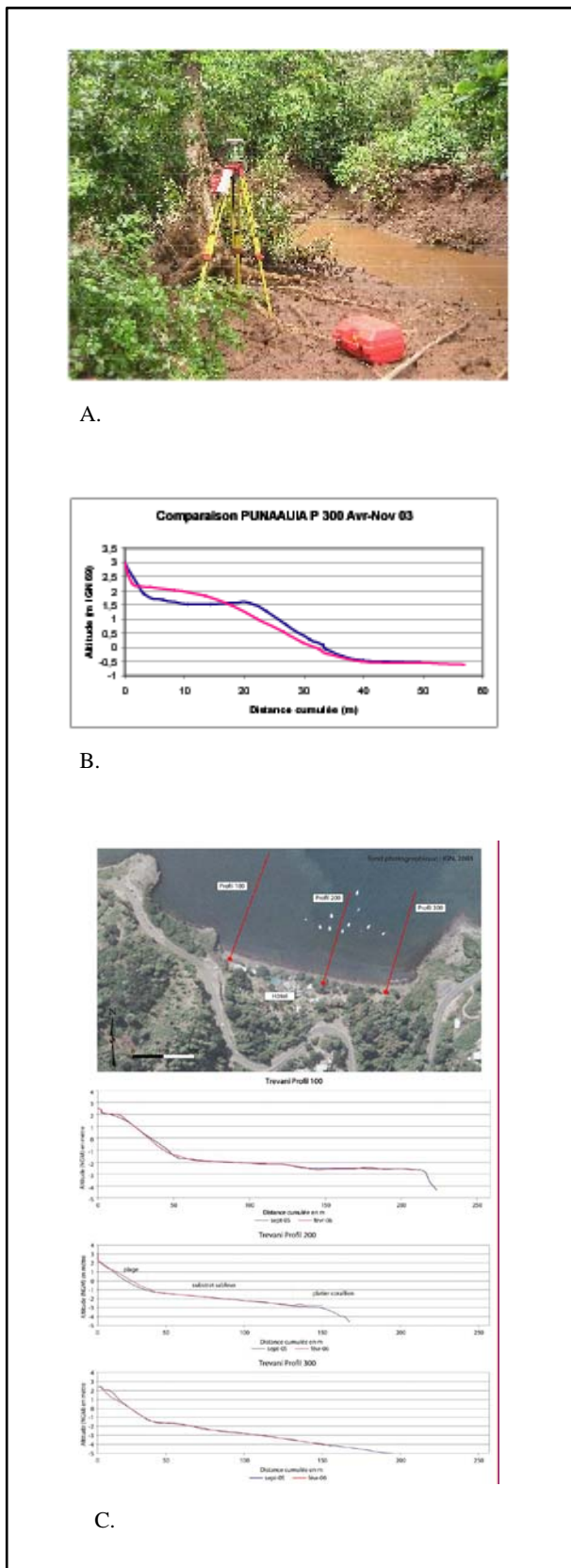


Figure 1. Examples of studies within the framework of the network.

A: Installation of benchmarks in a mangrove swamp in Mayotte.

B: Beach profiles of Punaauia, Tahiti, French Polynesia.

C: Beach topographic survey set-up and profiles in Mayotte.

D: Remote sensing image for cyclone impact survey, Martinique, French West Indies, and topographic survey sites (SPOT-IRD-SEAS).

In Mayotte, the work carried out combines two space and time scales. An analysis of coastal features from air photographs since 1949 has allowed for the identification of the long-term tendencies on 10 sites. The setting up of the topographic survey network makes it possible to refine these observations and to isolate them from the seasonal variations.

A significant erosion of mangroves in bays located at the south and the west of the island was noted, as well as complex substrate interactions (DE LA TORRE *et al.*, 2006). Preliminary analysis of offshore swell shows a reinforcement of waves from the south (JEANSON, 2005). The seasonal variations experienced by the island (a dry season following a stormy rainy season) are also recorded by the short-term coastal evolution pattern, which is characterised by alternations of the littoral drift due to seasonal changes in deepwater wave approach direction and by cross-shore sediment redistribution due to water exfiltration on the beaches.

In the long term, the objective of the network in Mayotte is to contribute to the creation of a littoral observatory aimed at better integrated management.

DISCUSSION AND PERSPECTIVES

The three sites presented constitute the first steps of a network in full expansion. This network is already operational since 2003 and the recorded profiles constitute a constantly reusable data base following each extreme marine meteorological event. The network thus operates in a stand-by and ready framework.

The first comparative datasets enable a better understanding and differentiation of seasonal from longer-term multi-annual sediment dynamic patterns, especially in Mayotte. This concept is fundamental in the characterisation of the recovery processes of the sandy coastal formations in each particular sedimentary, climatic and hydrodynamic context.

This network also makes it possible to gain knowledge on, and store up new quantitative data on, sites where morphodynamic measurements are very rare, or even non-existent. In the future, it is intended that the network will be extended to other sites located on the principal pathways of cyclone propagation (the north Caribbean, Bahamas, Cuba and Yucatan for the Atlantic area; Wallis and Futuna in New Caledonia, Philippines for the Pacific area; Madagascar and Réunion for the southern Indian area).

This extension of the network can only be done by involving local researchers in the project and through funding of research by supranational organisations.

CONCLUSION

The direct objective of this project in terms of applied research aims at a better comprehension of the recovery processes of tropical sandy beaches exposed to extreme weather-related marine events, in order to better gauge the reaction strategies and adaptation costs that the local societies face within a context of strong demographic growth.

The first results from this recently operational monitoring survey network are encouraging but the network still needs to show proof of efficiency in the face of climatic and/or marine hazards. The main research objective tied to this project is that of the characterisation of post-event sedimentary resilience and this objective must now get into full operation. The interest shown by decision-makers and coastal managers in the monitored sites suggests that the tools developed from the results generated by the network will have full utility within the framework of studies on the effects of global change on sensitive coastal tropical environments.

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