A NEW GENERATION OF EARLY WARNING SYSTEM FOR COASTAL RISK. THE ICOAST PROJECT.

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A new coastal early warning system CEWS called iCoast for the NW Mediterranean Sea is under development. It is composed of three numerical modules: meteorological, hydrodynamic and morphodynamic. The CEWS is designed for use on open sandy beaches, pocket beaches, secondary harbours as well as areas of coastal defences. A set of hotspots, prone to erosion or flooding, along the Catalan coast are being identified through a coastal hazard and risk mapping. Special attention is given to a set of intervention and emergency protocols based on the forecast outputs and the application of Quick Defence Measures (QDM) to diminish the risk. This paper presents the initial architecture and highlights the next step for QDM under the iCoast project.

Keywords: coastal early warning system; transient defence measures; coastal risk; erosion modelling

INTRODUCTION

A significant part of the European Mediterranean coast is limited in its ability to deal with environmental, physical and hydro-meteorological hazards due to the presence of hard structures such as for example promenades, buildings, roads, railways. In many cases, this occupation of the coastal domain was progressed under the assumption that the coastal fringe remains stable. This idea is probably reinforced by a gentle sea state during most of the year resulting in a false perception of security by society. However, high wave energetic conditions are frequently observed and, when they are associated with high water levels, can cause significant damages. In the last 20 years, extreme storms have been responsible for at least 50 casualties (drowning swimmers and walkers who have been caught/hit by waves) alone in the NW Spanish Mediterranean coast and for significant damages in coastal defences, harbours and infrastructures amounting over 30M €. Thanks to advances in numerical tools and coastal observations it is now possible to implement operational morphodynamic predictions (water and sediment fluxes) yielding timely and valuable intervention data to reduce coastal risk due to incoming storms.

Forewarning (about e.g. storm impacts) allows the selection of the best coastal management strategy. This is the basic idea of the iCoast (Integrated Coastal Alert System) EU Project the main objective of which is to develop a tool to address coastal risks caused by extreme waves and high sea water levels in European coastal areas. iCoast is planned to be used not only as a coastal early warning system to forecast storm events but also as a tool to help in decision making for coastal interventions and eventual management. In a first phase, the project will be implemented in the Spanish NW Mediterranean coast. The main targets will be urban beaches and coastal defences and infrastructures where most of the casualties (more than 50) and damages (over 30 M€) have been reported in the last two decades.

The main objective of this paper is to show the structure of the iCoast project and present initial findings. The paper is structured in 4 parts following the main architecture of the project: (i) coastal hazard and risk mapping, (ii) intervention guidelines, (iii) data assimilation and modelling and (iv) communication protocols.

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COASTAL HAZARD AND RISK MAPPING

Coastal risk mapping provides a global risk landscape associated to extreme marine weather events through an inventory of reported disasters. The selected coastal stretch has been the Catalan Coast (NW Spanish Mediterranean, see Fig. 1).

The Catalan coast has an approximate length of 700 km and presents a wide range of coastal environments. Typically the northern sector is characterized by cliffs (about 280 km of the total length) and pocket beaches with coarse sediment (sand) whereas the southern region is represented by a low lying coast with fine sediment. The central sector is under the influence of the main urban settlements (metropolitan area of Barcelona) and although open beaches can be found they are typically fragmented due to the construction of harbours and coastal protection works. The coast is administratively organized in 76 municipalities.

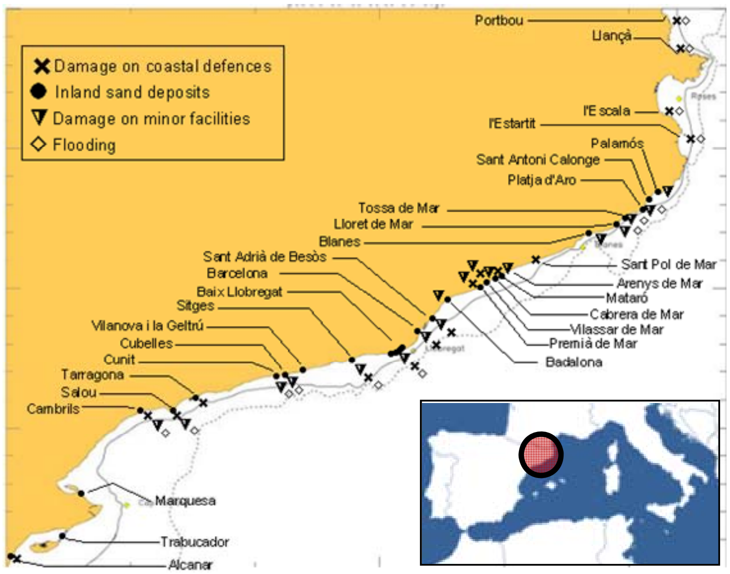

Figure 1. The Catalan coast and main impacts reported during the major storms of November 2001 and December 2008.

Sandy beaches represent 36% of the total length of the Catalan coast and of these approximately 60% have been designed with an urban concept - a sandy beach limited by a seafront promenade or other type of infrastructures resulting in the first 100 m being urbanized. An exception of this is the Ebro delta coast at the South, a unique environment of about 55 km of coastline of almost pristine sandy beaches without any human intervention. The 86% of the coast (without considering the Ebro delta) can be considered as urban.

In the last years, the maintenance and development of promenades has been one of the major investments taken by the Spanish government (more than 50M€ only in the Catalan coast alone). As most developed countries, the Catalan coastal region supports the main economic activities of the area (commerce, agriculture and residential development) being tourism the dominant one (Sardá *et al.*, 2005; Valdemoro and Jiménez, 2006).

The maximum offshore significant wave height recorded in last decades is 6.3 m (maximum wave heights of 10 m) with peak periods in the range of 13 to 17 seconds. Storms present three main directions from a coastal impact point of view: NE, E and South. In the 1994-2008 period, 297 wave storms were recorded (Guillén 2008) in which 147 were considered as weak, 82 as moderate, 59 as important, 8 as severe and 1 as extreme (2001 November). More than 50 casualties have been reported.

Cateura *et al.* (2004) identify two main meteorological situations which trigger wave storminess: a) intense high-pressure centre on the British islands which induce strong NE and E winds and b) Mediterranean cyclo-genesis in front of Catalan coast generating E winds. Mendoza *et al.* (2011) proposed a storm classification according to the associated energy in five categories. In their analysis the authors identify three meteorological situations in which storms take place: the Mediterranean Cyclone (MC) characterized by a low pressure centre over the W Mediterranean generating storms with meso-scale features and weak intensity or covering a wide area with strong intensity, the South Advection (SA) situation in which a low pressure centre is established over the Atlantic typically generating southern winds of varying main direction (SE, S, SW) and the East Advection (EA) in which a high pressure centre over North or Central Europe and a low-pressure centre over North Africa results in eastern winds blowing along the Catalan coast.

From the iCoast point of view, the existence of high and low water levels associated to storms is a fundamental aspect because gives a completely different morphodynamic answer. Although the Catalan coast is in a micro-tidal environment (tidal range of about 0.4 m) meteorological tides (surges) can be very important and reach values up to 0.6 m. Two main storm patterns have been defined from the existing hydrodynamic data sets, representing single and a double peak (in spectral terms) events. Single peak typically correspond to a 24 hours storm mainly from the E which can reach wave heights intensities up to 4-5 m whereas double peak episodes are associated to the most energetic storms. In each category the mean water level (astronomic tide and surge) can be approximately constant or present a growth pattern (in phase or uncoupled with waves). This classification will serve to initially estimate the potential effects of the forecasted storm within the iCoast prototype and propose an accommodation or defence action.

The action of wave storms along the Catalan coastal has implications for the complex problems in land-use planning problem. An analysis of the reported coastal damages on local newspapers of the last 14 years (in order to reflect present conditions) has been done to identify the main typologies and hot spots. The analysis (see Figure 1) has provide four main types of storm impacts: (i) damages on coastal defences, (ii) massive inland sand deposits, (iii) damages on minor facilities (urban and beach furniture) and (iv) coastal flooding (affecting the existing infrastructures). In addition there have been reported a number of human casualties (years 2001, 2003, 2008 and 2010).

A representative subset of the Catalan coast (see Figure 2) has been selected clustering these targets as open beaches, harbours, coastal defences and enclosed beaches. In open beaches we have two categories: natural beaches and human-controlled beaches. We have selected small craft harbours as Llançà at the north and Port Forum in Barcelona because the main commercial ports have already their own early warning systems. Finally an armoured coastal stretch (Cabrera de Mar) has been also included in the project due to its importance for the communication within the coastal communities near Barcelona. All the above mentioned environments will be used as pilot sites where the forecasting will be implemented.

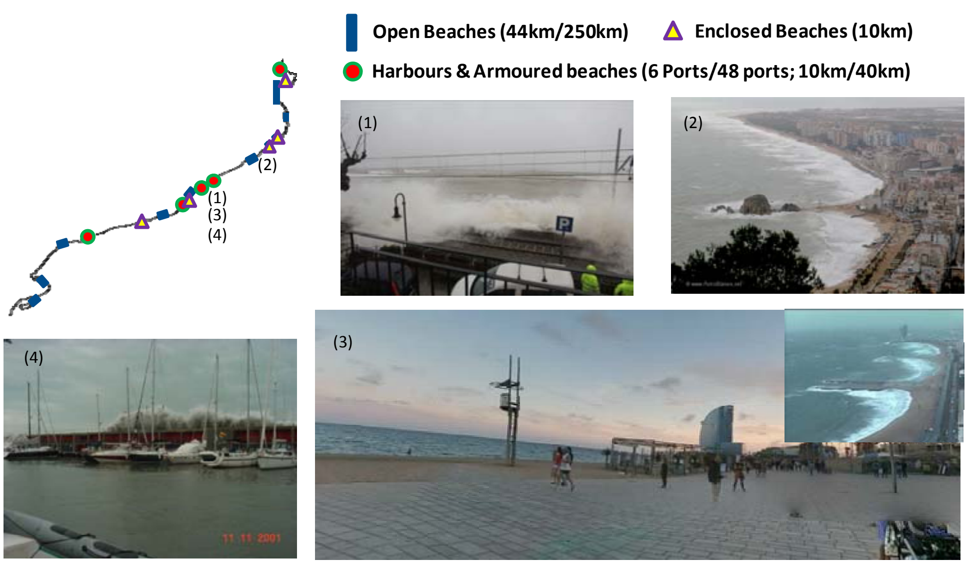

Figure 2. Beach targets selected within iCoast project and examples of storm impacts.

INTERVENTION GUIDELINES

During the last decades, coastal managers have tried to control the coastline through hard infrastructures (i.e. revetments and breakwaters) and beach nourishment (Hanson *et al.* (2002), Van Rijn (2011)). Unfortunately, several of these measures have modified the sediment natural fluxes in an unexpected manner which has lead to exacerbated erosion and accretion patterns. Moreover, these solutions present other two disadvantages: hard works induce a "steady" hydrodynamic behaviour and require periodic beach nourishment. This has been the root cause of several coastal conflicts along the Mediterranean coast and has resulted in policy makers demanding to the scientific community an interdisciplinary solution (Sánchez-Arcilla *et al.* (2011)).

Short-term strategies, focused on coastal protection during periods with high energy conditions only, may be a plausible alternative for alleviating the aforementioned issues. Designing short-term structures that will protect the coast while not affecting the coast during normal events is a "soft" and "new" coastal management strategy. Termed Quick Defence Measures (QDM), these temporary actions may be implemented in advance in the coastal zone in order to reduce risk from forecast storms. To be effective, however, the design of such transient works requires detailed information on the hydrodynamic conditions of future forecast events and an assessment of the effect on subsequent beach evolution. With that aim, the objective of this action task is to understand the functioning of transient solutions and evaluate their feasibility for coastal protection within a coastal early warning system.

In the iCoast project, special attention is given to these actions as a link between high resolution forecasts and actual field conditions. Firstly, an extensive literature review and practitioner survey is being carried on, trying to identify synergic contributions from relevant projects and organisations. The expected results will be a set of guidelines, best practices and lessons learned that will provide useful insight for QDM design and their application range at other coastal areas.

The definition of QDM requires a set of intervention protocols involving thresholds of activation, typology of the solution and the required time for their deployment/withdrawal. One of the primary assumptions is that the proposed actions must be taken within 24 hours or less prior to the forecasted storm episode. The defence strategies include the physical intervention on the beach by constructing transient dunes and trenches or by placing sand bags filled "in situ" at the beach backside among others (Figure 3). Interventions will be associated to a range of wave and mean water levels where they are functional. Results obtained from coastal hazard and risk mapping will help managers to identify thresholds (storm intensities) and its consequences will be evaluated with the modelling framework presented below.

Simulations results through near-shore modelling show the feasibility of the transient dune as a QDM. Using the wave-averaged coupled hydro-morphodynamic model XBEACH (Roelvink *et al.* 2009), several layout alternatives are being checked. As an example, Figure 4 shows a representative beach transect from a 2DH simulation of a beach located at the Southern part of Barcelona. A synthetic trapezoidal-shaped wave storm with 5 years return period and different maximum sea levels has been used as driver, showing that this gentle slope beach in conjunction with a transient dune can handle water levels up to 40 cm. However, if a similar dune is located near the shoreline, for the same water level threshold, the defence collapses.

DATA ASSIMILATION AND MODELLING

The obtained hotspots during the coastal hazard and risk mapping tasks are the targets of the proposed forecasting system. This framework consists of four steps: (a) meteorological module; (b) hydrodynamic module and (d) coastal state indicators module (Figure 5).

The system will be uploaded with the 120-hours forecasted conditions from the Global Forecasting System (GFS) with 50x50 km grid resolution with temporal coverage every 3 hours. These fields will serve as initial and boundary conditions for the meteorological model WRF-ARW (Skamarock et al. 2008) at 15 km horizontal grid resolution. In order to refine the meteorological fields a nested simulation is run with 3 km horizontal grid resolution. Finally, the WRF-ARW outputs at 3 km are downscaled through running a meteorological model called CALMET (Scire et al. (2000). The CALMET model will provide high resolution wind fields for the coastal targets with a spatial resolution of 400 x 400 meters. The Local Analysis and Prediction System (LAPS) is the selected tool to perform data assimilation of meteorological observations (AWS, Satelite, Metars, Roab, etc) into the WRF-ARW model at 3 km horizontal grid resolution to improve wind forecast.

The hydrodynamic module will use an on-line coupled version of the circulation model ROMS (Shchepetkin and McWilliams, 2005) and the SWAN (Booij *et al.* 1999) wave model with a minimum grid size of 350 x 350 meters. The nesting sequence is similar than the presented in Sánchez-Arcilla *et al.* (2012) and the suitability of the locally fitted SWAN model during storm events for the NW Mediterranean sea has been tested with buoy and satellite data (Sánchez-Arcilla *et al.* (under revision), Pallarés *et al.* (2014), Alomar *et al.* (2014)). The meteorological module will provide the forcings for the wave model (wind fields) and for the hydrodynamic model (wind, sea level pressure, temperature, humidity, heat fluxes). The MyOcean forecasting service (Bahurel *et al.* 2009) will provide the boundary conditions of sea level height, salinity, temperature and general circulation for the hydrodynamic model.

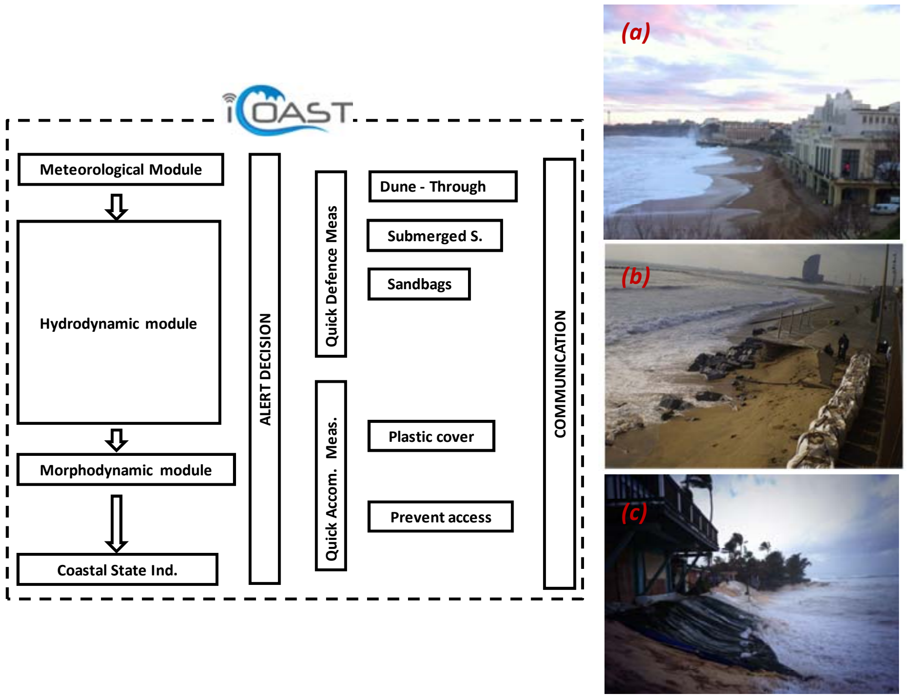

Figure 3. (Left) iCoast framework for modelling and intervention protocols. Starting from an early warning system forecast, the managers can adopt and evaluate the feasibility of a set of decisions for reducing coastal risk (quick defence measures and quick accommodation measures). The decision will be communicated to the intervention group 24 hours prior to the storm event. (Right) Examples of QDM: a) transient dune system at Biarritz beach (Spain) during Hercules storm (January 2014), b) sand bags at Barcelona beach (March 2010), c) Geotextile covering at Oahu Island (January 2014).

Directional wave spectra and sea level will serve as boundary conditions for the nearshore hydrodynamics and morphodynamics module. For open sandy beaches, the wave-averaged model XBEACH (Roelvink *et al.* 2009) will be used whereas for harbours, revetments and pocket beaches the transient model SWASH (Zijlema *et al.* 2011) will be run instead. The latter model is chosen because its ability to handle phenomena which requires a wave-by-wave computation (e.g. wave diffraction). A combination of analytical models will be also implemented to evaluate specific phenomena as wave overtopping in harbours, complementing the high resolution models cited above. The minimum gridsize will be around 20 x 20 meters. Depending on the storm magnitude, different beach layouts and alternatives will be numerically tested as the proposed in the intervention protocols.

The Coastal State Indicator module will post-process all the output from all previous modules, providing relevant integrated information for coastal managers included expected run-up, minimum beach-width after an erosive event, the final beach profile or the discharge at the emerged beach. . For instance areas more prone to coastal damages will be identified taking into account significant parameters considered as trigger for a damaging event, such as height of waves, orientation of coastline, etc. These indicators, classified under the different beach layouts will become the closing link with already implemented decision support systems.

COMMUNICATION PROTOCOLS

The decision to activate an alert would be taken after aggregating the detailed information into a set of coastal state indicators. The collected data in the CSI module would also be processed to propose a range of management defence/accommodation strategies according to the intensity of the predicted storm. Three major levels of users have been initially defined: end-users, the municipality managers and the national level administrators. The highest level has all the information during the whole forecasting process, which is initially estimated in 72 hours (the first time horizon of the iCoast predictions). In the opposite end, end-users will just receive information on the final actions and the predicted consequences of the storm (Figure 3).

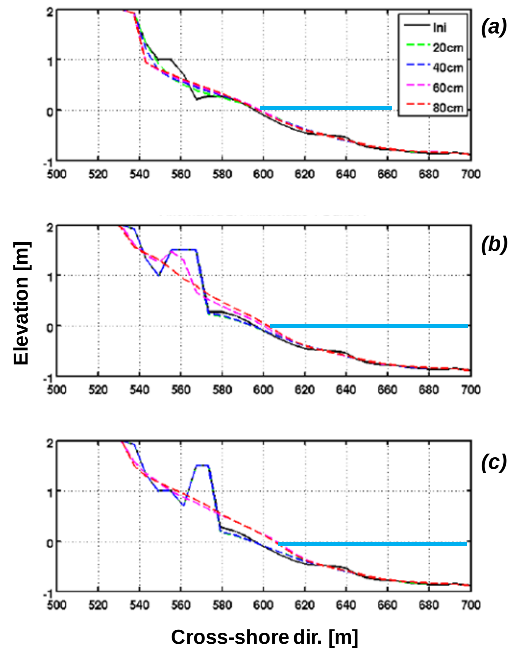

Figure 4. Assessment of the QDM through nearshore modelling at the Barcelona beach. Initial (solid black line) and final beach profiles (coloured dashed line) for a wave storm with a return period of 5 years and different configurations of maximum water level (20 cm, green; 40 cm, blue; 60 cm, magenta and 80 cm). The solid blue line delimits the still water level. Subplot (a) reports the final beach profile without intervention; subplot (b) consist of the same profile but with a transient dune inshore whereas subplot (c) has a similar dune but closer to the shoreline.

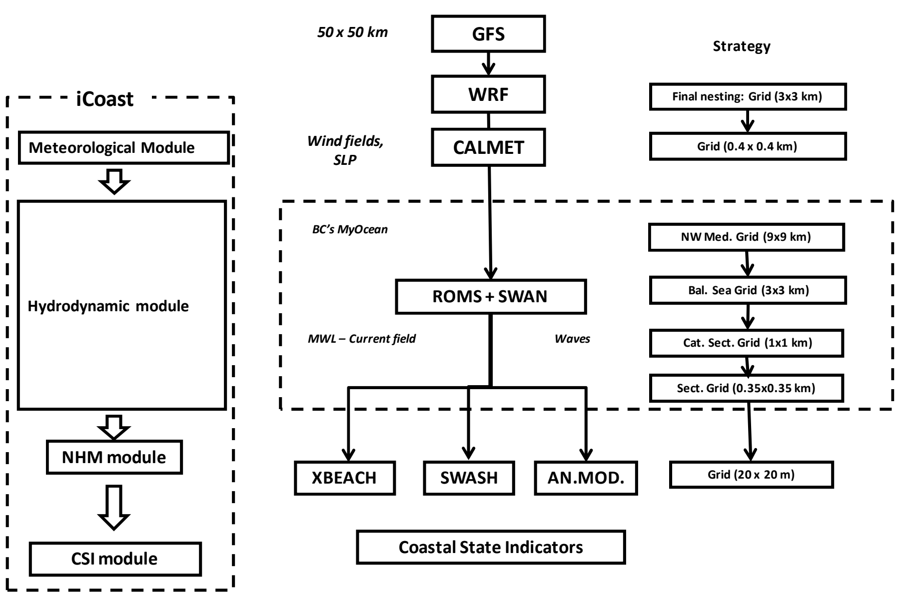

Figure 5. iCoast modelling framework, nesting strategy and hierarchical modules: a) meteorological module, b) hydrodynamic module, c) nearshore hydrodynamics and morphodynamics and d) coastal state indicators module.

Figure 6 shows an example of the iCoast prototype for the case of the Mataró small craft harbour. The shows the predicted harbour agitation and current patterns at the peak of the storm event of December 2008, the largest one in recent years. In addition, due to the use of a NSWE model, the wave induced mass flux that enters into the harbour can be also modelled. With the joint combination of analytical models, the system may be able to forecast not only the exterior hydrodynamic conditions but also the safety of the moored vessels. A set of harbour intervention protocols for extreme cases may be thus prepared, such as the temporal mooring in a nearby harbour where calmer conditions are forecasted.

Initially the project, is planning to use the existing communication channels (FAX,SMS services, e-mail and phone) to inform about the alert to the highest level of the administration and harbour responsible but the potential use of social media (Twitter, Facebook) will be subsequently investigated.

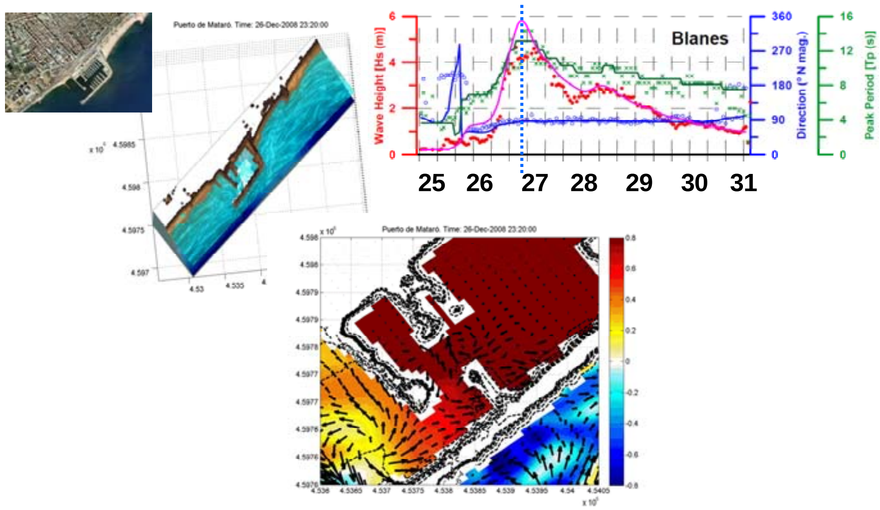

Figure 6. Mataró harbour hydrodynamic conditions during the peak of a ten year return period storm event (December 2008). The colour range represents the free surface elevation (in meters) and the black arrows the depth-averaged currents.

FINAL REMARKS

The inventory of wave storm impacts on the Catalan coast has highlighted the importance of a common database to properly document the typology and effects of these energetic events. We are thus building a database for better assessment of future storm episodes. The data base is structured in three levels: a general description of the event, the effects reported by the different municipalities and the storm data meteorological and hydrodynamic information. Municipalities will be kindly invited to fill the database (under their knowledge) and send it to the project office whereas the specific meteorological and hydrodynamic data will be provided by the members of the project. The information will be gathered and processed with the aim of presenting them in a Web Map Server (WMS) .

This approach will result in a database that highlights possible vulnerability hot-spots due to the joint action of waves and surges. These maps provide a rough estimate of forecast scenarios along the Catalan coast from which the vulnerability and risk levels will be determined, suggesting also the areas that need further analysis through high resolution nearshore modelling in order to build better coastal strategies under storm events (see www.icoast.eu).

ACKNOWLEDGMENTS

This work has been done under the framework of the iCoast project (Grant Agreement ECHO/SUB/2013/661009) funded by the European Commission, Directorate General for Humanitarian Aid and Civil Protection, DG ECHO. The second author acknowledges the PhD scholarship from the Government of Catalonia (DGR FI-AGAUR-14). The modelling part has also been supported by the Spanish research projects COVARIANCE (CTM2010-19709) and PLAN-WAVE(CTM2013-45141-R).

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