CARIB-COAST - CARIBBEAN NETWORK FOR COASTAL RISKS RELATED WITH CLIMATE CHANGE

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Abstract: Exposed to extreme cyclonic episodes and the progressive rise of sea level in relation with climate change, the coastlines of the Caribbean are subject to natural hazards such as coastal erosion and marine inundation. The associated risks relate mainly to the safety of goods and populations, but also to the tourism economy linked to the maintenance of beaches and the natural heritage of these interface environments where biodiversity is particularly rich (mangroves, coral reefs, meadows).

The CARIB-COAST project (2018-2022, https://www.carib-coast.com/en/), was based on the principle of efficient networking. Its ambition was to pool, co-build and disseminate surveillance approaches, coastal risk prevention and adaptation to climate change.

The program had 3 major objectives that are detailled in the current article: 1. the implementation of a modelling platform for hydrodynamics, based on a Caribbean measurement network, for the simulation of present-day and future coastal hazards, 2. the development of a Caribbean network for monitoring coastal erosion and mitigation using natural ecosystems and 3. the development of tools to assist decision-making, exchange, training and sensitization of Caribbean stakeholders.

Introduction

Caribbean territories, which include both island economies and countries bordering the Caribbean Sea, are considered highly vulnerable to natural disasters. Extreme weather events are common – the region experienced nine hurricanes at Category 3 and above in 2019-2020, and a record number of named storms in the 2020 hurricane season.

Direct losses due to tropical cyclones in the 2017 Atlantic hurricane season across the region exceeded US$70 billion for the Hurricane Harvey only. This major category 4 event was followed by several major events: Irma, Maria, José, Katia that seriously damaged Caribbean islands and the southern part of the USA. More recent events confirmed the high vulnerability of caribbean territories: Dorian in 2019 particularly in the bahamas, Ian and Fiona in 2022 with high impacts in Puerto-Rico, Florida,…

The Caribbean is also subject to extreme terrestrial phenomena, such as tsunamis (Lisbon in 1755, the Virgin Islands in 1867, Montserrat in 2003). Hurricanes and tsunamis cause waves and higher water levels that can lead to the flooding of low areas on islands and to the erosion of their coasts. The impact of these events is likely to increase in the future with the progressive rise of sea level in relation with climate change. The associated risks relate mainly to the safety of goods and populations (115 M people living around the sea), but also to the tourism economy linked to the maintenance of beaches and the natural heritage of these interface environments where biodiversity is particularly rich (mangroves, coral reefs, meadows).

The cost of inaction facing the climate change, taking into account only the impact of cyclones, the loss of tourism revenus and damage to infrastructures in the Caribbean would be $ 10.7 billion annualy in 2025 and would exceed 46 $ billions in 2100 (Bueno et al., 2008).

In this context, the CARIB-COAST project (2018-2022, https://www.carib-coast.com/en/), supported by the Association of Caribbean States (ACS), was launched in 2018. It is based on the principle of efficient networking. Its ambition is to pool, co-build and disseminate surveillance approaches, coastal risk prevention and adaptation to climate change. It has an international partnership including european community partners: BRGM, IFREMER, ONF, IRD, SPAW-

RAC and CNRS and extra-community partners: UWI, IMA, Ministry of Works and Transport from Trinidad and Tobago, CARICOOS from Puerto Rico, MonaGIS from Jamaica and ACS.

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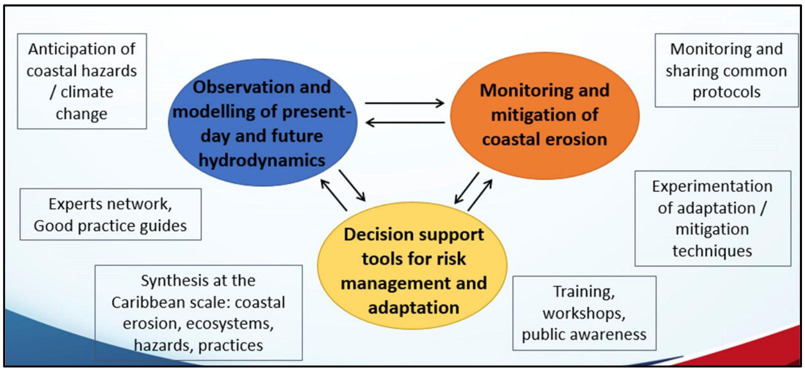


Fig. 1. Technical components and main outcomes of the project Carib-Coast.

Present-day and future hydrodynamics

The Caribbean is subject both to extreme meteorological phenomena, such as hurricanes (the 1928 hurricane, Hugo in 1989, Dean in 2007), and to terrestrial phenomena, such as tsunamis (Lisbon in 1755, the Virgin Islands in 1867, Montserrat in 2003). Hurricanes and tsunamis cause waves and higher water levels that can lead to the flooding of low areas on islands and to the erosion of their coasts. The first objective of Carib-Coast was to develop and share numerical modelling outputs to improve the knowledge on present-day coastal hazards and evaluate the impact of climate change (by 2100) on ocean circulation and characteristics, as well as evolution of coastal hazards. A numerical platform was implemented to vizualize and download all products detailled in the following subsections (see https://www.carib-coast.com/en/).

Hydrodynamics campaigns

To obtain field data to validate the numerical models, several field campaigns and monitoring devices have been implemented. These campaigns involved current, water levels, temperature and wave measurements: 6 ADCP (Acoustic current profiler) around Guadeloupe and Martinique Islands, 6 pressure transducers around Puerto Rico, a new wave buoy close to Saint-Martin island and ADCP and video monitoring stations in Jamaica, Trinidad & Tobago and French islands.

Hydrodynamics modeling

A hydrodynamic modelling platform has been created to improve the knowledge of the 3D circulation of water masses in the region by detailing the role of eddy structures (< 30 km) in the control of hydrological properties in the vicinity of Caribbean islands taking into account the impact of extreme events such as hurricanes. This work was undertaken at two spatial scales (from the entire Caribbean Sea to the French West Indies (Guadeloupe and Martinique)) and two temporal scales: reanalysis for the period 1980-2010 and projection for the period 2070-2100 to take into account the effects of climate change.

Caribbean climate and ocean circulation modeling

A hydrodynamic platform using the NEMO (www.nemo-ocean.eu) code has been developed to improve the knowledge of the 3D circulation in the region, and in particular the role of eddy structures (<30 km) in the control of hydrological properties near the Caribbean islands. First, a regional configuration at 10 km resolution was developed, to determine the sensitivity to atmospheric forcing over the last 10 years (DFS vs ERA5). The spatial resolution was then refined around the Lesser Antilles, down to 3km (red area in the fig. 2), to better represent the mesoscale processes in the archipelago, and compare the simulations with available observations. The variability spectra for the ocean currents are very similar to those from ADCP measurements, indicating that the local processes are well represented by this model. But individual events, such as sea level anomalies propagating from the south to the north, east of the archipelago, are not represented at the right time/place due to lack of data assimilation. Finally, we produced simulations of future climate, circa 2100, to explore the impact of climate change on local hydrodynamic conditions. These projections, which have been produced with a regional ocean + atmosphere model of 25 km resolution, are to be compared with their counterparts for the present climate. An ultimate configuration was developed to bring resolution up to 1km around the archipelago (green area in the fig. 2).

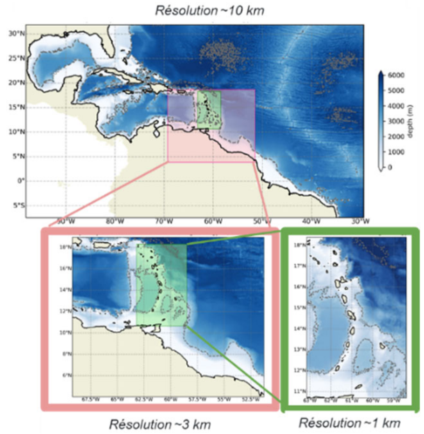


Fig. 3. NEMO configurations (nested grids) developed for the modeling of current and future climate and ocean circulation.

Regional circulation modeling

The simulation of regional circulation and water quality around the islands of Martinique and Guadeloupe. 5 years of hindcast (2016-2020) have been computed using the MARS3D model (Lazure, and Dumas, 2008). After various tests, a configuration combining meteorological forcing from CFSv2 and oceanographic forcing from Hycom was selected. This configuration was then used to study four major oceanographic phenomena in the area:

- Barotropic tide: the modelled current velocities agree with the elements known from the literature;
- Regional circulation: the simulations confirmed the known elements on the surface circulation, with a flow coming from South to South-West and flowing into the channels between the islands. A very significant deep circulation in the North-South direction along the Atlantic coast has also been highlighted.
- Wind induced circulation: simulations have shown that wind induced circulation is significant over the entire domain. It represents about 20% of the total offshore current speed, where the regional current is significant.
- Internal waves: the simulations showed large oscillations of the thermocline which may indicate the generation of internal waves, mainly in the southern part of the domain. Martinique would therefore be more concerned than Guadeloupe by this phenomenon

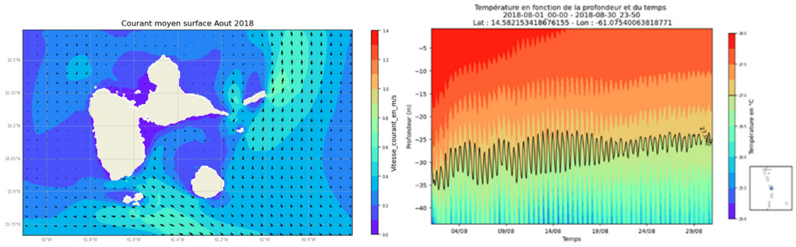


Fig. 3. Circulation modeling outputs: Mean surface current in august 2018 around Guadeloupe (left); variation of temperature with depth and time, evidencing internal waves (right).

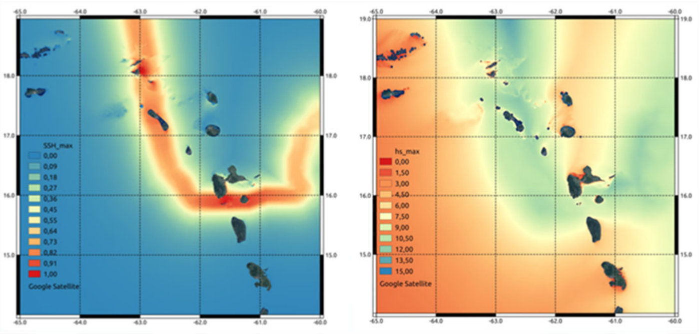
The produced data, available on the web platform and downloadable in NETCDF format, have a temporal resolution of 3 hours and a spatial resolution of 500 m on a structured grid. The variables available are 3D current speed and direction, temperature, salinity, sea level.

Waves and water levels (hurricanes and tsunamis)

In order to provide an evaluation of hurricane-induced water levels and waves, a probabilistic approach was developed and used to estimate 100 y return period and joint probabilities under present-day and future climate. A synthetic track database for present-day and future (STORM, Bloomendaal et al., 2020) was used. In order to overcome the need of many synthetic cyclones to have robust statistical analysis, a statistical estimation of spatial information was developed (Ryota et al., 2022) and 685 simulations were performed to compute the statistics.

The unstructured model UHAINA 2DH (Filippini et al., 2018) with a grid ranging from 300 m to 20 km was used to simulate water levels and the wave spectral model WW3 (Tolman, 1997) was used to simulate waves. Both models were validated using historical hurricanes (Dean and Irma). Comparison between simulated and observed water levels indicate a good performance of the model. Some growing discrepancies moving away from the hurricane's best track are observed that could be linked to the poor parametrization of the pressure field (Joyce et al., 2019), to the improvable resolution used to describe the continental shelf, or to the wave setup contribution to the measured water level.

685 simulations of water level and waves were calculated and are available for tropical storm to cat 5 hurricane scenarios representative of 10000 years (Fig. 4). 100 years return period maps were produced for waves (Hs, Dp, Tp) and for sea surface elevation (ssh).



Atmospheric surge

Wave Hsig

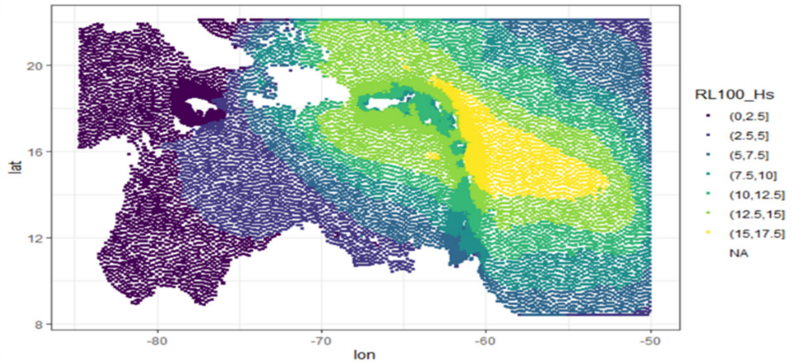


Fig. 4. Example of cat 5 hurricane simulation (top) and 100y return period significant wave high (Hs, bottom).

For tsunamis, a deterministic approach was developed to simulate coastal water levels and time delay using the worst credible tsunami sources case hypothesis. 13 tsunamigenic areas were selected for simulations in the Caribbean and the Atlantic basin. Once these areas have been identified, geometries of rupture were proposed. For each geometry, several stochastic realizations were done for each co-seismic slip distribution. Several simulation were then performed for geometry retained, bringing the total number of scenarios to ~300 (fig. 5). For each scenario, computation of the sea surface response is done using the FFaultDisp software (Okada, 1985). The propagation of the tsunami was then made using UHAINA 2DH model (fig.5), previously validated against FUNWAVE-TVD (Shi et al.2012) calculations.

Simulations of the 30 most impactful scenarios of the different tsunamigenic zones are available on Carib-Coast website, together with water level evolution and arrival time maps. Maps of the maximum expected sea surface height, of the most impacting scenario by sector and of the arrival times by tsunamigenic area have also been computed by post-processing the ~300 scenarios simulated.

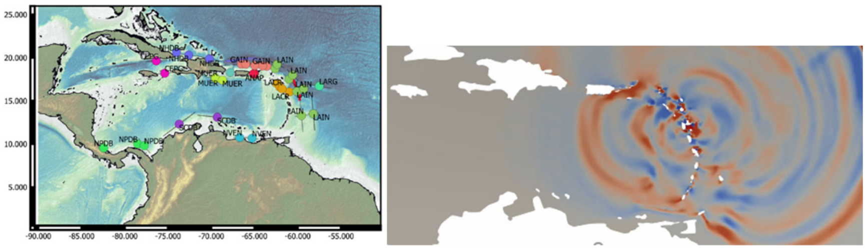


Fig. 5. Map of scenarios of tsunami sources (left). *Example of a simulation of tsunami generation and propagation. Source inspired by Feuillet et al. 2011.*

Storm monitoring networks

In order to anticipate storm impacts for a given event, field data is needed to properly evaluate the morphological evolution, the marine inundation, as well as damages. This field data is very scarce and can be the main obstacle to develop Early warning systems able to anticipate coastal impacts. To tackle this need, storm-monitoring networks were implemented in Guadeloupe and Martinique with the aim to gather quantitative and qualitative information on coastal evolution and impacts during the hurricanes and storm events. These storm monitoring networks put together actors already involved in coastal management, and provide them with tools to better obtain field data and share it publically.

When a storm is announced, waves and water levels of existing forecasts are extracted and compared to previously defined morphological and impact thresholds (Fig. 6). If the waves/water levels are exceeding the threshold, the network receives an email with a technical bulletin that provides all partners with physical characteristics of the event, as well as a map with evolution of the impact index for the coming 5 days. People participating to the network are then informed of the expected impact and location of most vulnerable sites. They can go for monitoring before/after the event to obtain quantitative (shoreline evolution, measured water levels, …) or qualitative information (pictures of impacts, …). A smartphone app (©i-infoterre) can be used to send all observations to the Storm Database.

The storm monitoring network was activated in sept 2022 during the hurricane Fiona, permitting to obtain quantitative information on shoreline evolution, beach volume variations, … using field measurements and video monitoring systems.

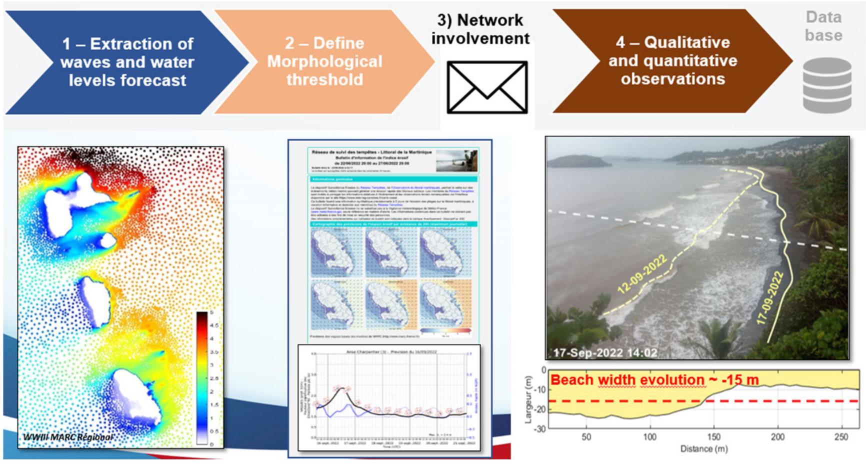


Fig. 6. Storm monitoring network of Martinique Island: from the forecast, to the edition of an automatic bulletin on expected impacts and to the gathering of all observations in the Storm DataBase.

Coastal erosion monitoring and mitigation actions

The main objective of the project Carib-Coast was to develop an observation network of coastal erosion, and a network of experts on natural coastal risks and mitigation techniques making use of natural ecosystems. Four main actions were undertaken in the project: the implementation of field monitoring on pilot-sites, the assessment of the protective role of coastal ecosystems, the development of a tool to evaluate coastal vulnerability according to the state of health of ecosystems, and finally the experimentation of mitigation/restoration techniques.

Field sites monitoring

15 pilot sites have been chosen in all participating countries to monitor coastal erosion, and to evaluate the efficiency of mitigation techniques. At most of the sites, shoreline evolution, swash extension limit, hydrodynamics have been measured using field surveys and/or video monitoring devices.

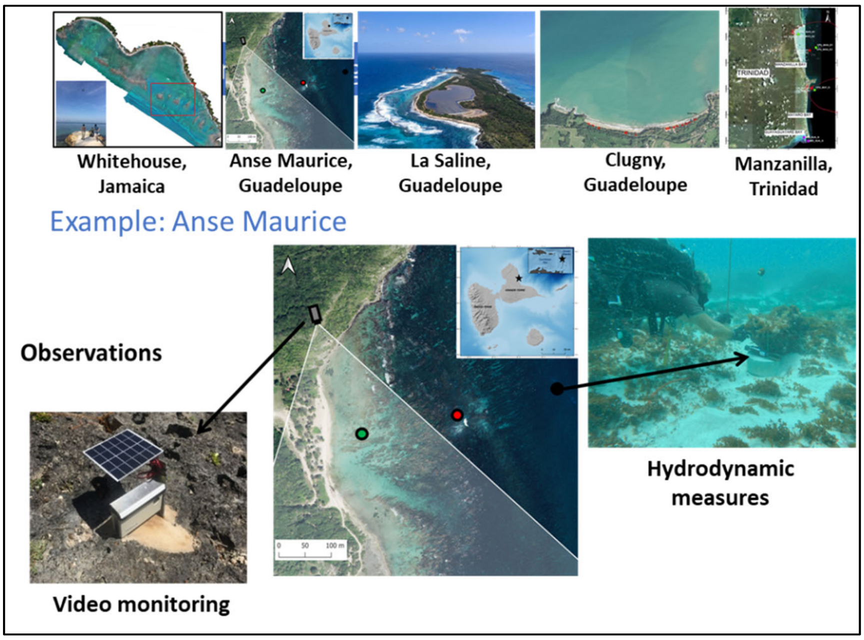


Fig. 7. Some of the field sites monitored within Carib-Coast (top) and example of video/hydrodynamics measurements at Anse Maurice, Guadeloupe (bottom).

Assessment of the protective role of ecosystems

Small Caribbean islands are highly vulnerable to coastal flooding hazard. The role of ecosystems in mitigating this hazard is increasingly emphasized. Specific field campaigns and modeling using X-Beach model (Roelvink et al., 2009) were undertaken at several sites: White house in Jamaica (Daly and Nienhuis, 2018, Van den Broek, 2021), Anse Maurice and les Salines in Guadeloupe (Laigre et al. 2021, 2022). At Anse Maurice, field data permitted to quantify the respective effect of wave transformation over the reef and charateristics of upperbeach vegetation on the maximum runup. Using 2 years and 10 months video monitoring of wave runup, as well as measurements of wave dynamics on the fringing coral reef, processes involved in swash inundation were analyzed; from event scale to seasonal scale (Laigre et al. submitted).

This work highlights the implication of processes involved in wave-induced coastal inundation (runup) from annual to hour time scales. Seasonal variations in water bodies expansion (called steric expansion) which are triggered by fluctuations in temperature and salinity (Torres and Tsimplis, 2012) strongly modulate the runup. On shorter time scales, tides affect wave propagation over the coral reef directly influencing residual dynamics at the shoreline level. Thus, storm events impact on coastal inundation is greatly modulated both by the annual periodicity of sea level and by tide level at short timescale. The upperbeach vegetation also reduces beach inundation. These results bring new elements to understanding wave-induced coastal inundation in the context of reef-lined beaches.

Fiedl data was used to validate X-Beach non hydrostatic model to simulate various scenarios of ecosystem health (Laigre et al. in prep) as well as the potential effect of Sea level rise in the protection of the coast by ecosystems.

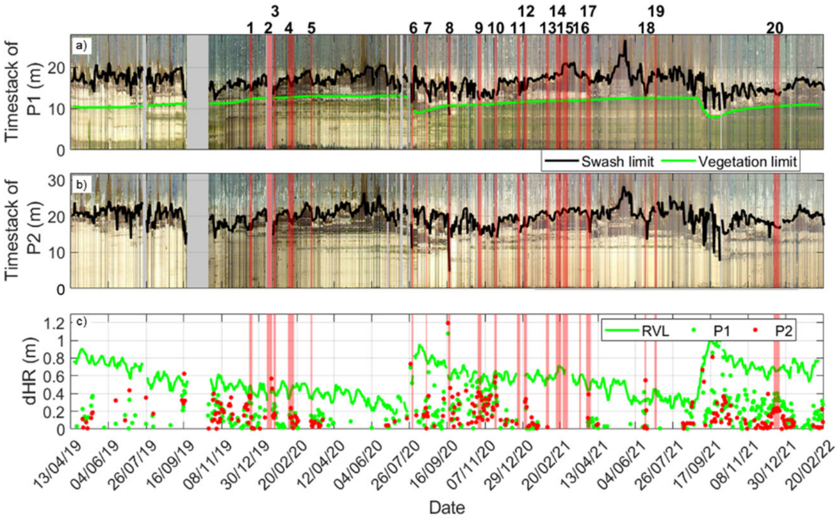


Fig. 8. The camera-derived observations from April 2019 to February 2022 (Laigre et al., submittted). (a) and (b) Daily timestacks with detection of maximum swash limit (black line) and vegetation limit (green line) on P1 and P2 respectively. (c) Evolution of the daily highest runup (dHR) on both profiles and Relative vegetation Limit (RVL). Events when the vegetation limit is outpassed by dHR are highlighted with a red background.

Tools to evaluate the coastal vulnerability according to the state of health of ecosystems

To quantify the ecological services relating to coastal erosion in terms of natural protection (coastal vegetation, coral reef, mangrove, etc.), the use of satellite imagery was chosen because this method is a suitable tool for mapping marine ecosystems given the extent of the study area. A vulnerability index was defined using the following variables: coastal forcing (mean wave height, tidal range, storm frequency/probability, relative sea level rise), coastal characteristics (geological variables: shoreline change, geomorphology, elevation, bathymetry, slope), terrestrial ecosystems (mangrove density, width, …), marine ecosystems (coral, seagrasses) as well as socio-economic variables (urban areas, population density, roads).

All variables were obtain using Sentinel-2 satellite imagery for all ecosystems in several fiedlsites in Jamaica, Porto Rico, Trinidad and the French West Indies. All the results are available on the Carib-Coast website: https://www.carib-coast.com/erosion-cotiere.

Moreover, satellite data used, as well as the scripts to calculate the vulnerability index are available online:

- Sentinel 2 data → https://scihub.copernicus.eu/dhus/#/home
- Mangrove mapping scripts → https://gitlab.com/latelescop/caribcoast/-/tree/main/scripts-windows
- EBCVI scripts → https://forge.ird.fr/espace-dev/personnels/catry/-/tree/main/CaribCoast

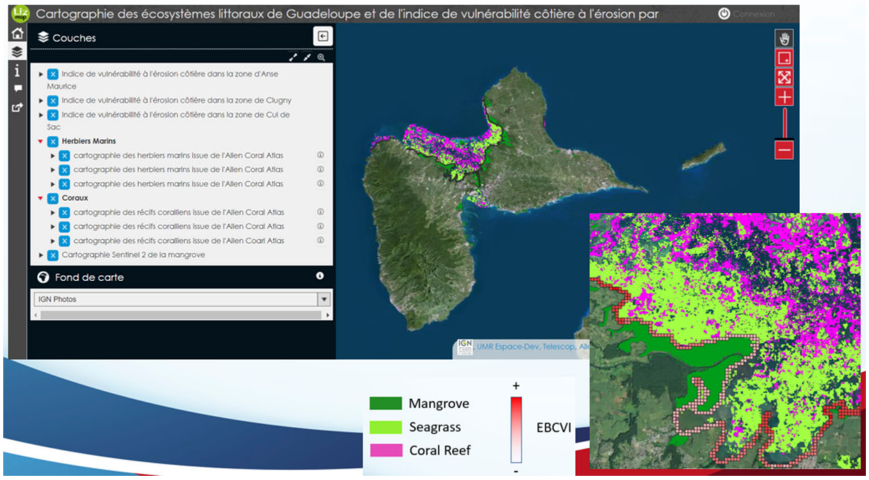


Fig. 8. Example of coastal vulnerability index maps available on www.carib-Coast.com

Experimentation of mitigation/restoration techniques

The project was concentrated on three ecosystems, typical from the caribbean environment, playing a key role as regards protection against erosion processes: planted backshores, coral reefs and mangroves. The main objective of this task was to implement experiments of these mitigation techniques using these ecosystems on the pilot sites.

In Guadeloupe, backshore ecosystems have been restored with new plantations and protected by enclosures to prevent vegetation from trampling. Despite the management of the backshore is too recent to have a significative effect on coastal erosion, progression of the vegetation in protected areas was significant.

In Tobago, with the Environmental Research Insitute Charlotteville, an experimentation was performed to help the reproduction of pillar corral colonies uding genotyping and sexing by bringing together male and female colonies.
In Puerto Rico, with Protectores de cuencas, seagrasses restoration have been implemented through the reduction of land-based sources of pollution.
In Grand Bahama and Abaco with Perry Institute of Marine Science, experiment was done to evaluate the impact of the hurricane Dorian on the mangrove functions and to implement mangrove restoration work with local community and experts.

Fig. 9. Experimentation of nature-based solutions to enhance natural protection against coastal hazards undertaken within the Carib-Coast project.

Conclusion - Strengthening cooperation and tools to mitigate coastal erosion in the Caribbean

One major objective of the project was to supply decision support tools for managing natural coastal risks. This relates to the strategy of managing the risk and adaptation, the use of operational tools, the dissemination and availability of the results via a web portal and the actions of training and awareness.
During the entire project, and despite the Covid crisis context, actions were undertaken to disseminate the results, transfer the knowledge and raise awarness. Several public conferences, technical workshops and webinaires were done on coastal monitoring techniques, coastal modelling, ecosystem restoration, …

All the results of the project are available on the carib-coast website (www.carib-coast.com), including the modeling platform that provides with a insight on all the modelling effort of the project on present-day and future oceanic circulation and climate, tsunami and hurricanes hydrodynamics. These simulations are freely available for further studies on coastal hazards and climate change in the Caribbean.

Acknowledgements

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References

Broek (van den), M.A. (2021), The effect of coral degradation on the wave transformation and runup near Withehouse Beach, Jamaica, Master report, University of Utrecht, 60 p.

Bueno, R., Herzfeld, C., Stanton, E.A., Ackerman, F. (2008). The Caribbean and climate change – The cost of inaction. Report Stockholm Environment Institute – US Center, Global Development and Environment Institute, Tufts Univ. 37 p.

Daly, C. and Nienhuis, J. (2018), Effect of reef degradation on sediment flushing through reef gaps, American Geophysical Union, Fall Meeting 2018, abstract #OS11E-1449.

Filippini, A.G., et al. (2018), UHAINA : A parallel high performance unstructured near-shore wave model, XVèmes Journées Nationales Génie Côtier - Génie Civil, May 2018, La Rochelle, France. https://www.paralia.fr/jngcgc/15_06_filippini.pdf

Joyce, B.R. et al. 2019 : U.S. IOOS coastal and ocean modeling testbed…*Journal of Geophysical Research: Oceans*, 124, 2876–2907

Laigre, T., Balouin, Y., Villarroel-Lamb, D., Moisan, M. and De La Torre, Y. (2021). Observation of shoreline and upperbeach vegetation evolution by video: field assessments in the Caribbean. *Proceedings Coastal Dynamics 2021.*

Laigre, T., Balouin, Y., Villarroel-Lamb, D., Valentini, N. Moisan, M and De la Torre, Y. (2022). Impact of fringing reef and upperbeach vegetation state on storm runup in a Caribbean context, *Proceedings Int. Coastal Eng. Conf.*

Laigre, T., Balouin, Y., Villarroel-Lamb, D., Valentini, N. Moisan, M and De la Torre, Y. (submitted). Seasonal and episodic runup variability on a Caribbean reef-lined beach, submitted to *JGR - Oceans*.

Lazure P, Dumas F. (2008). An external-internal mode coupling for a 3D hydrodynamical model for applications at regional scale (MARS). *Adv. Water Resour.,* 31, 233–250.

D. Roelvink, D. Reniers, A. van Dongeren, A. van Thiel de Vries, J. McCall, R. Lescinski, J. (2009). Modelling storm impacts on beaches, dunes and barrier islands. *Coast. Eng.,* 56 (11–12) (2009), pp. 1133-1152

Okada Y. (1985) Surface deformation due to shear and tensile faults in a half-space //*Bull. Seis. Soc. Am*., 75(4),1135-1154

Ryota, W. et al. (2022). Statistical estimation of spatial wave extremes for tropical cyclones from small data samples. *Nat. Hazards Earth Syst. Sci*. 23, 431-444.

Shi, F., et al. (2012), A high-order adaptive time-stepping TVD solver for Boussinesq …, *Ocean Modell*., 43–44, 36–51.

Torres, R. R., and Tsimplis, M.N., (2012). Seasonal sea level cycle in the Caribbean Sea, *Journal of Geophysical Research: Oceans*, *117*, C07011, doi:10.1029/2012JC008159.