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Monitoring and management of coastal hazards: creation of a regional observatory of coastal erosion and storm surges in the Pays de la Loire region (Atlantic coast, France)

Riwan Kerguillec*, Morgane Audère, Agnès Baltzer, Françoise Debaine, Paul Fattal, Martin Juigner, Patrick Launeau, Baptiste Le Mauff, Florent Luquet, Mohamed Maanan, Pierre Pouzet, Marc Robin, Nicolas Rollo,

* UMR 6554 CNRS, Laboratoire Environnement Télédétection Géomatique Nantes, Université de Nantes, chemin de la censive du tertre, BP 81 227, 44 312 Nantes, France

Abstract: The OR2C (Observatoire Régional des Risques Côtiers) is a new observatory of coastal hazards located in the Pays de la Loire region on the Atlantic coast of France. It was created, in 2016, in a context of high regional vulnerability to coastal erosion and storm surges. The OR2C is in charge of monitoring nearly 400 km of coastline. Its major mission is to reinforce the scientific knowledge and improve tools for managing coastal hazards, reducing thus exposure to risks. Its set-up is also related to the need of a regional body to gather all parties involved in researching and managing coastal hazards, with the aim to create a regional dynamic of observation. The OR2C is based on original governance that creates a strong interface between academics and managers because it combines public institutions, research centers, decisional bodies, and operational bodies. This governance strengthens the dynamic of observation of coastal erosion and storm surges along the regional coast by improving the networking of the OR2C twenty-eight members. Monitoring strategy is based on an airborne LiDAR technology that provides annual topo-bathymetric data. One of the OR2C first actions was to establish an initial LiDAR acquisition survey (t0) in 2016 along 140 km of sandy coasts. The obtained data are updated every year and freely accessible to the coastal managers. The data are also used in an innovative toolbox of spatial analysis of coastal risks (MAp-RISC), which has an ability to map predisposition of coastal sectors exposed to coastal hazards. MAp-RISC provides several indicators to support decision-making, and could also be used in the future to update policies or strategic documents.

Key words: coastal observatory, coastal erosion, storm surges, governance, risk management, topo-bathymetric LiDAR,

1. Introduction

Since the 19th century, new forms of urbanization have emerged including widespread tourism, in France and other developed countries (Dowling and Pforr, 2009). After World War II, urban development in both coastal zones and ports greatly increased. This new dynamic, known as littoralization (i.e. movement of humans and activities towards coasts), provoked spatial extension of built-up areas on coastal fringes (Deboudt, 2010; Le Berre *et al.*, 2016). In France, the spatial extension dynamic has largely increased human vulnerability to coastal erosion and storm surges, so that the French coast is considered a prime example of an at-risk territory (Deboudt, 2010).

In this context, monitoring the shoreline and studying closely coastal hazards have become essential to provide long-term data for coastal evolution and risk management (Ruggiero *et al.*, 2000; Rieb and Walker, 2001; Meur-Ferec *et al.*, 2008; Suanez *et al.*, 2012), especially from the perspective of sea level rise in relation to climate change, which exacerbates the vulnerability of the most exposed areas (Neumann *et al.*, 2015). Observatories of regional shoreline and coastal hazards have emerged in France since the 2000s to provide fundamental knowledge on coastal phenomena and homogenous long-term quality data in a coherent time scale. According to the classification of Suanez *et al.* (2012), these observatories can be defined by several characteristics that refer to their spatial limits (i.e. spatial extension), durability, data acquisition conditions

(e.g. equipment, protocols, frequency and planning), and main missions. In France, regional observatories are perennial monitoring structures established at a regional level (i.e. more than 100 km of coastline) providing long-term homogeneous quality data, regularly updated. Their main missions are: giving access to the data to a wide audience; conducting scientific studies with the aim of strengthening the scientific knowledge on coastal risks; and, in some cases, carrying out coastal expertise.

The OR2C (Observatoire Régional des Risques Côtiers/ Regional Coastal Hazards Observatory) is a new regional observatory of coastal hazards located in the Pays de la Loire region on the Atlantic coast of France. This observatory is the most recent to be set up in France and its main objective is to collect, strengthen, and transmit scientific knowledge and data on coastal erosion and storm surges.

The OR2C was set up post-storm Xynthia to improve the existing tools used for coastal hazard management. Being part of a decentralization program of coastal risk management, the OR2C implements a regional shoreline management based on the French State strategies (Deboudt, 2010). Furthermore, the OR2C was created to respond to the need for a regional branch that combines the dynamic of observation engaging all involved parties in the study, management of coastal hazards, and promotion of collective actions.

The major aim of this paper is to present the context for setting up the OR2C and its conditions of deployment. It also focuses on the governance of the OR2C and describes its missions. The second aim is to highlight the main actions carried out since 2016 and the main outcomes. The paper gives an overview of the tools provided by the OR2C for acquisition, update, processing, storage, and transmission of data. The paper also highlights an observatory model based on an original network founded in close relationships from a local to a regional level and vice-versa (e.g. data exchange, synergies, feedback, etc.).

2. Background

2.1. Regional settings

The OR2C is located on the Atlantic French coast, extending from Pont-Mahé Bay in the north to L'Aiguillon Bay in the south. The coast is bounded by two islands located not far from the mainland (i.e. Noirmoutier Island, Yeu Island). Its general axis is orientated NW-SE and the elevation is mostly less than 10-20 m. The continental shelf is maximum 200 km wide with a water depth of less than 20 m for several kilometers off the mainland coast. The coast comprises three main coastal facies (i.e. two natural and one artificial), with 140 km sandy and 111 km rocky coasts, and 135 km present coastal defenses (Juigner, 2017) (**fig. 1**).

The regional coast can be divided into two sections. The northern section, extending from Pont-Mahé Bay to Les Sables d'Olonne, is situated on the southern margin of the Massif Armoricaire. It corresponds to the rocky coasts (i.e. low elevated rocky coasts or cliffs of less than 20 m elevation) that are locally very sensitive to erosion processes in relation to the terrain nature. As an example, the case of the small clay cliff of Bayadène, located south of Pont-Mahé Bay, which is regularly affected by mass movements threatening several houses. A large part of the coastal length of the first section is represented by marshes barred by dune ridges or moles protecting salt production areas, or even polders established during the 18th and 19th centuries (e.g. west of the Breton marsh; Noirmoutier Island) (Verger, 2011). The southern section, extending from Les Sables d'Olonne to L'Aiguillon Bay, is part of the northern margin of the Bassin Aquitain (Juigner, 2017; Ters, 1961). It is characterized by large low-lying areas barred by complex dune ridges (i.e. multiple successive dune ridges), sand spits, or moles (e.g. the Marais Poitevin in particular, the largest French Atlantic wetland).

The regional coastline is subjected to mesotidal and macrotidal semi-diurnal tides (Pirazzoli, 2000), and exposed to North Atlantic marine weather influences, with main WNW and SW winds (Juigner *et al.*, 2017). Stormy conditions occur from November to March. Winter storms may be the main cause of the strong shoreline retreats (Gautier, 1979; Fattal *et al.*, 2010; Juigner, 2017) (**fig. 2A**). As Juigner *et al.* (2017) stated, the Pays de la Loire region sandy coasts experience strong long-term trends in shoreline position changes (from $+5.1 \pm 0.35$ m/y to -1.5 ± 0.35 m/y within the period 1950-2011). Several sites, essentially located in the Vendée Department (i.e. south east of the Pays de la Loire region), are closely monitored because they are vulnerable to erosion (**fig. 2A**) (DHI and GEOS, 2007). These sites are essentially sandy coasts. The rocky coasts are

unsurprisingly less sensitive to fast shoreline retreat with a change rate of ± 0.35 m/y over the same period, as suggested by the French national Indicator of Coastal Erosion (MEDDE, 2016).

The Pays de la Loire region is particularly well known for its vulnerability to storm surges (Chevillat-Miot and Mercier, 2014; Juigner, 2017). This vulnerability is largely explained by the extent (i.e. approximately 200 000 ha) of the low-lying areas (Perherin *et al.*, 2010) subjected to a high level of urbanization. In this region, the second half of the 20th century experienced the strongest urbanization growth of the coastal zone, including the low-lying areas (Pottier, 2007; Juigner *et al.*, 2017, Chauveau *et al.*, 2011b). Juigner *et al.* (2017) noticed that buildings represent a significant part of the coastal zone land cover, with 23% of the regional coastal municipality area urbanized in 2007 (DREAL, 2007). Breaching of coastal dunes is a determinant factor for storm surge risks in the Pays de la Loire region (Devaux *et al.*, 2012; DREAL, 2012; Juigner *et al.* 2017) (**fig. 2B**).

One of the most dramatic coastal flood events of the last 10 years was storm Xynthia that occurred in February 2010. This storm hit the French Atlantic coast between the Loire estuary and the Gironde estuary where sea levels were recorded with 100-year recurrence intervals (e.g. a surge of over 1.50 m was recorded at La Rochelle) (Jacquet *et al.*, 2016). The storm wind force, high spring tide, and wave setup (Bertin *et al.*, 2015) were recognized as the main causes of these high water levels. Xynthia resulted in significant coastal flood along the urbanized coasts of the Vendée and Charente-Maritime Departments (Anziani, 2010; Chadenas *et al.*, 2011; Chauveau *et al.*, 2011a and b; Vinet *et al.*, 2012a; Kolen *et al.*, 2013; Chadenas *et al.*, 2014). The flood caused 47 deaths in France and is regarded as one of the most dramatic natural disasters in France in recent decades. La Faute-sur-Mer and L'Aiguillon-sur-Mer (Vendée Department) counted 29 deaths and experienced severe damages. During storm Xynthia, many coastal dunes were affected by breaches (e.g. Guerande marsh, Breton marsh, Belle-Henriette lagoon, etc.) and strong shoreline retreats were also recorded (e.g. retreat records of -5 m in Saint-Hilaire-de-Riez and -15 m in La Tranche-sur-Mer).

2.2. Institutional background

After the French State set the general guidelines down regarding the coastal risk policy in the early 2000s (Deboudt, 2010), the storm surge of 2010 urged the authorities to enhance and complete the national flood prevention policy (Jacquet *et al.*, 2016). In 2011, the French State established a National plan for rapid floods to improve the safety of people living in flood zones (i.e. the National plan for rapid submersions, "Plan Submersions Rapides" or PSR). Created in 2002, the Action Plans for Prevention of Floods, "Plans d'Actions de Prévention contre les Inondations" (or PAPI) a key public policy tool for flood prevention initially designed for continental floods, were extended to storm surges in 2011. The PAPI is a comprehensive flood prevention policy for at-risk areas with the aim to reduce the consequences of storm surges through management partnership between the French State and local authorities. In 2012, the French State also launched a National strategy to implement integrated coastline management of the French coasts ("Stratégie Nationale de Gestion Intégrée du Trait de Côte" or SNGITC). This strategy recommends consolidating the knowledge of coastal hazards in order to enhance the actions performed against the risks. The SNGITC also promotes the regionalization of local strategies, as well as a real territorial strategy to reduce the exposure to coastal risks.

Difficulties of coastal risks are both national and European. European legislation and policies provide a strategic framework for all aspects of spatial planning and development within the European Union, including coastal hazards (e.g. Flood directives in 2006). Since the early 2000s, the European Union has also supplemented numerous recommendations based on data provided by some research programs (e.g. recommendations for Integrated Coastal Zone Management in 2002 and EuroSION program in 2004). However, monitoring techniques are still poorly applied in Europe. Furthermore, there is a significant gap between Northern and Southern Europe in using systematic coastal monitoring techniques. For example, the United Kingdom and Netherlands have advanced programs for coastal monitoring using mainly airborne LiDAR technology or video systems.

In the United Kingdom, the establishment of new legislation in the 2000s (e.g. European Flood Directive adopted in 2007) emphasized by significant vulnerability of coastal populations to storm surges and

coastal erosion have resulted in the creation of a national strategy for coastal management. The Environment Agency, in partnership with local authorities and other services (e.g. the National Trust), has developed storm surges and coastal erosion management strategies, which identify and evaluate different options for putting management policies into practice. The British government has adjusted this strategy, adapting it to coastal erosion, storm surges, and sea level rise at different spatial and time scales. Therefore, the entire coastline in England and Wales is monitored. The coast is divided into coastal cells which fit in to a Shoreline Management Plan (SMP) with the aim of reducing exposure of populations, properties, and environments at risk of erosion and storm surges. Several options of implementing management policies are applied within each cell at three time scales for the next 25, 50, and 100 years (LICCO, Conservatoire du littoral and Syndicat Mixte Littoral Normand, 2014; Bermon *et al.*, 2016).

In the Netherlands, coast protection and management are the prime concern considering that an important part of the coast is low-lying, vulnerable to coastal flooding, inhabited by 60 % of the population (Isle of Wight council, 2005). A national strategy for low-lying land protection has started in the 1990s, including a Parliament policy to stop coastal recession. A “basal coastline” was determined on the 1st January 1990 followed by several actions conducted to prevent further coastal retreat (e.g., annual coastal measurements and comparison with “basal coastline”; preventive actions such as sand nourishment, close cooperation between Central Government, coastal water boards, Provincial Authorities, and coastal consultative bodies). The “basal coastline” has been almost maintained with this strategy (i.e., in 1990, 30% of the coast was landward of the “basal coastline”, and in 2000, 10%). Measurements in 3D have been conducted since 1998 to improve coastal sand transport movement and morphodynamic understanding, providing thus new information and tools for coastal zone practices.

In contrast, Portugal and Greece apply fewer coastal monitoring techniques; they even limit their applications to experimental research projects. In France, these techniques have been applied only in recent years (e.g. CLAREC project between 2008 et 2013; airborne LiDAR survey by the DREAL Languedoc-Roussillon in 2009; airborne LiDAR acquisition survey by the OR2C since 2016; Litto 3D monitoring by the coastal observation network, Normandie-Hauts-de-France regions since 2017).

In the Pays de la Loire region, local initiatives for monitoring shoreline and coastal hazards were launched in the late 1990s. Since 1998, the University of Nantes has conducted annual beach surveys in Les Sables d'Olonne. Moreover, the Community of Communes of Noirmoutier Island created Noirmoutier Coastal Observatory in 1999. In addition, more recently, Pays de Monts coastal observatory has been collaborating since 2009 with the National Forests Office (ONF), the French Geological Survey (BRGM), and the University of Nantes, following a decision of elected local officials. Their combined expertise allows the development and perpetuation of time-series data acquisitions (i.e. DGPS, LiDAR, hyperspectral imagery, bathymetry) (Le Guern *et al.*, 2011, 2012, 2013). Their actions also make the 3 local observatories' decision support structures in coastal management.

Six years after storm Xynthia, the Pays de la Loire region decided to create a regional observatory of coastal hazards in accordance with the National strategy. Named the OR2C, the observatory has been funded by the council of Pays de la Loire region since 2016 and also by the Authority of Environment, Planning and Housing of the Pays de la Loire region since the end of 2018 (“Direction Régionale de l'Environnement, de l'Aménagement et du Logement” or DREAL). The deployment of the OR2C fits into a general context of regional coastal observatories development in France. The observatories are promoted at present day because they are perennial in providing a precious scientific knowledge for coastal hazard management. Five regional observatories, found along the French coast, monitor a total of 2600 km of coastline (**fig. 3**). Two other observatories are currently in progress: the OSIRISC project in the Brittany region and a project supervised by the BRGM (i.e. French Geological Survey) on the Occitanie region coastline South of France.

In the national and European context, the experience of the OR2C is therefore very recent compared to other French observatories having longer coastal action experience, such as the Observatory of the Aquitaine Coast (OCA), which has been acting for 20 years. However, the OR2C has several characteristics of governance: the network to which it belongs; its general organization; and its data acquisition processes. These characteristics ascribe a model observatory to the OR2C based on an original network.

3. Governance and structure

3.1. Governance and regional network

The governance of the OR2C includes two different levels. The first is a decision-making steering committee whereas the second is a technical committee (**fig. 4**). Both committees meet up three times a year, but also convene in cases of extreme weather events. The animation of the OR2C is entrusted to the OSUNA (“Observatoire des Sciences de l’Univers Nantes Atlantique”), a department in the University of Nantes. The animation team is composed of three dedicated research engineers, one of whom is the project coordinator, another is a coastal hazard specialists and the last is a GIS-web specialist. There are also seven senior lecturers and four PhD students from the University of Nantes.

The steering committee is comprised of seven members from the regional commission for sustainable management of the shoreline (“Commission Régionale de Gestion Durable du Littoral” or CRGDL). Created in 2015, this commission assembles the regional and department Authorities (council of Pays de la Loire region, council of Loire-Atlantique, and Vendée Departments) as well as four State Authorities (Department of Regional Affairs, Authority for Environment, Planning and Housing; Department Authorities for Territories and Sea of the Loire-Atlantique and Vendée). Thus, the commission is highly political, working closely with the State authorities, and other services for the Pays de la Loire region and departments. The steering committee makes all the decisions concerning the OR2C, and oversees the latter’s development. Its role is to define the strategy of the OR2C and to ensure its political representation.

The technical committee is an advisory body, which expresses opinions on the OR2C questions and projects before their submission to the steering committee. The members have also the opportunity to present their work during the committee meetings (e.g. research, projects, protocols, equipment requirements, etc.). The technical committee consists of twenty-one members in addition to those belonging to the steering committee (**fig. 4**). The technical committee brings together the main stakeholders involved in the study and management of coastal risks, including many topics such as geology and geophysics, marine hydrology and oceanography, coastal vegetation, and other scientific researches. Thus, the main institutions concerned with coastal hazards in France are represented in the committee. The committee also comprises nine PAPI managers, whom are in fact local authorities present on the Pays de la Loire region coast (i.e. communities of communes or communities of agglomerations). Also, it comprises three other members: the first member is from the Pays de la Loire region data center (i.e. GEOPAL, <https://www.geopal.org/>); the second member is from the coastal observation network Normandie-Hauts-de-France regions (“Réseau d’Observation du Littoral Normandie-Hauts-de-France” or ROL); and the third member is from the OSIRISC regional project in charge of the preliminary study for setting up a coastal regional observatory in Brittany region.

The governance of the OR2C is unique in France because it combines public institutions (e.g. SHOM¹, IGN², ONF³), research centers (e.g. IFSTTAR⁴, CEREMA⁵, University of Nantes), decisional bodies (i.e. State, regional and department authorities), and operational bodies (i.e. PAPI managers). This governance is currently the only one in France that has chosen to include PAPI managers. This choice is justified by their vested interest in coastal hazards under their responsibility area (overseeing moles and coastal defenses, monitoring shoreline, etc.). Three among the PAPI managers also take in charge local coastal observatories (i.e., three coastal observatories: Noirmoutier Island; Pays de Monts; and Saint-Gilles-Croix-de-Vie).

The governance strengthens OR2C operations at the local level, in accordance with its goal, which promotes coastal risks observation dynamic along the regional coast, at a short, medium, and long term. Therefore, the OR2C gives a global and coherent overview of coastal hazards in the Pays de la Loire region. The

¹ SHOM: Oceanographic and Hydrographic service of the French Marine

² IGN: National Geographic and Forest Information Institute

³ ONF: National forests office

⁴ IFSTTAR: French Institute of Sciences and Technology for Transport, Development and Networks

⁵ CEREMA: expertise center for risks, environment, mobility and planning

governance also helps to improve OR2C members networking as well as the knowledge and management of coastal risks. The OR2C has thus a strong territorial dimension. The OR2C missions and partnerships have recently been formalized by a charter outlining its objectives and specifying the scope of its actions (e.g. geographic, thematic implications).

Moreover, the OR2C collaborates with the regional coastal observation network of Normandie-Hauts-de-France regions (i.e. ROL). The latter, established in 2010, acts as a technical committee member of the OR2C and is also involved in the National integrated coastline management strategy. In addition, the OR2C participates in several actions of the National network of coastal observatories (“Réseau National des Observatoires du Trait de Côte” or RNOTC) and integrates the interregional and National networks of coastal observatories.

3.2. A modular structure

The actions of the OR2C are conducted according to a modular structure, with six different technical or thematic elements called “Modules” (fig. 5).

The major aim of Module 1 is to produce a comprehensive inventory of coastal hazards data in the Pays de la Loire region, but also to identify the needs in order to better target and prioritize the acquisitions. This module uses a thorough bibliographic research, questionnaires, and interviews conducted with the twenty-eight OR2C members. Module 1 is regularly updated along with an inventory of available equipment for coastal hazards studies and monitoring in the Pays de la Loire region.

Module 2 is entitled “Structuring and acquisition of the scientific knowledge of coastal hazards”. As its name suggests, this module aims to strengthen the scientific knowledge with acquisition of new data, and also organize and transmit knowledge on coastal hazards. This module is responsible for the LiDAR airborne acquisitions performed by the OR2C and is intended to provide data chronically (i.e. every year) or following an extreme event. The OR2C website was also designed and created within this module as a major vector for transmitting information and data.

Module 3 is thematic and deals with the history of coastal hazards in the Pays de la Loire region. It was carried out in the context of two PhD theses at the University of Nantes. The goal of the first thesis was to provide information on past extreme storm events (i.e. paleo-storms) and reconstruct paleo-storm chronology based on sediment analysis and dendrochronology. The project was achieved using sediment cores sampled in marshes that had not been subjected to humans’ impacts before the 19th century (Pouzet, 2018; Pouzet *et al.*, 2018b). The objective of the second thesis was to study historical storms and their impacts on coastal societies through historical documents (Athimon, 2019).

Module 4 deals with geoindicators of coastal hazards. Its main purpose is to provide geoindicators using a spatial toolbox analysis capable of detecting coastal areas exposed to coastal erosion and/or storm surges (i.e. MAp RISC, see below). This tool has a high accuracy because it provides information within spatial units 25 m wide. The tool was developed as part of a PhD thesis conducted on the sandy coasts of the Pays de la Loire region (Juigner, 2017). It was then deployed by the OR2C as a coastal spatial analysis toolbox in open access on the OR2C website. The tool development as part of the OR2C has automated all the necessary treatments for the creation of the spatial units along the coast, the calculation and combination of geoindicators. The tool’s final objective is to guide coastal managers in making a precise assessment of the most exposed zones in order to set up preventive measures (e.g. coastal defenses, beach nourishment or reshaping, relocation, etc.).

Module 5 is a communication and enhancement module in which all the OR2C actions of communication are organized (e.g. TV reports, radio programs, press releases, updating of the OR2C website, newsletters, etc.).

Module 6 is a recently added thematic module that analyses the relationship between biodiversity and coastal hazards, considering biodiversity as particularly vulnerable in coastal zones especially in the changing climate context. This module aims to strengthen the knowledge of the dynamics of coastal vegetation communities, and also to assess the consequences of disturbances induced on vegetation communities by natural and anthropogenic pressures.

4. Missions and results 2016-2018

The actions conducted by the OR2C since 2016 are compatible with its three main missions (**fig. 5**). The first mission is to reinforce the scientific knowledge of coastal hazards, according to the recommendations of the National integrated coastline management strategy which can be summarized as follows: “to know better to better act”; the second mission aims to organize and transmit this knowledge in multiple ways to a large public and especially to coastal managers. The last mission is to federate a regional dynamic of observation in the Pays de la Loire region and to promote collective actions, according to the recommendation of the National strategy.

4.1. First mission: strengthen the scientific knowledge

Module 1, from March 2016 to March 2017, provided an overview of available data in the Pays de la Loire region (Robin and Kerguillec, 2017). This work also showed that some data were missing or not very recent (e.g. some bathymetric data date to the 18th century). In addition, it considered the needs of the OR2C members, and particularly the requirements of local authorities (e.g. PAPI managers). The needs are essentially related to data, equipment, and training. Therefore, this work targeted the need for new data in order to advice the technical committee members about acquisition surveys.

4.1.1. LiDAR monitoring protocol

Acquisition surveys proposed by the OR2C are widely based on annual topo-bathymetric data carried out using airborne LiDAR technology. One of the first actions was to establish an initial LiDAR acquisition survey (t0) in 2016, using an airborne topo-bathymetric LiDAR (trademark Optech Titan DualWavelength) Titan DW600 acquired by a consortium, jointly founded in 2015 by the Universities of Nantes and Rennes. LiDAR data were collected on all sandy coasts of the Pays de la Loire region by GEOFIT Expert. The acquisition surveys take place every year from March to May and also at the end of summer (i.e. calm weather and reduced turbidity are required). Three LiDAR acquisition surveys have been conducted since 2016, including bathymetric acquisitions in shallow water areas in 2017-2018. In addition, the OR2C offers the opportunity to mobilize the LiDAR during the month following an extreme storm event in order to learn more about resilience of coastal systems (Le Mauff *et al.*, 2018). Furthermore, the LiDAR is coupled to hyperspectral imagery (i.e. ground and airborne mapping, spectrometry) used in Module 6 for mapping vegetation communities and invasive species, and also to extract several indicators of the stability/instability of coastal dunes (Launeau *et al.*, 2018).

Airborne LiDAR surveys register topographic data in three dimensions (Woolard and Colby, 2002; Pye and Blott, 2016) from which many morphometric parameters are extracted (Brock *et al.*, 2004; Saye *et al.*, 2005). For example, LiDAR technology offers monitoring solutions for beach/dune systems, already tested in the Pays de la Loire region (Le Mauff *et al.*, 2018). Morphometric information is automatically extracted from LiDAR data for large areas (e.g. bases and crests of dunes, coastal dune morphometry, contact and transects of beach/coastal dune, zero-topography, etc.) providing thus valuable information about beaches, coastal dune evolution, and shoreline mobility (i.e. erosion, accretion, stability). The technical committee members may request special flight plans in accordance with their needs. Several requests have already been processed since 2016, particularly in the context of mole monitoring to furnish coastal local authorities' GIS with high precision data or for the development of a PAPI.

4.1.2. Seismic, sedimentological and bathymetric surveys

Because it is essential to consider total sediment flux (sand) from land to sea and from sea to land to understanding resilience possibilities of beaches, the OR2C carried out in 2018 seismic, sedimentological, and bathymetric surveys in the area between the island of Yeu and the mainland (see **fig. 1**). This offshore mission was accomplished along with a LiDAR airborne survey to gather land/sea data for an entire hydro-sedimentological cell, and identify the main sand accumulations related to hydrodynamic conditions.

The first step was to acquire high resolution seismic profiles and bathymetry datasets that are used to identify sediments (sand) partitioning. The offshore mission was carried out on the R/V Haliotis (Génavir, IFREMER), which is equipped with interferometric sonar (bathymetry and imagery) and a Chirp system (seismic profiles) fixed to the hull. Bathymetry, imagery, and seismic profiles were simultaneously acquired on board. In order to achieve a centimetric spatial resolution for data positioning, an Aquarius Thales GPS coupled to an RTK beacon fixed in the study zone was used. Raw data were processed with CARAIBES software (IFREMER) to obtain bathymetric maps and sonar mosaics. The seismic profiles were processed with the SUBOP software (IFREMER).

On the north of Yeu Island, a detailed bathymetric map was realized to delimitate the exact position, shape, and source of the sandy bank “La Sablaire” in 2018. Sedimentological analyses have not yet been completed, but the dune geometry indicated a main transit direction, along the shore, from the west and a potential secondary order from the east. New data acquisitions are planned for June 2019 with the aim to understand rhythmicity of sediment fluxes by seasons and storm events.

4.1.3. History of coastal hazards

The history of risks has been studied with the help of local authorities and the Authority of Environment, Planning and Housing of the Pays de la Loire region (DREAL). Noirmoutier Island local authorities were consulted about building a dense historical storm database (Athimon and Maanan, 2018). Its construction is based on historical archive data acquired during the PhD thesis of Athimon (2019) following the method described by Athimon *et al.* (2016). The historical research was based on ancient documents preserved in libraries and archives (municipal, department and national). Over 19 888 documents were consulted, from which only 936 (around 5%) contained data on past storms and coastal floods since the 14th century. For the Pays de la Loire region, especially Noirmoutier Island and Olonne, the first well-documented event was the winter storm of the year 1351-1352 with a memorable storm surge.

Using a geophysical approach, Pouzet (2018) also showed that the Pays de La Loire region has experienced extratropical storms during the Holocene. Past storms have been identified in sedimentological and dendrochronological data in sensitive territories (Pouzet *et al.*, 2019, 2018a, 2018b). For instance, the Marais Poitevin, the second largest wetland in France located in a low-lying coastal area, have undergone intense urbanization since 1705 (Pouzet *et al.*, 2015). Urbanization was the main cause that provoked significant damage during the Xynthia event, resulting in 47 deaths in France (Vinet *et al.*, 2012b). Following the method built by Liu and Fearn (1993, 2000), washover marine layers were extracted from lowland coastal depositional environments. Historical and geophysical approaches were crosschecked to produce an innovative method to study extreme past storms and storm surges. The obtained results were accurately matching (Pouzet *et al.*, 2019; Athimon, 2019; Pouzet, 2018): for example, the hurricane of the 14th-15th March 1751 was found in both geophysical and historical archives for the Pays de la Loire region. The accuracy of the results opened new perspectives for reconstruction and characterization of past storms and storm surges.

With precise knowledge of this natural hazard, local authorities may assess the overall coastal risks in an area with historically demographical data. Overlapped with historical data, it helps to enhance adaptation of societies facing storms and coastal flood risks.

4.2. Second mission: organize and transmit the scientific knowledge

The second OR2C mission is to organize and largely transmit the data concerning coastal hazards. All the data acquired by the OR2C progress including the datasets provided by the airborne LiDAR surveys are freely accessible on the OR2C website as DEM (i.e. Digital Elevation Model) or DSM (Digital Surface Model). In fact, these data are stored in a Spatial Data Infrastructure (SDI) created and led by the OSUNA (University of Nantes) with a special dedicated staff. However, data-sharing policy applies with an exchange agreement. Several agreements have been signed with the OR2C members to use the data in their own projects (e.g. coastal studies and research, coastal management and development of the PAPI, etc.). Other agreements have been signed between the OR2C and structures outside the observatory with a general perspective of exchanging

data (i.e. an agreement between the OR2C and RTE Company was signed in 2018 for the exchange of seismic, bathymetric and sedimentological data). Therefore, OR2C acts as a multi-destination data provider for offshore development projects, preparation of strategic documents (e.g. PAPI), coastal studies and expertise, or to complement the GIS of local authorities.

4.2.1. The OR2C website

The main vector for transmitting information and data is the OR2C website at: <http://or2c.osuna.univ-nantes.fr/>. Public access to information is a distinctive feature of all regional observatories (Suanez *et al.*, 2012). After being developed over a period of fifteen months, the website was officially inaugurated in early 2018. Its architecture is built around 5 sections (1: OR2C overview; 2: Coast of Pays de la Loire region overview; 3: Coastal hazards; 4: Data and resources; 5: Actualities). The first three sections are respectively dedicated to an overview of the OR2C organization and background, diversity found on the Pays de la Loire region coast, and involved processes and coastal hazards (i.e. coastal erosion and storm surges). The information is essentially informative; the sections supply multiple documents to download (i.e. summary sheets, maps, papers, etc.). These elements can also be downloaded in section 4 "data and resources" which is the website core. This section also includes all the thematic sheets as well as a bibliographic database of more than 600 references. Here, the user can access the spatial toolbox MAP-RISC.

The OR2C website also offers to the user a diachronic analysis of the coastline based on postcards and old photographs from various sources dating to the beginning of the last century (e.g. scientific studies, department archives, private collections, etc.). This application superimposes an old photograph on a recent one taken from the same spot, angle of view, and focal length. Comparison of images highlights the physical coastal dynamics (e.g. coastal erosion or accretion; dynamics of vegetation cover, etc.). The diachronic application also shows human effects on the coastline (i.e. land use, urbanization development, etc.). It is also participative by giving the opportunity to the users to share their own photographs.

The successive stages of data acquisition process are shown in **figure 6**. The acquisition surveys are validated by the steering committee after consulting the technical committee. The data are processed and eventually stored in the Spatial Data Infrastructure of the OSUNA, then transmitted by the OR2C website. The technical committee members may also make available their own datasets. Discussions are currently taking place with OR2C members to insert their data in MAP-RISC.

4.2.2. MAP-RISC: a geo-treatment tool for coastal hazard analysis

Considering the vulnerability of the Pays de la Loire region to coastal hazards and following the recommendations of the National integrated coastline management strategy (MEDDTL, 2012), a GIS solution using coastal hazard indicators has been developed and implemented along the coast of the Pays de la Loire region (program DiDUNE founded by the Fondation de France, see applications proposed by Juigner *et al.*, 2017; Juigner and Robin, 2018). The aim of OR2C module 4 is to further develop this program by implementing along the Pays de la Loire coast an original toolbox that computes and maps fine-scale coastal hazard indicators (i.e. 1/5 000e) using GIS technics.

Geo-treatment tool for coastal risk spatial analysis is called MAP-RISC ("Module d'Analyse sPatiale des RISques Côtiers", or "spatial analysis system for coastal hazards"). It largely contributes to the specificity of the OR2C. Coastal hazard analysis is documented in the international scientific literature. A large number of publications present GIS solutions to compute coastal hazard indicators and indices (see examples suggested by Saye *et al.*, 2005; Debaine and Robin, 2012; Olsen *et al.*, 2012; Pye and Blott, 2016; Bonetti and Woodroffe, 2017; and the large review proposed by Nguyen *et al.*, 2016).

Indicators are defined here as proxies of environmental changes. In coastal zones, they are used not only to evaluate potential risks and damages but also translate complex coastal observations into an operational, synthetic, and comprehensive form used to help managers and decision-makers in management processes (see Lescinski, 2010; Carapuço *et al.*, 2016).

The method applied here is similar to the one used in rocky coasts by Young and Ashford (2006), sandy coasts by Debaine and Robin (2012), and various coast types in DiDUNE program (see above sections). It

consists of a continuous and regular segmentation of the coast into polygons (i.e. spatial units) positioned perpendicularly to the coastline direction. The units obtained are particularly adapted to integrate and aggregate various spatial information types such as geometric primitives (point, polyline and polygon), or raster datasets (Juigner, 2017). Thus, the spatial unit segmentation is suitable to compute and combine multiple indicators extracted from different data sources. The module objective is not to create new dataset, but to exploit existing generic data (e.g. land occupation, topography i.e. LiDAR, orthophotography), and create new spatialized information computed inside each spatial unit.

MAp-RISC is developed with an open-source database management system PostgreSQL and its spatial extension PostGIS in order to incorporate the tool to the web architecture. It allows easy integration in a web map server, and has substantial optimization of computing time performances. The process runs in four steps. The first step examines spatial unit segmentation. Spatial units of 25*100 m are pre-executed along the Pays de la Loire coast. Their creation can be launched through different executions in other coastal territories (see example below). The second step is selecting one existing indicator. At the stage of development, available proxies are relative to: (i) the exposure index suggested by Juigner *et al.* (2017), i.e. the shortest shoreline-building distance (in meters), the first row building footprint (in square meters), and the coastal erosion estimated between two dates (in square meters); and (ii) susceptibility index of coastal dunes to flooding as proposed by Juigner and Robin (2018), i.e. dune volume above a topographic level. Other indicators relative to dune susceptibility (e.g. dune width, dune altitude, low-lying areas) are in progress (see the tool on the OR2C website for more information). The third step consists of selecting a territory to conduct a spatial analysis. Territories are defined following administrative or natural limits (e.g. regions, departments, municipalities, littoral cells). The fourth and last step is related to cartographic restitution of the results through the web-mapping platform. Two different spatial types of information are available. First metric indicators are mapped using a graphic semiology based on color changes. For example, spatial unit n° 9159 in La Tranche-sur-Mer (see **fig. 1**) is characterized by the presence of at least one building located at 7.7 m from the shoreline. In the same spatial unit, a strong shoreline recession (-878.7 m²) is recorded during the 1950-2011 period (see **fig.7-A**). Figure 7-B presents the result of the shortest shoreline-building distance in La Tranche-sur-Mer coast section. A dark color tone shows the proximity of a building to the shoreline. A light color shows a building far from the shoreline. The second information is contained inside each spatial unit. Spatial units are described by a unique spatial unit identifier (classified from north to south of the regional coastline), and by a metric corresponding to the indicator value. The spatial units' geometry and attribute table are downloadable on the website.

From a local (spatial unit level) to a regional scale (higher synthesis level), the geo-treatment tool contribution is related to its ability to map predispositions of certain coastal sectors exposed to coastal physical hazards, such as coastal erosion and storm surges. One of the most important advances is the creation of new fine, spatialized, quantitative, exhaustive, and homogeneous geographic information. Using GIS and spatial unit segmentation provide a quantitative value of an indicator every 25 m. The entire coast is mapped by the system; thus, the entire at-risk configuration is precisely detected. Spatial information provides a synoptic view of the hazards and/or risks at various scalar levels. At a spatial unit scale, partners will have access to precise metrics describing the state of the coast. At a smaller scale (e.g. municipality, department, region, and littoral sedimentary cells), multiscale synthesis can be executed to give a territorial view of the hazard/risk (see demonstrations proposed by Juigner, 2017).

MAp-RISC aspires to develop and diffuse reference data for the OR2C's partners at a local (e.g. PAPI managers, coastal dune managers, local coastal observatories) and regional scale (e.g. State, territorial authorities, and services). This new reference could be used to update policies, strategic documents, coastal studies, and coastal GIS territories.

MAp-RISC proposes responses to several recommendations of the National integrated coastline management strategy. First, the combination of non-human at stake indicators with historical shoreline mobility responds to a need of identifying at-erosion-risk territories. Secondly, the indicators relative to dune's susceptibility (i.e. current dune volume and shoreline retreat) reveal the ability of the spatial unit segmentation to create and combine multi-risk indicators (here, identified as coastal erosion and storm surges). Furthermore, this application responds to the need to consider the role of natural ecosystems against physical hazards

following the recommendations of the National strategy, and especially in the case of danger-evaluation studies (Deniaud and Ledoux, 2018). Thirdly, the National strategy recommends the development and sharing of common methodologies, to produce homogenous knowledge about coastal zone dynamics and hazards. In this sense, an initial experiment was conducted to detect the predisposition of building exposure to coastal erosion along 120 km of sandy coast in Normandie, in partnership with the coastal observation network of Normandie - Hauts-de-France regions. Fourthly, web mapping of the results can diffuse knowledge and inform the public about coastal dynamics and coastal hazards. Currently, the development of this tool is in progress. Four indicators are proposed at the present time, and the future development would consist of aggregating the indicators to compute synthetic risk and/or multi-risk indexes following the recommendations of the decision-making steering committee and OR2C technical committee.

4.3. Third mission: federate a regional dynamic for coastal hazards observation

The last mission of the OR2C is to impulse a dynamic of observation in the Pays de la Loire region, between all the structures involved in coastal risk studies and management. This objective does not mean replacing the existing structures, but it does act as a link between all the OR2C technical committee members to strengthen actions against coastal hazards and promote collective actions. The objective also promotes improved coherence and relationships at various levels in the territory (see **Fig. 4**) in order to go beyond sectoral management of coastal risks and benefit from a global approach in this management. Reducing information gaps on coastal risks is one of the first steps towards achieving this goal, in accordance with the recommendations of the National integrated coastline management strategy. In this sense, the OR2C acts to include all territories in terms of production of information. The OR2C also connects various operators for data acquisition and management on coastal risks, by promoting mediation through an exchange space aimed at defining a common strategy of data acquisition and common protocols for shoreline monitoring. Moreover, the OR2C promotes a dynamic of observation by encouraging the OR2C members to exchange their theoretical and technical skills as well as their methods. In early 2018, the observatory organized and supervised a 3-day training on shoreline monitoring, during which partners shared their knowledge. These collective actions are in accordance with the National integrated coastline management strategy. A second training session on the use of LiDAR data was proposed in January 2019. The objective was to help coastal managers use LiDAR data for coastline monitoring. The OR2C also organizes working groups on topical issues, such as defining shared indicators for shoreline monitoring (September 2017), considering climate change in the context of public policy (Marsh 2019), and relocation (ongoing). These working groups bring together the OR2C members around common themes and lead shared visions and proposals.

5. Conclusion

Regional coastal observatories like the OR2C are recognized as appropriate networks to fight against coastal risks because of their spatial dimension, data quality, and sustainability. Generally, regional coastal observatories aim to rationalize and mutualize expensively acquired and shared data in regards to coastal risks, in order to respond to public and private requirements for better management of coastal areas. Thus, the OR2C is set-up in response to the recent dramatic disaster (i.e. storm Xynthia) and to improve the national context for strengthening the tools that counteract coastal risks. Moreover, the decentralization to local authorities, of policy making against coastal risks in French coastal regions, can also be found in this set-up. This trend can be seen for the GEMAPI competence transfer from the French State to local authorities in 2018 (i.e. the GEMAPI competence deals with managing aquatic environments and preventing floods including storm surges). This trend is also noticed in the context of two new French laws: the first decreed in 2014 called MAPTAM, "Modernisation de l'Action Publique Territoriale et d'Affirmation des Métropoles", and the second in 2015 called NOTRE, "Nouvelle Organisation Territoriale de la République". The National network of regional shoreline observatories, led by the French Ministry of Environment, Ecological, and Solidary Transition ("Réseau National des Observatoires du Trait de Côte" or RNOTC), is largely based on regional observatories.

Despite the fact the OR2C is recent, it provides in this context a new model of integrated regional collective actions against coastal hazards, strongly anchored at the local level, based on high-precision data used to strengthen the scientific knowledge, develop and strengthen strategic tools, and provide a new tool for coastal hazard management (MAp-RISC).

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Fig.1: hazards and vulnerability of the coastal area monitored by the OR2C since 2016.

Fig. 2: A. An erosional dune cliff at Les Becs in the Vendée Department after the stormy winter of 2013/2014 (© OR2C - M. Juigner, 2014). B. The dramatic storm surge at La Faute-sur-Mer during storm Xynthia, February 2010 (© DDTM 85, 2010).

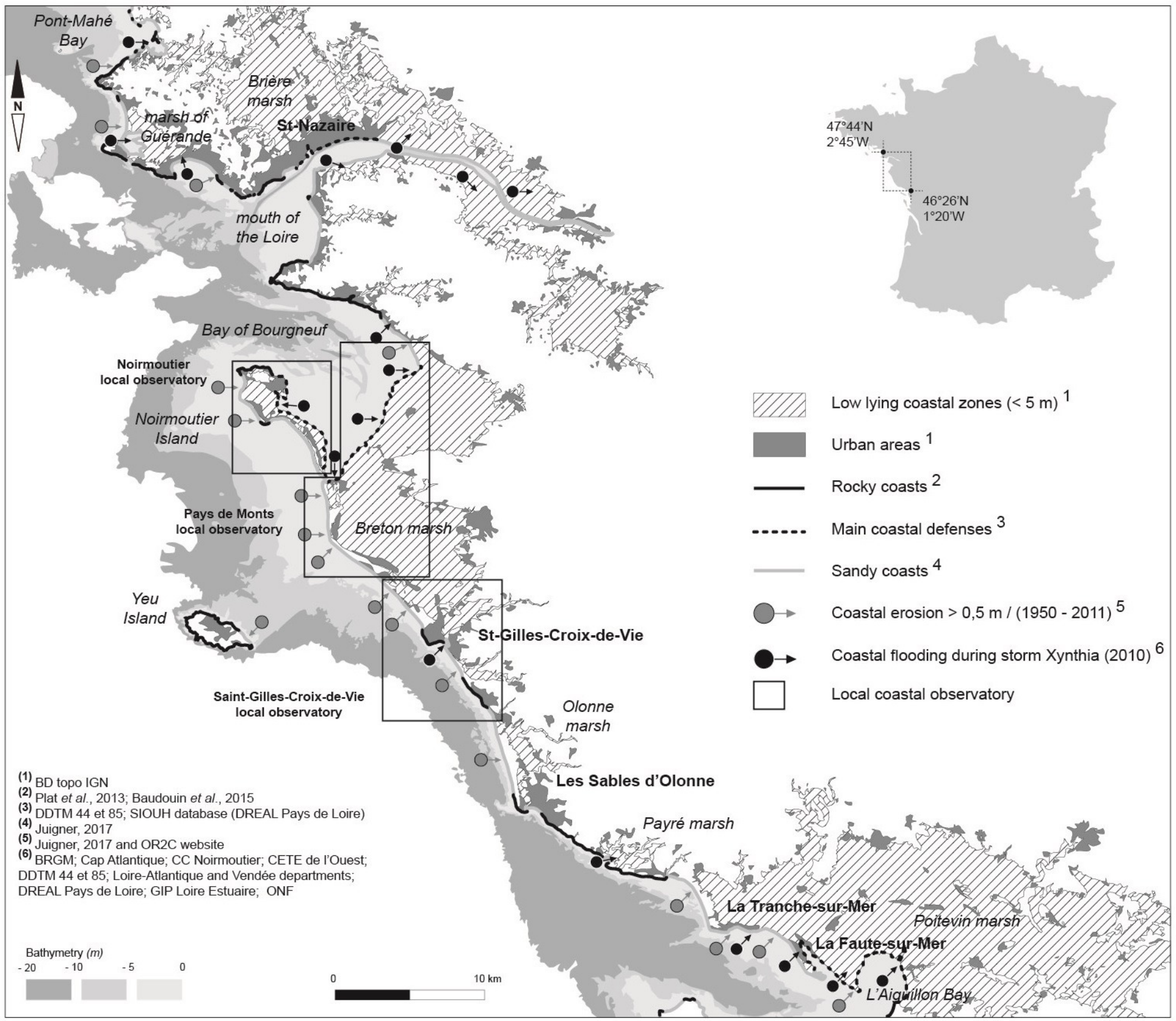
Fig. 3: establishment year and coastline length of regional French coastal observatories.

Fig. 4: the OR2C governance and partnership. Geographical location of the Pays de la Loire region in France, showing the departments and local authorities of the OR2C.

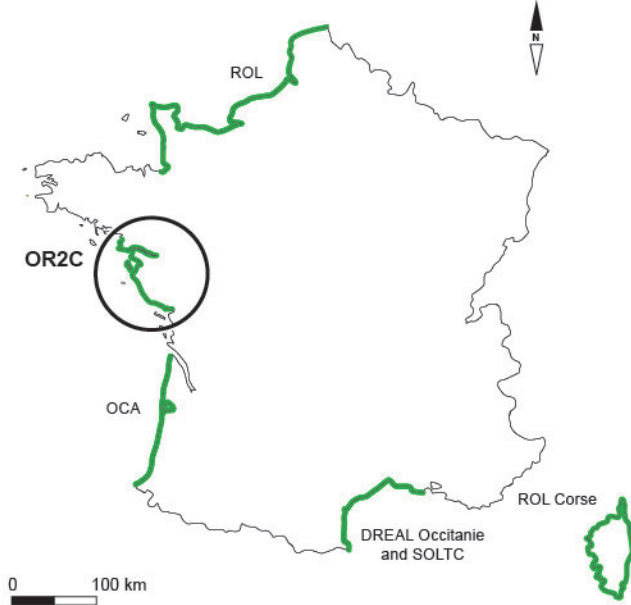
Fig. 5: the six modules and three goals of the OR2C.

Fig. 6: the OR2C procedure for acquisition and transmission of data.

Fig. 7: spatial display of two indicators from the MAp-RISC web-page located in the eastern coast of La Tranche-sur-Mer (Vendée). Per spatial unit: A. Coastal erosion (m²) with full spatial units; B. Shortest shoreline-building distance (m) with onshore spatial units.







Observatory	Date	Coastline length
ROL Corse (Réseau d'Observation du Littoral Corse)	1999	≈ 800 km
OCA (Observatoire de la Côte Aquitaine)	2000	≈ 350 km
DREAL Occitanie and SOLTC (Direction Régionale de l'Environnement, de l'Aménagement et du Logement / Système d'Observation du Littoral - Trait de Côte)	2008	≈ 220 km
ROL (Réseau d'Observation du Littoral Normandie-Hauts-de-France)	2010	≈ 800 km
OR2C (Observatoire Régional des Risques Côtiers)	2016	≈ 400 km

Sources: Suanez *et al.*, 2012, websites of ROL Corse, OCA, SOLTC and ROLNP.



The partnership of the OR2C (28 members)

3 Others members

- GEOPAL ⁽¹⁾
- OSIRISC ⁽²⁾
- ROL ⁽³⁾

9 PAPI ⁽⁴⁾ managers

(i.e. local authorities, see the map)

- PAPI Cap Atlantique
- PAPI Carene
- PAPI Ocean-Maraais-de-Monts
- PAPI Noirmoutier
- PAPI Pays de Saint-Gilles
- PAPI des Olonnes
- PAPI Marais du Payré
- PAPI Bassin du Lay
- PAPI Vendée-Sèvre-Autizes

4 State authorities

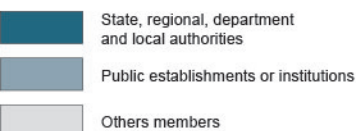
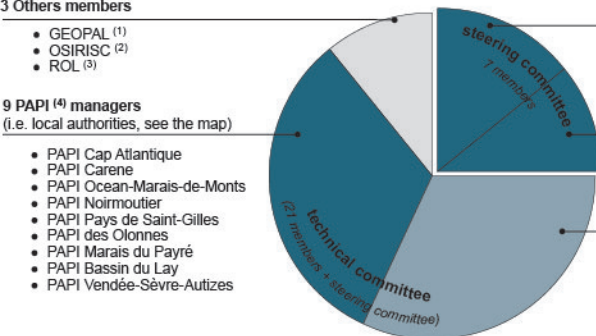
- SGAR ⁽⁵⁾
- DREAL de Pays de la Loire region ⁽⁶⁾
- DDTM Loire-Atlantique ⁽⁷⁾
- DDTM Vendée

Regional and department authorities (see the map)

- Council of Pays de la Loire Region
- Council of Loire-Atlantique Department
- Council of Vendée Department

9 Publics institutions

- Water agency
- French Agency for Biodiversity
- BRGM ⁽⁸⁾
- CEREMA ⁽⁹⁾
- IFSTTAR ⁽¹⁰⁾
- IGN ⁽¹¹⁾
- ONF ⁽¹²⁾
- SHOM ⁽¹³⁾
- University of Nantes



Regional, department and local authorities of the OR2C



⁽¹⁾ GEOPAL: web data center of Pays de la Loire region; ⁽²⁾ OSIRISC: project for a future regional observatory in Brittany Region; ⁽³⁾ ROL: Réseau d'Observation du Littoral Normandie-Hauts-de-France (regional coastal network of Normandie-Hauts-de-France regions); ⁽⁴⁾ PAPI: Programmes d'Action de Prévention contre les Inondations (action plans for prevention of floods); ⁽⁵⁾ SGAR: Secrétariat Général aux Affaires Régionales (department of regional affairs); ⁽⁶⁾ DREAL: Direction Régionale de l'Environnement, de l'Aménagement et du Logement (regional authority of environment, planning and housing); ⁽⁷⁾ DDTM: Direction Départementale des Territoires et de la Mer (department authority of territories and sea); ⁽⁸⁾ BRGM: Bureau de Recherches Géologiques et Minières (french geological survey); ⁽⁹⁾ CEREMA: Centre d'Etude et d'expertise sur les Risques, l'Environnement, la Mobilité et l'Aménagement (expertise center for risks, environment, mobility and planning); ⁽¹⁰⁾ IFSTTAR: Institut Français des Sciences et Technologies des Transport, de l'Aménagement et des Réseaux (French Institute of Sciences, Transports, Planning and Networks); ⁽¹¹⁾ IGN: Institut National de l'Information Géographique et Forestière (national institute of geographic and forest information); ⁽¹²⁾ ONF: Office National des Forêts (forests national office); ⁽¹³⁾ SHOM: Service Hydrographique et Océanographique de la Marine (Naval Hydrographic and Oceanographic Service).

OR2C 6 «modules»

Module 1	Module 2	Module 3	Module 4	Module 5	Module 6
Data inventory	Structuring and acquisition of the scientific knowledge of coastal hazards	History of coastal hazards in the Pays de la Loire region	Geoindicators of coastal hazards (i.e. MAP-RISC)	Communication and enhancement	Biodiversity

OR2C 3 major goals

