Operational forecast framework applied to extreme sea levels at regional and local scales

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Abstract

The design, implementation and demonstration of a novel and generic computational forecast framework for multi-scale prediction of extreme sea levels and associated flooding is presented. Denoted Water Information Forecast Framework (WIFF), it integrates process-based models for waves, tides and surges from regional to local scales, predicting the flooding of coastal areas, and supporting the routine and emergency management of coastal resources. WIFF manages the simulations and the real-time monitoring data, archives the data and makes the information available through a WebGIS that targets users with distinct access privileges. Additionally, the web component of WIFF adapts automatically and transparently to any device. WIFF also provides ways to assess the model accuracy and generates tailored products based on model results and observations. WIFF is demonstrated in the prediction of extreme water levels in the Portuguese coast, simulating processes at different scales: at basin scales, waves are simulated in the North Atlantic and in the Portuguese shelf, and sea levels due to tides and atmospheric forcings are simulated in the North-east Atlantic; at estuarine scales, high-resolution, fully coupled wave/circulation predictions are performed in the Tagus estuary to account for wave-current interactions. User-oriented georeferenced products are generated, including automatic model/data comparisons, targeting the needs of civil protection agents and combining for the first time an agile, service-oriented platform with high-resolution, process-rich predictions of the Tagus dynamics.

Keywords: Forecast systems; WebGIS; real-time information framework; Portuguese shelf; Tagus estuary; storm surge.

1. Introduction

Many coastal zones in the world are at a high risk of flooding. On the one hand, these areas are usually densely populated, hence particularly vulnerable to extreme events; on the other hand, coastal areas are often low-lying lands, exposed to tides, storm surges and waves. Climate change further aggravates the flood hazard through sea level rise and the increase of the intensity and

frequency of extreme events. This risk is illustrated by several catastrophic events in the last decade, such as the 2005 hurricane Katrina (Dietrich et al. 2011), and the 2010 Xynthia (Bertin et al. 2012; Liberato et al. 2013), and 2014 Hercules (Castelle et al. 2015) storms.

Waves, tides and surges have been successfully simulated in the past few decades using process-based models (e.g. Dodet et al. 2010, Dietrich et al. 2011, Bertin et al. 2012), taking advantage of increasingly faster computational resources. In recent years, the need to provide the information required to initiate preventive and emergency actions has triggered the development of dedicated forecast systems to predict the occurrence of extreme events (Bajo and Umgiesser 2010; Dresback et al. 2013, Zhang et al. 2013, Gallien et al. 2013). As coastal flooding events typically result from large-scale phenomena propagating from the ocean to localized coastal areas, a modeling approach that covers multiple spatial scales and distinct processes is required. As a result, the large computational resources necessary to provide accurate and timely early-warnings of extreme events have fostered the use of high-performance computing (HPC) environments, such as computer clusters (Ramakrishnan et al. 2006; Rogeiro et al. 2015).

Recent developments in Information Technology (IT), such as communication networks, Geographic Information Systems (GIS) and decision support systems, are also enhancing disaster management and communications. In recent years, many web-based emergency response systems have been developed (e.g., the Global Disaster Alert and Coordination System, http://www.gdacs.org/; and the Global Disaster Information Network http://www.gdin.org) with increasingly complex designs (Kyng et al. 2006). Other examples with complex software architectures, integrating GIS, web-based spatial databases (Herold et al. 2005) and providing authenticated users access to targeted information on-demand (Kulkarni et al. 2014), have also been proposed. IT solutions integrating process-based models have therefore an enormous potential to transform coastal zone management by providing accurate and autonomously updated information. In particular, web platforms combining multiple access levels to different hierarchic roles, with the capacity to adapt to specific use cases without significant code changes, constitute a major contribution to sustainable coastal zone management, and will probably continue to evolve in the near future (Gomes et al. 2015).

Forecast information systems are fundamental components of emergency response systems. They are now emerging as operational tools for the management of harbors and marine resources (Daniel et al. 2004; Baptista 2006, Anselmi-Molina et al. 2012; Chandrasekar et al. 2012; Wernera et al. 2013), by providing precise and timely predictions on water conditions. Forecast systems integrate remote monitoring networks, HPC resources (due to demanding computation processes), either for short-term forecasting or resulting data processing, and web-based information systems to support management decisions (Baptista et al. 2015).

The balance between the need to provide timely alerts and the adequate spatial and temporal resolution for reliable water predictions motivates the search for an optimal forecast setup, from both modeling and infrastructures viewpoints. Besides adequate water process representation, computational requirements for water forecasts include the need to scale up to multiple spatial scales and the time for forecasts to be available.

Building on these experiences, a web-accessible framework denoted as WIFF (Water Information Forecast Framework) has recently been developed to provide access to real-time observations and model predictions to decision-makers, constituting at the same time a repository of historical information (Jesus et al. 2012, Oliveira et al. 2014). Herein, this concept is extended to flood forecasting, seamlessly integrating high-resolution models across processes (waves, tides, storm surges) and spatial scales (from regional to local), combined with an innovative, responsive, real-time information web interface for enhanced support to flood risk emergency in estuarine areas, targeting multiple users with distinct access privileges.

The framework is demonstrated in the integrated prediction of extreme water levels in the Portuguese coast and the Tagus estuary. The primary aim of this deployment is to provide the civil protection authorities with all the information required to anticipate and react to flood events along the margins of the Tagus estuary, focusing on flooding originating from the sea. Besides the forecast platform described herein, additional information such as vulnerability and risk indexes were also implemented in the WIFF WebGIS interface (Tavares et al. 2015, Gomes et al. 2015).

101 This paper is organized as follows. The generic computational forecast framework is described
102 first, including the requirements, the infrastructure and the technological choices for the WebGIS
103 interface. The functionalities of the framework are then illustrated through an application to the
104 Portuguese coast. The deployment involves the implementation and validation of the operational
105 models: a regional wave model of the North Atlantic with a nested grid on the Portuguese shelf, a
106 tide and surge model of the Northeast Atlantic, and a coupled wave-circulation model of the
107 Tagus estuary. Finally, some challenges associated with this type of systems are discussed.

108 ## 2. Methodology and implementation

109 ### 2.1. *Requirements*

110 The real-time information forecast framework WIFF aims to support flood risk management in
111 coastal areas, targeting multiple users with distinct access privileges. Therefore, its
112 conceptualization was based on a user's requirements analysis targeting all potential users and
113 purposes. The following user requirements were identified:

114 - web access to relevant georeferenced information from wireless sensors, high-resolution
115 forecasts and comprehensive risk analysis;
116 - fast and automatic adaptation to different devices;
117 - user-dependent access to data and products;
118 - portability to other coastal and urban systems.

119 The next two sub-sections present the framework's overall architecture and the forecast modeling
120 infrastructure.

121 ### *2.2. The Water Information Forecast Framework*

122 WIFF aims to provide on-line, intuitive and georeferenced access to real-time observations and
123 model predictions, as well as on-demand services in support of routine management of coastal
124 resources and harbor operations. Simultaneously, WIFF provides a repository of historical
125 information, available at each deployment site to the relevant end-users. Originally conceived for

126 a single user type, the WIFF's WebGIS now allows for users with different access privileges,
127 following the requirement analysis summarized above.

128 The framework is composed by two distinct parts (Figure 1): the back-end, executed by the
129 server, runs the simulations and retrieves, processes and stores the observations and the model
130 results; the front-end, executed by the client's browser, interacts with the end-user and displays
131 the information made available by the back-end. The client-server architecture enforces the
132 separation of concerns in the two components of the system, making them simpler and more
133 robust since each one only has to worry about its own duties. Also, each component can be
134 replaced and developed independently, as long as the interface between them is not altered. This
135 interface uses Representational State Transfer (REST) web-services, a set of principles which
136 separates the communication protocols from the interaction between clients and servers. The
137 replies to the requests from the front-end to the back-end are wrapped in JavaScript Object
138 Notation (JSON), a format to exchange information that is easy to read and write by humans and
139 easy to analyze by computers.

140 [Figure 1 near here]

141 The back-end is composed by a deployment of CakePHP, a Model-view-controller PHP
142 framework. It has a PostgreSQL database, using PostGIS extension to interpret geographical
143 data, coupled with several instances of GeoServer, and some Perl and Python scripts. The PHP
144 code manages the control and user access to the data delivered to the front-end and connects the
145 different components of the back-end. The GeoServer, an open source map server that allows
146 users to publish geospatial information using open standards, manages and delivers
147 georeferenced images in normalized formats (e.g., Web Map Service – WMS), so that this
148 information can easily be used by different clients. This geospatial map server offers vector and
149 timed data, stored in PostgreSQL/PostGIS databases and in shapefile format files, thereby
150 allowing the exploitation of the model results in great detail (e.g., through the extraction of time
151 series in selected points by the user in the WebGIS interface or the display of non-pixelated
152 layers).

153 The front-end consists of a web application, adaptable to different types of devices, which allows
154 the user to visualize and interact with the results made available by the back-end in a simple and
155 intuitive interface. The adaptation of the platform to devices with a lower processing capability,
156 such as smartphones and tablets, requires the use of efficient web technologies: HTML5 and
157 CSS3, the bases of all modern web applications; AngularJS, a javascript framework that offers a
158 templating and two-way data binding dynamic system; Google Polymer, an implementation of
159 visual design patterns; and OpenLayers, a library that allows the manipulation of georeferenced
160 information and supplies tools to handle maps from the client side.

161 Because emergency response requires swift decisions, the rapid display of information to the end-
162 users is a stringent requirement for forecast systems such as WIFF. To address this requirement
163 with limited computational resources, WIFF's GeoServer caches all map layers, through an
164 integrated GeoWebCache, coupled with pre-seeding of the content at the moment of its creation.
165 This approach allows the server to have the content already rendered, ready to be delivered to the
166 user with minimal CPU usage. GeoWebCache is a Java web application used to cache map tiles
167 coming from a variety of sources, such as OGC Web Map Service (WMS) compliant servers
168 (such as the GeoServer). It implements various service interfaces (such as WMS-C, WMTS,
169 TMS, Google Maps KML, Virtual Earth) in order to accelerate and optimize map image delivery.
170 It runs as a proxy between a map client application and a map server, caching (storing) tiles on-
171 demand or pre-seeded, eliminating redundant request processing and thus drastically reducing
172 processing time.

173 ## *2.3. Modeling infrastructure*

174 The forecast modeling infrastructure used herein originated from the Rapid Deployment Forecast
175 System (RDFS – Baptista 2006), a generic forecasting platform, adaptable to any geographical
176 location. The original RDFS was extended to water quality (David et al. 2013) and waves,
177 integrated in a WebGIS tailored for coastal applications (Jesus et al. 2012) and extended to risk
178 analysis (Oliveira et al. 2014). The forecast system integrates a set of wave, circulation and water
179 quality models that run periodically in HPC environments to generate forecasts of water levels,

currents, water temperatures, salinity, waves and selected water quality indicators for target areas. For the particular case of flooding, only wave and circulation models are used.

While flooding occurs at small spatial scales, its triggering events can be generated in large oceanic basins. Regional scale models are thus required to adequately reproduce the processes that will eventually cause flooding (e.g., Blain et al. 1994): the generation and propagation of waves, tides and storm surges. Hence, these processes must first be simulated at basin scales, to provide boundary conditions for local, coastal models. In deep areas, the non-linear interaction between long (tides and surges) and short (surface) waves can generally be neglected, allowing the two processes to be simulated independently. In contrast, wave propagation is affected by tidal currents and water level fluctuations in shallow areas, and wave breaking can generate significant currents and elevation setup at the coast. This setup can propagate far inside estuaries, thereby affecting the total water levels. For instance, Fortunato et al. (2016b) showed that during a major storm, the wave setup reached about 0.5 m inside the Tagus estuary. Hence, tidal and wave dynamics in coastal areas should be simulated with coupled models that compute all the relevant physical processes and their interactions simultaneously.

Herein WIFF was extended to account for these interactions, integrating a coupled model for wave and currents. The forecast modeling system uses therefore different models at different scales. First, waves, tides and surges forecasts are produced at regional scales. The wave fields are generated with the third generation spectral wave model WAVEWATCH III (Tolman, 2009), allowing for several levels of nesting to accommodate the necessary grid resolution. Sea surface elevations are simulated at a regional scale using the shallow water model SCHISM (Semi-implicit Cross-scale Hydroscience Integrated System Model – Zhang et al. 2016). Derived from SELFE (Zhang and Baptista 2008), SCHISM is an open-source community-supported modelling system based on unstructured grids, designed for the seamless simulation of 3D baroclinic circulation across lake-river-estuary-shelf-ocean scales. SCHISM is stable even at high Courant numbers and its code is fully parallelized, using the Message Passing Interface (MPI) standard.

Waves and sea surface elevation regional forecasts, combined with atmospheric and riverine information, are then used to force local, high-resolution models that simulate water elevations

close to the coast and inside estuaries. Local-scale simulations are performed with SCHISM-WWMII (Roland et al. 2012), which couples SCHISM with the spectral wave model WWM. These two models share the same unstructured grid and its partition through the different MPI application processes. The circulation model provides water elevations and velocities to the wave model and receives the gradients of wave radiation stresses. This information is exchanged through the memory (RAM), instead of files, which strongly contributes to the efficiency.

While the present modeling approach describes phase-averaged wave effects on the water levels (wave setup), it neglects the effects at smaller time scales (wave uprush). This simplification is required by the use of a phase-averaged wave model and often by the coarse grid resolution. Inside estuaries, which are sheltered from the energetic sea waves, this simplification is usually valid. For instance, the highest significant wave height measured and simulated inside the Tagus estuary does not reach 1 m (Freire et al., 2009; Rusu et al., 2009) in spite of its large width. In contrast, neglecting the wave uprush can severely underestimate inundation in the open coast.

WIFF's forecast system runs on a Linux operating system. Its core is composed by a set of scripts, scheduled to run periodically, which prepare and launch each forecast simulation (Figure 2). The scripts interact with PostgreSQL databases to retrieve input data to force the models, including river flows and atmospheric forecasts, and to store some results. Simulation requirements include the results of the previous run, forecasts from global circulation and atmospheric models and data from field sensors.

[Figure 2 near here]

In order to optimize the use of available computational resources, an optional execution offloading process allows moving the execution away from the initiator resource. Each simulation can thus be executed on the machine where the scripts were launched or sent to other machines, often High Performance Computing (HPC) resources. To avoid having different code paths depending on the kind of execution resources being used, the offload process is transparent to the platform and completely model-agnostic. It uses the Secure Shell (SSH) services and Bash scripting facilities to provide a secure, reliable, simple and flexible offloading process. Every day, the system generates 48 hour forecasts of waves and sea levels.

3. Demonstration case study

3.1. General approach

The major and deadliest storm surges usually occur in areas with wide continental shelves (Breilh 2014). With a continental shelf about 20-70 km wide, the Portuguese coast has thus been spared from major catastrophes. Still, there are historical records of severe damages and casualties associated to storm surges in the Portuguese coast (Freitas and Dias 2013), and in the Tagus estuary in particular (Tavares et al. 2015). In 2014, the Hercules storm caused tens of millions euros worth of damage along this coast. These events motivated the development of a forecast system for extreme sea levels in the Portuguese coast.

The model setup is composed by three distinct applications (Figure 3): a regional scale wave model; a regional scale tide and surge model; and a local scale coupled wave-circulation model. The three applications are detailed below.

[Figure 3 near here]

3.2. Regional modeling: the North Atlantic and the Portuguese shelf

Regional wave simulations are performed with one-way nesting. The first WW3 domain covers the North Atlantic, from 0º to 70º N and from 0º to 80º W, with a 0.5º resolution (Figure 3). A nested grid with a 0.05º resolution is then used in the Portuguese shelf. The time steps are set to 15 and 3 minutes for the coarse and fine grids, respectively. The wave spectrum is resolved with 24 directions and 25 frequency bins, following Dodet et al. (2010). The simulations are forced by wind fields from GFS (Global Forecast System, www.ncdc.noaa.gov) with space and time resolutions of 1.875º and 6 hours, respectively.

This deployment is operational since 2011, producing daily forecasts of 48 hours. Results are compared automatically with online data from four wave buoys from the Portuguese Hydrographic Institute and the Lisbon Harbor available along the Portuguese coast: Leixões, Lisboa, Sines and Faro. In order to assess the accuracy of the forecasts, errors were computed at

these four stations for a period of 4 years, between 2011 and 2015 (Figure 4). The error metrics selected were the root mean square error (RMSE), the RMSE normalized by the mean of the observations (NRMSE) and the bias (Table 1). Results show the excellent behavior of the model in the western Portuguese coast (Leixões, Lisboa and Sines), where the errors are similar to hindcast models (e.g., Dodet et al. 2010; Rusu and Guedes Soares 2015). The model tends to underestimate the significant wave heights (10 to 20 cm bias), but the error is small even for the largest waves. Errors are larger in the southern coast (Faro buoy), possibly due to the inability of the atmospheric model to adequately represent the wind fields in the Bay of Cadiz.

[Figure 4 near here] [Table 1 near here]

The differences between the forecasts made for the same day and for the following day are negligible (Table 1), thus providing confidence in the use of the 48 hour forecasts. Also, since the forcing wind fields are occasionally delivered with some delay, this small difference allows WIFF to still generate reliable forecasts. In this situation, the WIFF forecast is forced by the most recent atmospheric forecast, as long as it covers the whole forecast period (48h). This possibility makes the system more resilient to failures.

Water levels due to tides and surges are simulated with SCHISM in depth-averaged barotropic mode in a domain that covers a significant portion of the Northeast Atlantic (Fortunato et al. 2016a). The resolution is particularly fine in the Portuguese shelf, reaching 250 m. The model is forced at the open boundaries by tides from the global tidal model FES2012 (Carrère et al. 2012) and by the inverse barometer effect, to account for atmospheric pressure variations. Inside the domain, the model is forced by the tidal potential, and forecasts of atmospheric pressure and wind from NOAA's GFS.

The model has been running operationally since March 2015. Results from the forecasts between March and December 2015 were compared with measurements at several Portuguese, Spanish and French tide gauges (Table 2). RMS errors are of the order of 5-7 cm along the western Iberian coast, and 11-13 cm in the Bay of Biscay. Fortunato et al. (2015) showed that the RMSE for the present forecasts are about 10-35% smaller than those provided by a standard model in the Portuguese coast (Maraldi et al. 2013). Time series of elevations and surges at the Cascais tide

gauge during a storm surge that hit the Portuguese coast in May 2016 show that the model is able to reproduce elevations during energetic events (Figure 5a).

[Table 2 near here; Figure 5 near here]

3.3. Local modeling: the Tagus estuary

The SCHISM-WWMIII application covers a domain of about 120 km long, including a coastal area with a radius of about 30 km (Figure 3). The local model is forced by results from the regional wave and sea level models at the ocean boundary. Some areas particularly prone to flooding, above the highest astronomical tide line (determined by Rilo et al. 2014), are included in the model domain (Figure 6a). A digital terrain model was constructed using the most recent bathymetric data from the Lisbon Harbor authority, LIDAR data of the coastal margins from the Portuguese Environmental Agency, and high-resolution topography from the Direção Geral do Território. The grid has about 80,000 nodes. The spatial resolution varies between 2 km at the outer bay and typically 20-60 m close to the margins (Figure 6b). The time step is set to 30 s. The friction coefficient in the estuary is defined based on the bed sediments (Guerreiro et al., 2015) and on the land cover from Chen et al. (2015) on dry land. The river boundary is forced by extrapolations of flow measurements (http://www.snirh.pt), which are automatically replaced by climatology when unavailable. Atmospheric pressure and wind forecasts from the 9 km implementation of the WRF model provided http://www.windguru.cz complete the model forcings.

[Figure 6 near here]

The model was validated through four different tests. The first test verifies the ability of the model to represent water levels variability throughout the estuary. Hindcast simulations were performed, forced by tides and river flow. Results were compared with synthesized tides from 13 tidal gauges distributed throughout the estuary. Results show the excellent accuracy of the model, with RMS errors of 4-16 cm (Table 3). These errors compare favorably with those previously reported for the same dataset (Fortunato et al. 1999; Guerreiro et al. 2015). The second test

assesses the ability of the model to reproduce energetic events. The most severe warning provided by the Tagus forecast system so far occurred on May 8, 2016, when over 30 cm of water were predicted for Seixal. Inundations occurred as predicted, and traffic had to be interrupted in the road that borders the estuary (Oliveira et al., 2016). Forecasts produced in May, 2016 are compared with tide gauge data at two stations (Figure 5b, c), showing the ability of the model to reproduce storm surges. The third test verifies the ability of the model to reproduce marginal inundation during an extreme event. The model was run for the period of the Xynthia storm, between February 18 and March 4, 2010. The extent of the flooding that occurred during those days in the Seixal old city center (Figure 6a) was determined through a post-event field survey, by interviewing the local authorities and analyzing photographs taken during the event (Freire et al., 2016). The extent of the flooding predicted by the model fully agrees with the field survey data to within grid resolution accuracy: all the surveyed points are located within the layer of partially wet elements (Figure 7). For the same event, the root mean square error of the elevations at the Cascais tide gauge was 7.5 cm. Finally, the fourth test verifies the ability of the model to produce accurate results away from the ocean boundary in forecast mode by comparing model results with data obtained with a Level Troll 700 tidal gauge installed in the Seixal Bay (Figure 8a) between March 20 and 31, 2015. The model accuracy is similar to the one obtained in hindcast mode, with a RMS error of 13 cm (Figure 8b). Together, the four tests show that the model accurately forecasts the flooding associated to extreme events in the Tagus estuary.

[Figures 7, 8 near here] [Table 3 near here]

3.4. WIFF deployment for the Tagus estuary

The WIFF deployment for the Tagus estuary is organized along four main components: early-warning, flood forecast, forcings and risk analysis (Figure 9a). The first component provides information on the vulnerable areas that may be flooded in the next 48 hours. The Seixal Municipality waterfront, which is flooded on a yearly basis, was chosen as a local-scale case for the warning component implementation (Freire et al., 2016). At selected critical points along the margins, the total water depth is evaluated every 15 minutes. Warnings of different levels of

inundation severity are provided when predefined thresholds are exceeded (Figure 9b) and an early-warning bulletin is automatically generated and sent by email to the civil protection agents. The flood forecast component uses layer maps, sourced from shapefile format files, and makes them available through geo-referenced maps (Figure 9c). These maps provide zoom and pan capabilities, as well as the ability to switch layers on and off and superimpose them. The forecasts are grouped by days and made available at each hour. This component also offers the possibility to visualize monitoring data, compare them to the model results and download this information in CSV format (Figure 9d). The forcings component provides access to the public site with the regional forecasts. Model results can be accessed as animations or as time series, and data/model comparisons can be performed. Finally, the risk analysis component provides access to both hazard and vulnerability maps.

[Figure 9 near here]

Since March 2016 the WIFF deployment for the Tagus estuary has been used by the Seixal Municipal Service for Civil Protection as a support tool for flood emergency management. So far, the flood warning alerts that occurred consisted mostly in the lowest warning level (yellow, corresponding to less than 0.2 m of water height). These warnings have been validated by in situ observations and the acquired experience on past flood events by the civil protection services. The early-warning bulletins have been particularly useful as a way to disseminate the relevant information for planning the emergency response through the several civil protection agents (e.g., fire brigades, police). However, a detailed evaluation of the impact of WIFF as a decision-making supporting tool for the emergency managers requires a longer operation of the system, particularly during extreme water level events.

4. Summary, discussion and outlook

A new computational forecast framework for flood risk management was developed and implemented in the Portuguese coast. The IT system is accurate, robust and agile and can be extended to other estuaries and coastal zones and to other emergency concerns. The regional-

scale results are publicly available, while the local-scale forecasts are only available to the coastal and emergency authorities, tailoring details and confidentiality of information to comply with the user requirements. By supporting the forecasts on high-resolution models that solve the adequate physical processes and their interactions, and making the results available at a friendly, multi-device interface, the proposed framework contributes to an enhanced support to coastal managers.

Forecast frameworks such as the one introduced herein can thus play a major role in optimizing the response of the authorities to extreme events, thereby avoiding or mitigating the effects of major disasters. The development of these systems is therefore expected to continue in the near future. However, several challenges remain to be addressed.

It is unclear at this point whether and how the full forecasts should be disclosed to the public, and there are strong arguments on both sides (Morrow et al. 2015). Clearly, a better informed public can avoid irrational decisions, both in the short-term (e.g., going to the sea-side during severe maritime conditions) and in the long-term (e.g., purchasing property in areas at risk). However, many coastal managers strongly oppose the open release of this type of information to the public, arguing that model results can be misread by the public, causing unjustified panic or false assurance. The approach followed in WIFF is to disclose the coarse-resolution results from the regional models to the public and make the results from the local model available to the proper authorities only. The decision on informing the public will be made by these authorities based on information from different sources. The adequate approach to disclose complex information such as those provided by the models used herein to the general public is also a challenge as it requires a detailed usability and public acceptance analysis.

Unveiling the forecasts to the public must take into account the uncertainty associated to the predictions. Indeed, in spite of the excellent accuracy of the models shown above, significant sources of errors remain. While the water elevation can be determined with errors of the order of 0.01-1 m (e.g., Bertin et al. 2012; Kerr et al. 2013), the uncertainty in the determination of the position of the water line is significantly higher. This uncertainty has several sources, including the model's horizontal resolution, and its inability to resolve short-scale features, common in

396 urban areas; the low topographic gradients, which amplify vertical errors in the water elevation;
397 outdated or inaccurate digital terrain models; neglecting water infiltration and sewage systems.
398 Yet, the position of the water line is one of the key information required by end-users. Estimating
399 this uncertainty and conveying it to the end-users is therefore a clear requirement for the forecast
400 systems, and sophisticated approaches based on ensemble simulations are now starting to be
401 followed (Höllt et al. 2015). In the Portuguese shelf, the sea surface variability is strongly
402 dominated by tides, which are easier to reproduce accurately than storm surges. Hence, the
403 uncertainty is lower than in areas of the world where storm surges can reach several meters. The
404 system described herein deals with the communication of uncertainty in two simple ways. First,
405 real-time data/model comparisons are an integral part of the system (Figure 9d). The user can
406 therefore obtain daily estimates of the errors. Secondly, the land-water interface is shown as a
407 strip, rather than a line. The strip is composed by the elements that have both wet and dry nodes
408 (Figure 7). While these details of the forecast system do not convey all the uncertainty associated
409 with the predictions, they help showing the end-user that models are not reality.

410 Forecast systems should provide information on a continuous basis. They are therefore totally
411 autonomous, and should be able to run without human intervention. However, they can fail for
412 several reasons, including power failures, internet communication failures and unavailability of
413 the driving atmospheric forecasts and other inputs. Not only can these failures have an impact on
414 the end-users, but they can also entail significant maintenance costs in terms of human resources.
415 The reliability of the system should thus be maximized. In WIFF, all forecasts run redundantly on
416 two different computers, with a few hours' delay, and most forcings have alternative sources
417 when the primary source fails. Further robustness can be obtained by resorting to cloud
418 computing services (Rogeiro et al. 2015), which can also be a way to progress in porting forecast
419 systems to the hands of the coastal managers.

420 This system will continue to be enhanced through the improvement of the models, the inclusion
421 of new datasets and local models, the extension of the forecast periods, the optimization of the
422 codes and the development of additional services provided by the interface. Risk criteria are also
423 being developed, in order to provide automatic alerts to the authorities.

Acknowledgements

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Tables

Table 1. Validation of the wave forecasts between 2011 and 2015 at four wave buoys along the Portuguese coast. Values between brackets refer to forecasts made for the following day.

Error measure	Leixões	Lisboa	Sines	Faro
RMSE (cm)	32 (33)	30 (30)	34 (34)	44 (44)
NRMSE (%)	17 (18)	27 (28)	22 (23)	48 (49)
Bias (cm)	16 (16)	23 (23)	8 (9)	-19 (-20)
Longitude	-9.10	-9.4	-8.95	-7.90
Latitude	41.20	38.6	37.90	36.90
Depth (m)	83	73	97	107

Table 2. Validation of the regional tide and surge model: RMSE obtained for the forecasts from March to December 2015. Data were retrieved from http://www.emodnet.eu. The mean sea level was removed from the time series before the evaluation of the error due to doubts on the reference level at some stations.

Station	RMSE (cm)
Las Palmas	6.7
Huelva	6.6
Sines	5.2
Peniche	6.2
Nazaré	6.3
Leixões	7.0
Vigo	6.6
La Coruña	12.8
Gijón	11.6
Santander	11.7
Bilbao	12.5
Port Bloc	11.9
Socoa	13.6

602 **Table 3. Validation of the Tagus model in hindcast mode: RMSE at 13 tidal stations. The**
603 **position of the stations is indicated in Figure 3.**

Station	RMSE (cm)
Cascais	4.6
P. Arcos	3.7
Trafaria	5.3
Lisboa	5.9
Pedrouços	4.1
Cacilhas	5.3
Seixal	6.4
Montijo	6.5
C. Ruivo	8.5
Alcochete	12.0
Sta. Iria	15.6
Pta. Erva	15.7
Vila Franca	12.0

604

Figure captions

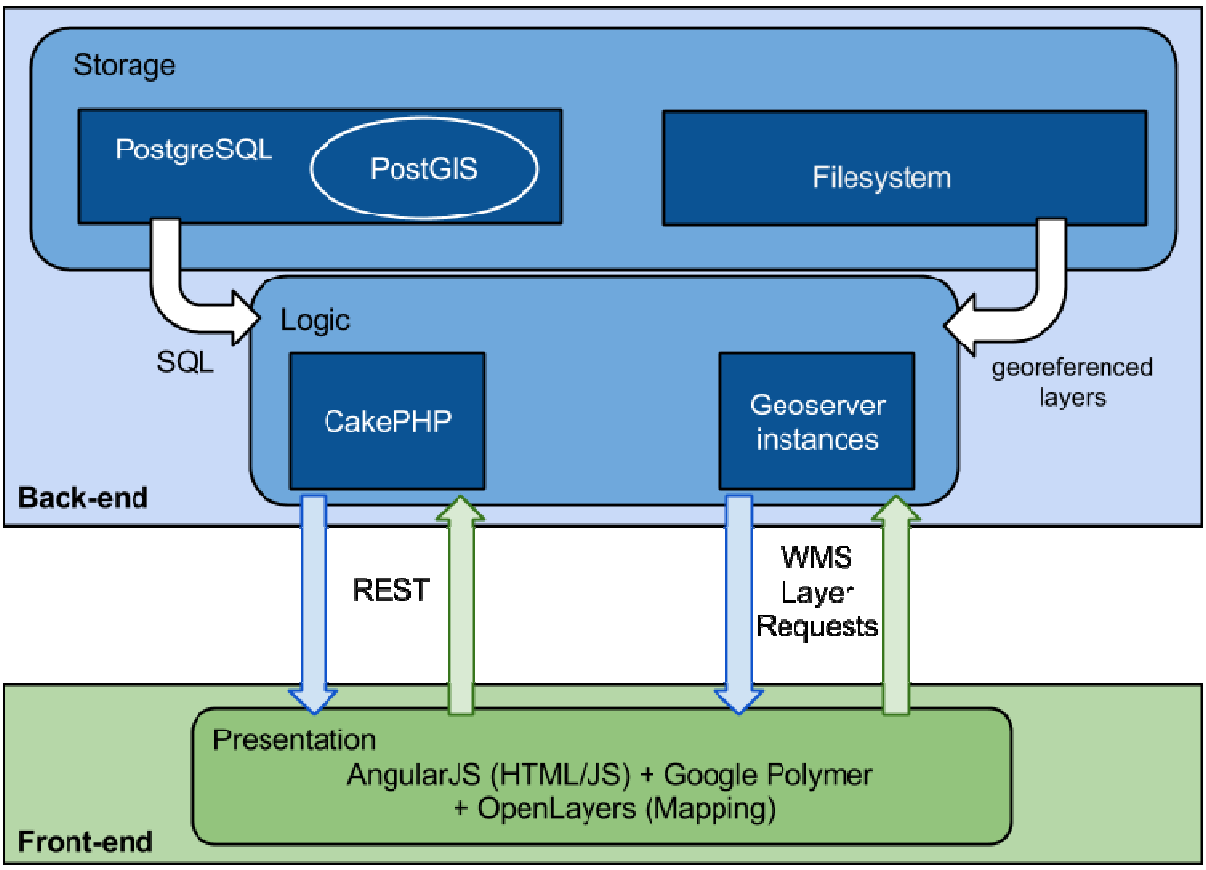
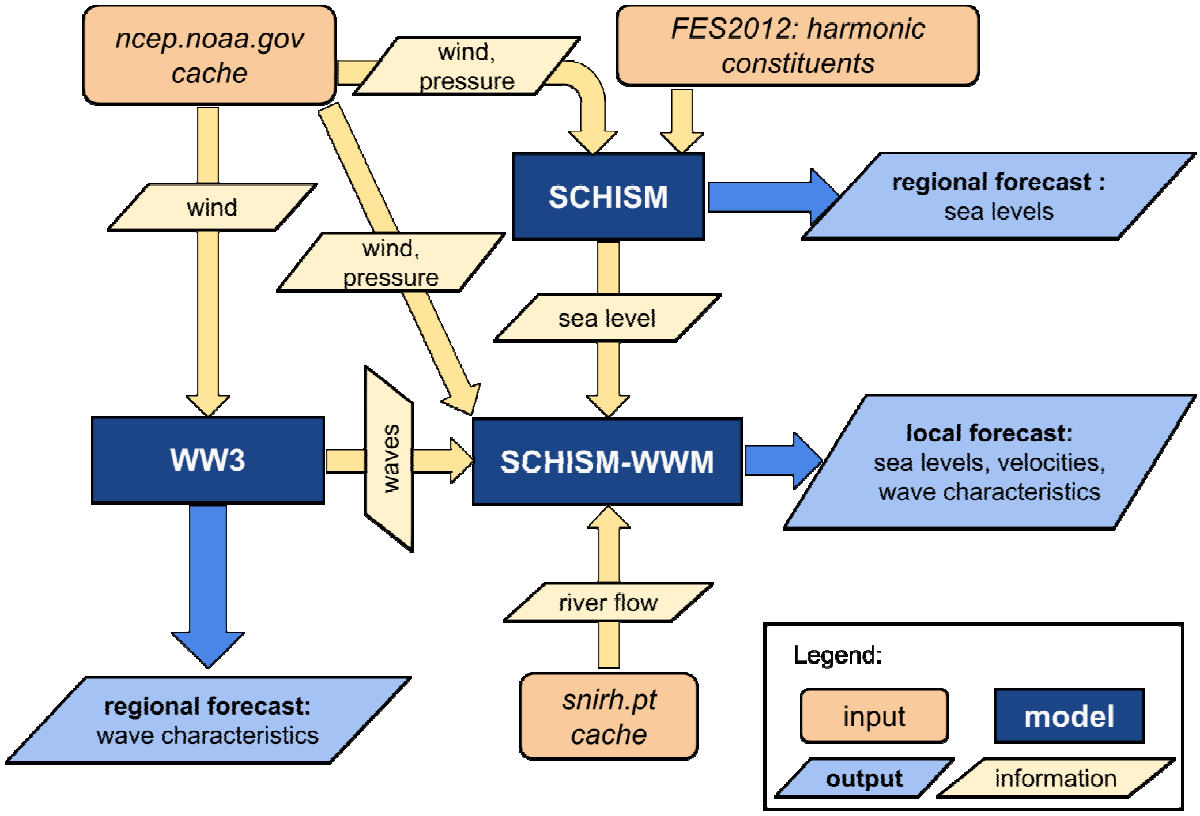


Figure 1. Information flow between the back-end and the front-end.



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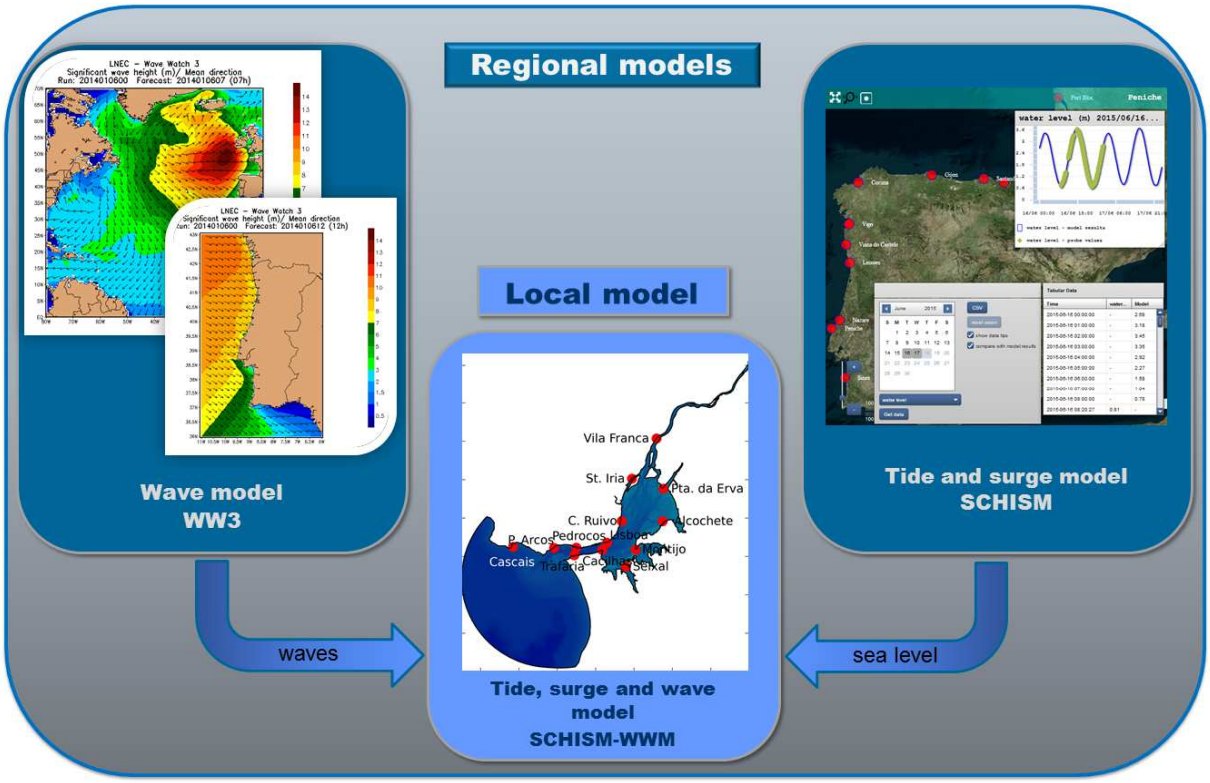
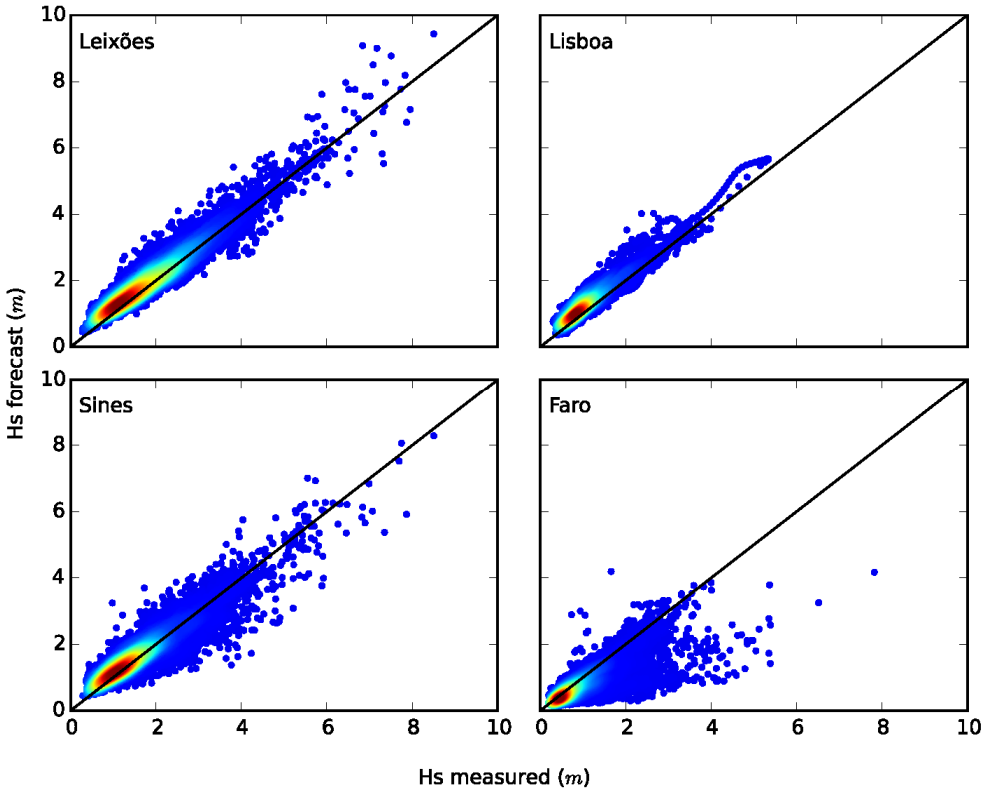
609 **Figure 2. Procedure workflow for the wave / current forecasts in the Tagus estuary.**



610

611 **Figure 3. Generic modeling scheme. The figures of the wave model show the significant**
612 **wave heights forecasts in early January 2014, during the Hercules storm. The figure of the**
613 **regional tide and surge model shows an aspect of the public interface, with the model/data**
614 **comparison (http://ariel.lnec.pt). The figure of the Tagus estuary shows the bathymetry, the**
615 **model domain and the tidal stations used for validation in hindcast mode.**



616

617 **Figure 4. Validation of the wave forecasts between 2011 and 2015 at four wave buoys along**
618 **the Portuguese coast: comparison between Hs estimated from measurements and forecast**
619 **results made on the same day.**

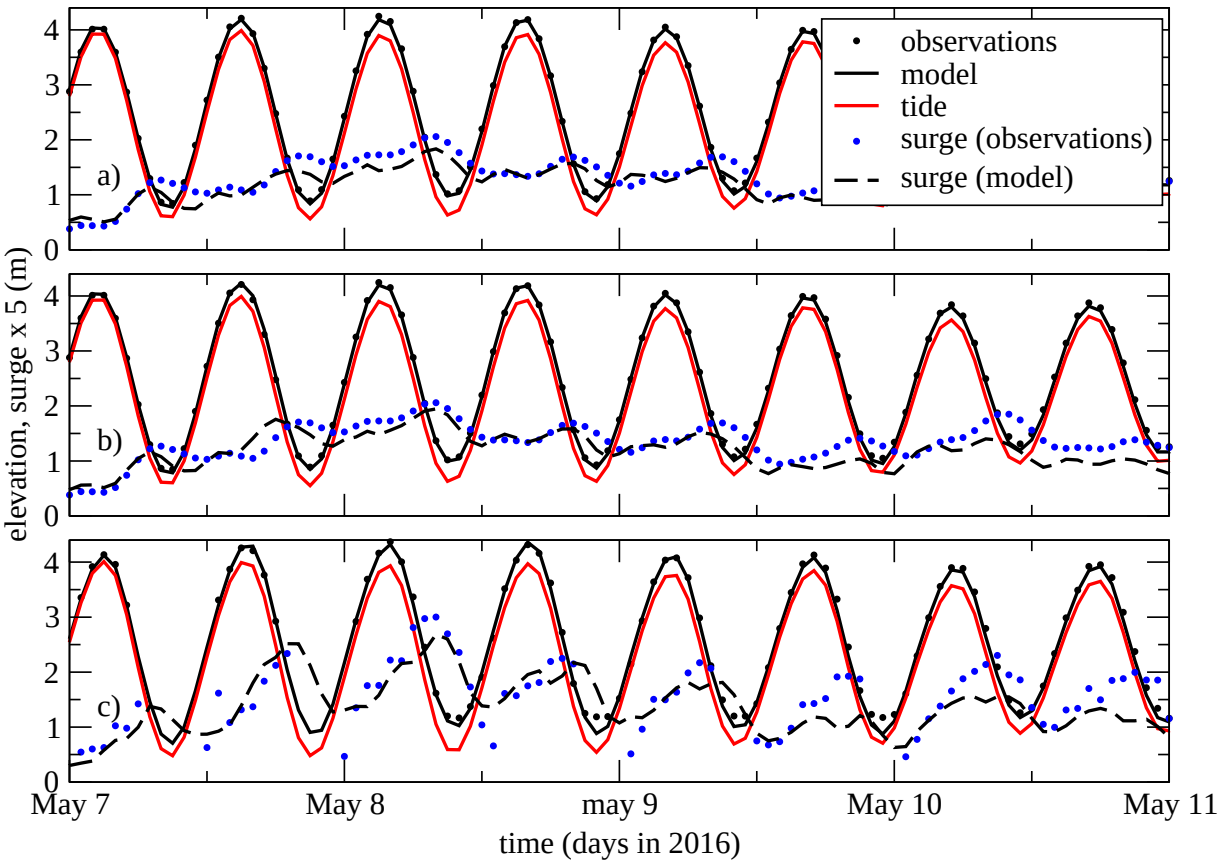
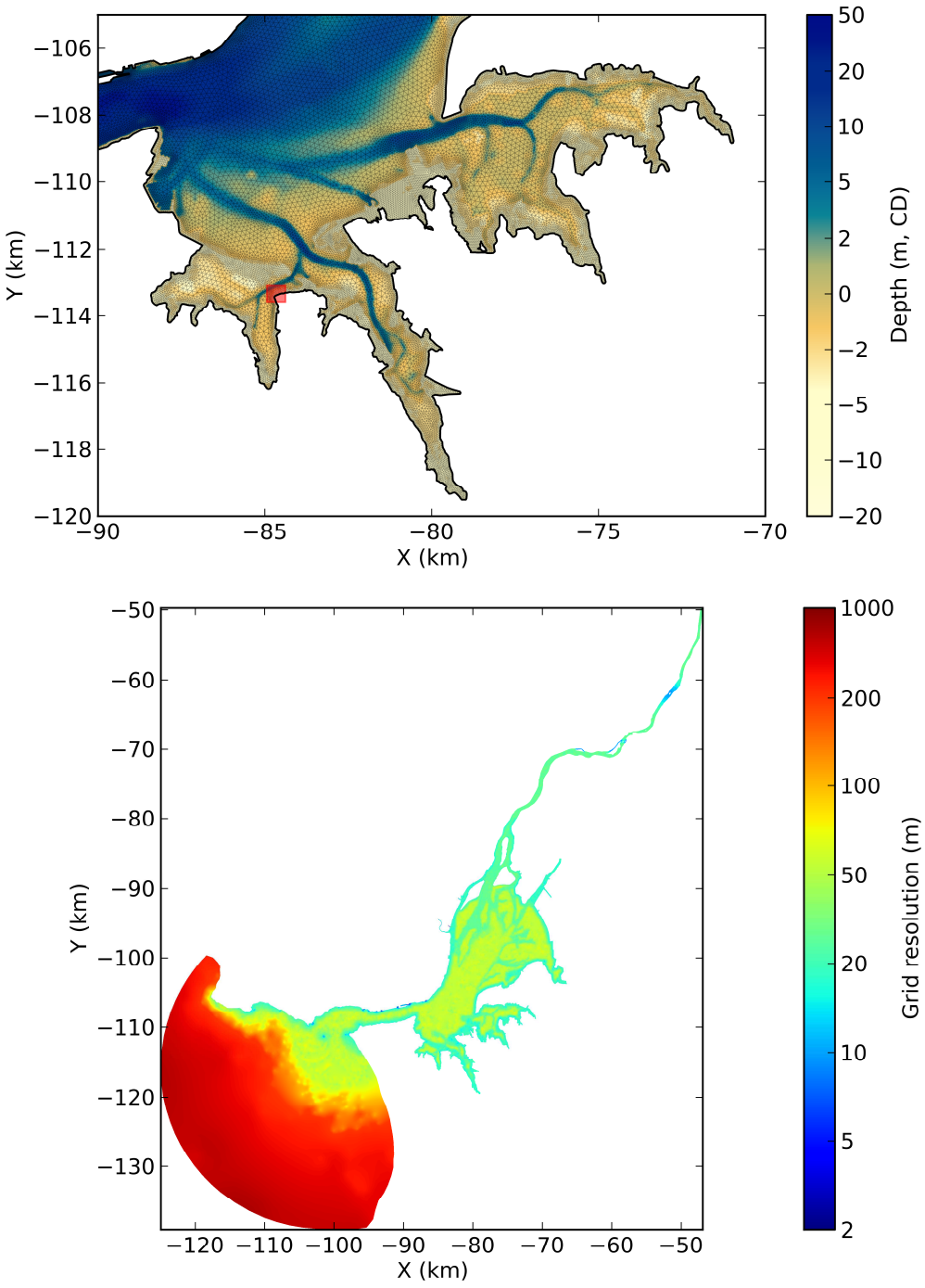


Figure 5. Validation of the tide surge models during a storm surge event in May, 2016: a) data and results from the regional model at Cascais; b) data and results from the Tagus model at Cascais; c) data and results from the Tagus model at Pedrouços. All surges were multiplied by 5 for clarity. Tides were synthesized from model results.



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626

627 **Figure 6. Tagus model grid: a) detail of the grid and bathymetry in the Seixal area; b) grid**
628 **resolution, defined as the equivalent element diameter. The red square in a) indicates the**
629 **area shown in Figure 7.**

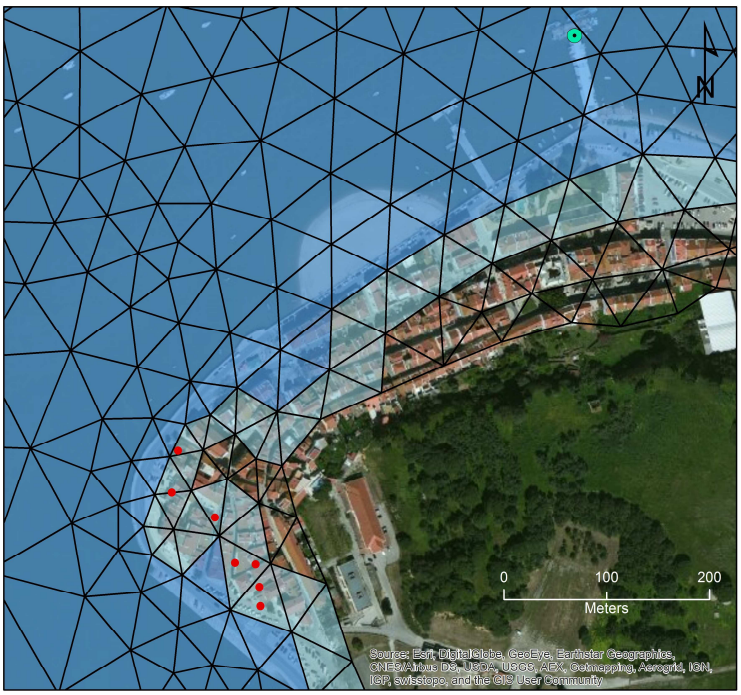


Figure 7. Validation of the Tagus model for an extreme event (Xynthia storm, February 2010). The location of this area is shown in Figure 6a). The red circles indicate the surveyed extent of the flooding in the city of Seixal. The wet elements (elements with three wet nodes) are indicated in dark blue, and the partially wet elements (elements with one or two wet nodes) are shown in light blue. The green circle indicates the location of the temporary monitoring station at Seixal (X= -84489.407 m; Y= -113102.754 m, ETRS89 TM-06).

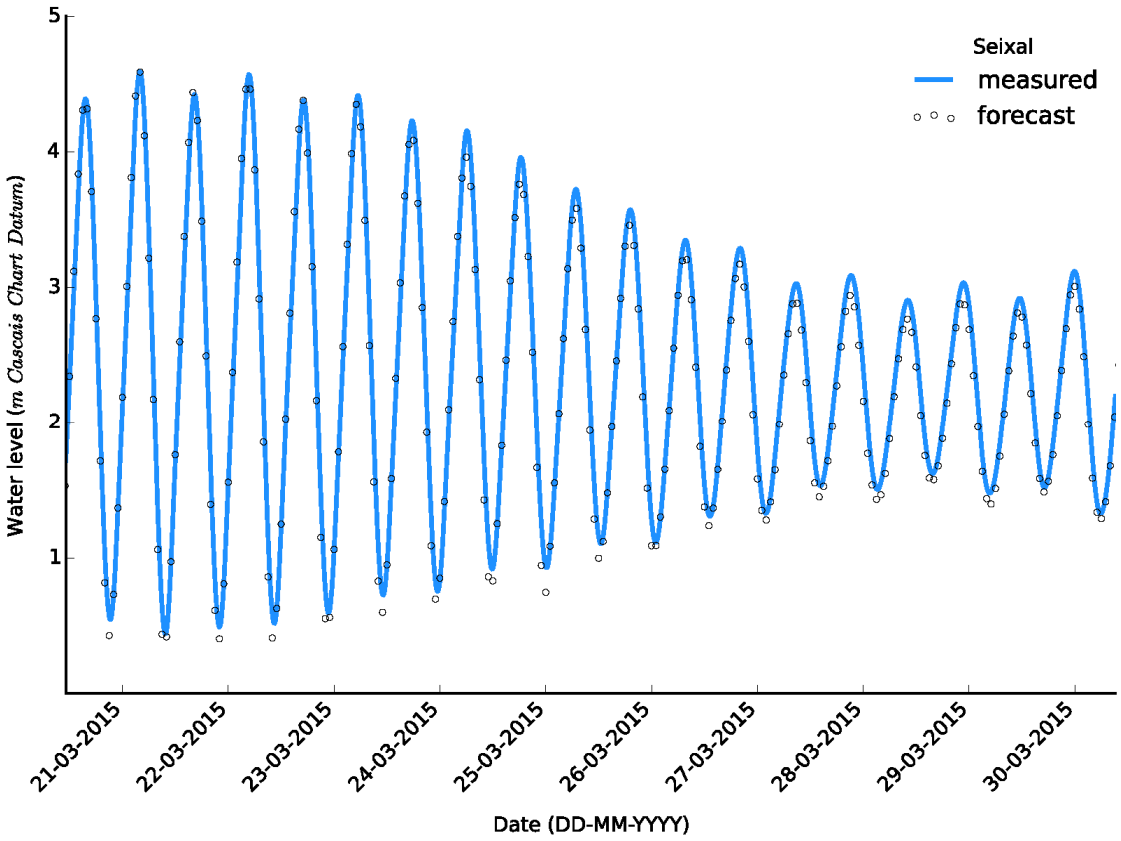
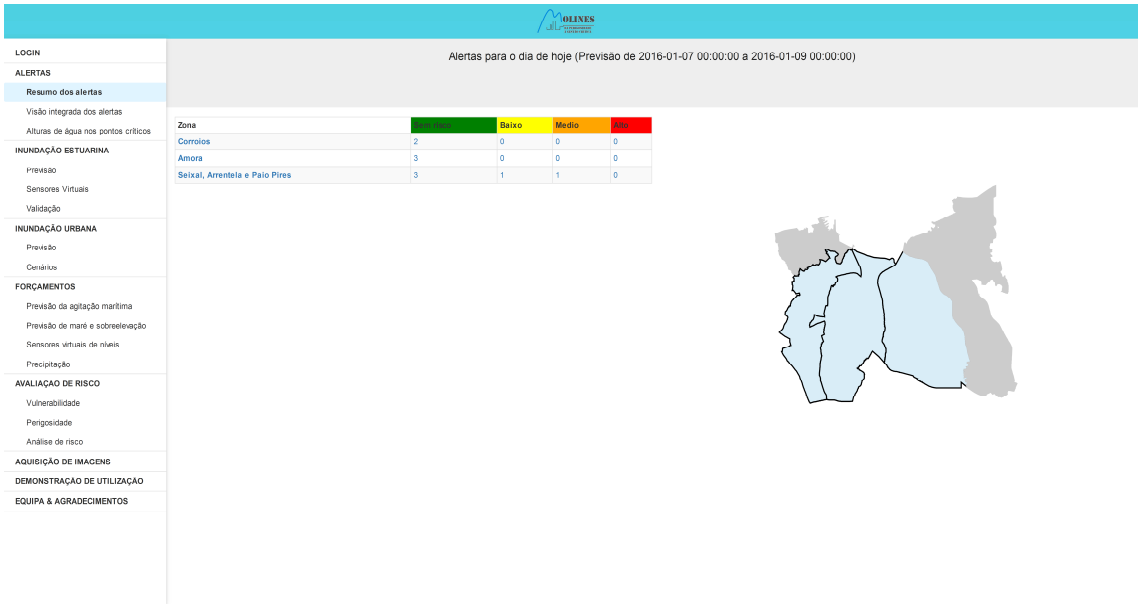


Figure 8. Validation of the Tagus model in forecast mode: comparison between observations and model results at the Seixal temporary station (Figure 7). The RMS error is 13 cm.


LOGIN
ALERTAS
Resumo dos alertas
Visão integrada dos alertas
Alturas de água nos pontos críticos
INUNDAÇÃO ESTUARINA
Previsão
Sensores Virtuais
Validação
INUNDAÇÃO URBANA
Previsão
Cenários
FORÇAMENTOS
Previsão da agitação marítima
Previsão de maré e sobreelevação
Sensores virtuais de níveis
Precipitação
AVALIAÇAO DE RISCO
Vulnerabilidade
Perigosidade
Análise de risco
AQUISIÇÃO DE IMAGENS
DEMONSTRAÇÃO DE UTILIZAÇÃO
EQUIPA & AGRADECIMENTOS
Alertas para o dia de hoje (Previsão de 2016-01-07 00:00:00 a 2016-01-09 00:00:00)
Zona
Sem risco
Baixo
Medio
Alto
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Amora
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Seixal, Arrentela e Paio Pires
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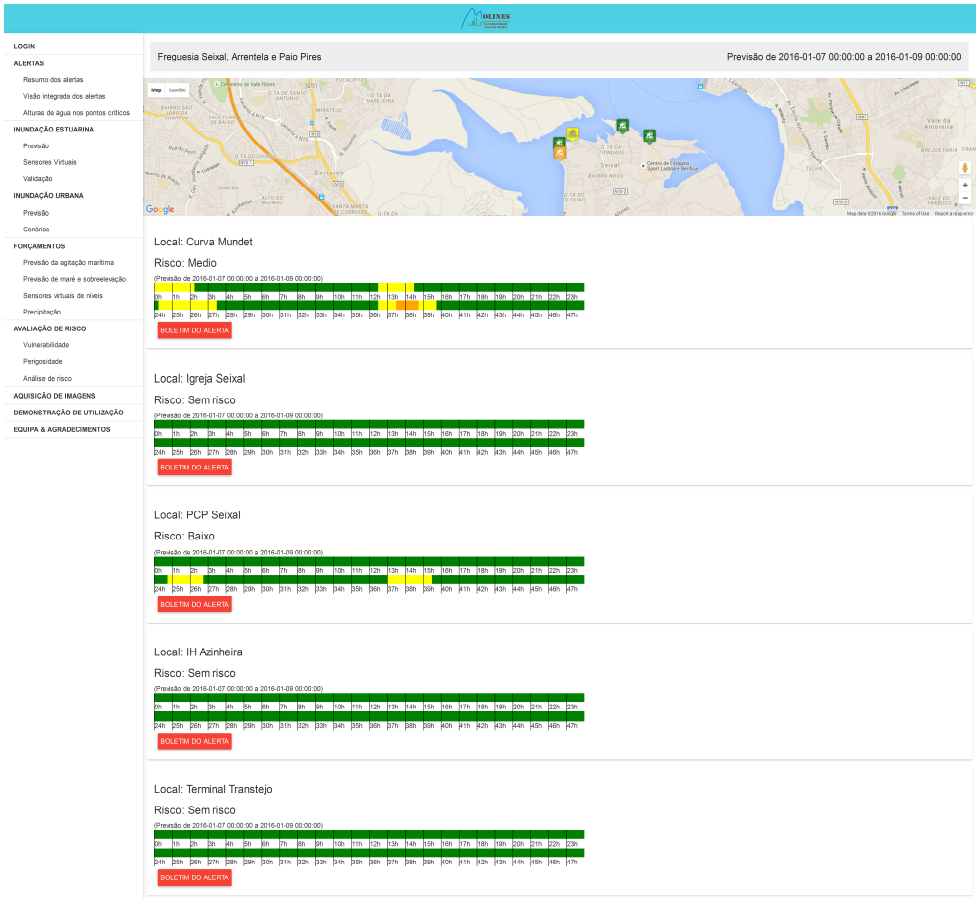
LOGIN
ALERTAS
Resumo dos alertas
Visão integrada dos alertas
Alturas de água nos pontos críticos
INUNDAÇÃO ESTUARINA
Previsão
Sensores Virtuais
Validação
INUNDAÇÃO URBANA
Previsão
Cenários
FORÇAMENTOS
Previsão da agitação marítima
Previsão de maré e sobreelevação
Sensores virtuais de níveis
Precipitação
AVALIAÇÃO DE RISCO
Vulnerabilidade
Perigosidade
Análise de risco
AQUISIÇÃO DE IMAGENS
DEMONSTRAÇÃO DE UTILIZAÇÃO
EQUIPA & AGRADECIMENTOS
Frequesia Seixal, Arrentela e Paio Pires
Previsão de 2016-01-07 00:00:00 a 2016-01-09 00:00:00
Local: Curva Mundet
Risco: Medio
(Previsão de 2016-01-07 00:00:00 a 2016-01-09 00:00:00)
BULLETIM DO ALERTA
Local: Igreja Seixal
Risco: Sem risco
(Previsão de 2016-01-07 00:00:00 a 2016-01-09 00:00:00)
BOLETIM DO ALERTA
Local: PCP Seixal
Risco: Baixo
(Previsão de 2016-01-07 00:00:00 a 2016-01-09 00:00:00)
BOLETIM DO ALERTA
Local: IH Azinheira
Risco: Sem risco
(Previsão de 2016-01-07 00:00:00 a 2016-01-09 00:00:00)
BOLETIM DO ALERTA
Local: Terminal Transtejo
Risco: Sem risco
(Previsão de 2016-01-07 00:00:00 a 2016-01-09 00:00:00)
BOLETIM DO ALERTA

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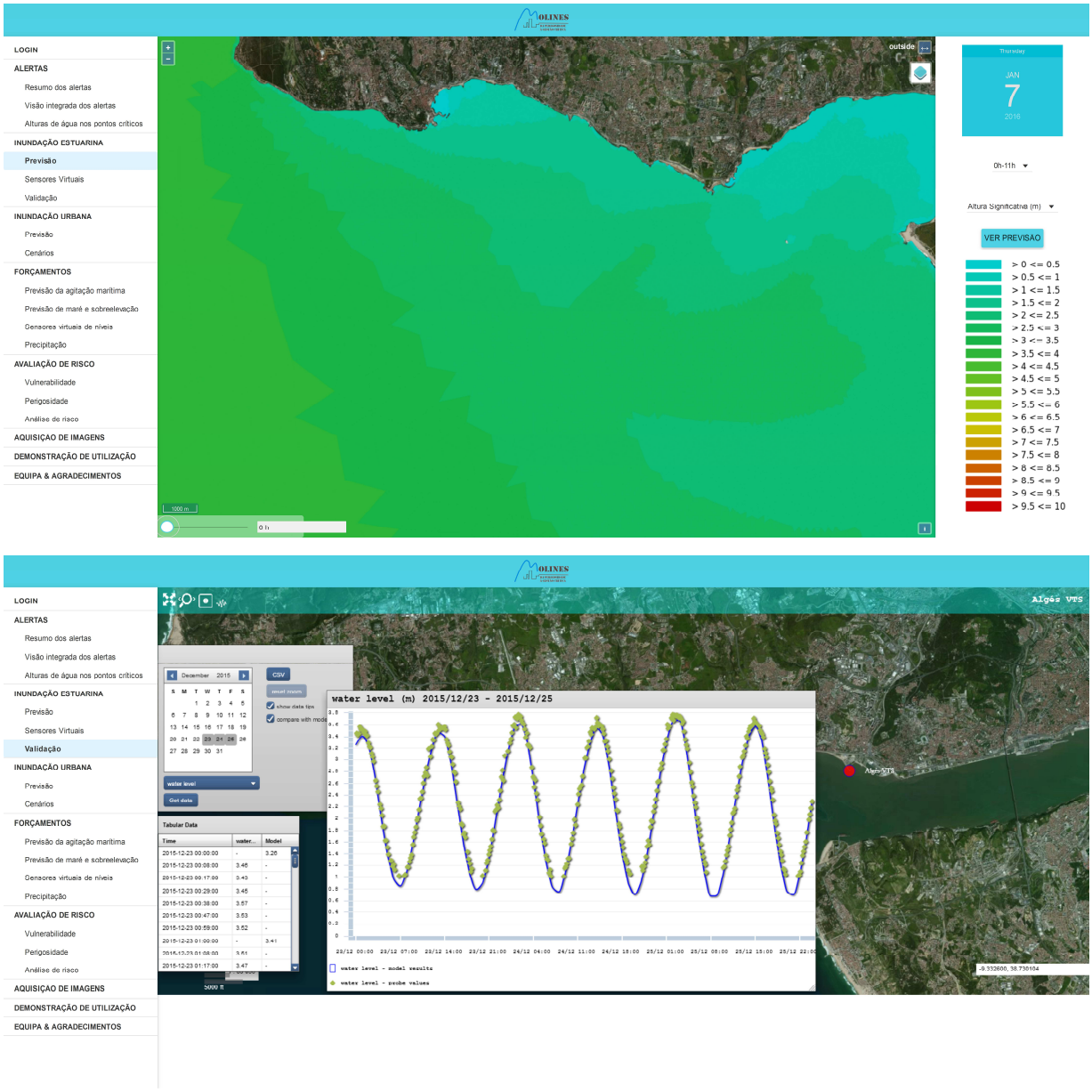

644

645 **Figure 9. a) General overview of the WIFF deployment for the Tagus and of its services,**
646 **showing an integrated geographical view of the warnings for the Seixal municipality; b)**
647 **summary of the warnings for the Seixal area, with the colored bars showing the warning**
648 **levels at several vulnerable locations selected by the civil protection agents; c) forecast of**
649 **the significant wave heights, in meters; d) automatic data / model comparison at the Algés**
650 **tide gauge. The menu on the left-hand side of the figure (in Portuguese) reads: Login,**
651 **Alerts, Estuarine inundation, Urban inundation, Forcings, Risk evaluation, Images**
652 **acquisition, Demonstration of use, Team and acknowledgements.**