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Coastal ocean forecasting in Spanish ports: the SAMOA operational service

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ABSTRACT

SAMOA (*Sistema de Apoyo Meteorológico y Oceanográfico de la Autoridad Portuaria*) is the latest initiative of Puertos del Estado, the Spanish Public State Port Agency, to enhance the delivery of user-customised operational met-ocean information to aid Spanish Port Authorities making harbour safety, environmental management and operational decisions. This initiative provides high-resolution coastal operational prediction systems in domains such as harbours and nearby coastal waters. Forecast systems implemented are fully operational from January 2017 for nine Spanish ports in the Mediterranean, the Iberian Atlantic and the Canary Islands. This paper provides an end-to-end description of these SAMOA systems that are based on high-resolution ROMS model applications. The SAMOA systems are CMEMS downstream services, being the coastal models nested into the regional IBI forecast solution. At the surface, SAMOA systems use as forcing daily updated hourly winds and heat and water fluxes from the Spanish Meteorological Agency forecast services. Highlights from the scientific pre-operational model evaluation phase and the multi-parametric validation are shown, illustrating agreements between SAMOA products and in-situ and remoted sensed observations. To this aim, skill metrics (such as bias, errors, Taylor diagrams and correlations) are presented. Finally, a look ahead to future SAMOA developments and operational innovations is provided.

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SAMOA; coastal modelling; port circulation; operational forecasting; dynamical downscaling

Introduction

Increased maritime traffic has resulted in rapid growth of the ports and port activity. The total gross weight of goods handled in EU (European Union) ports was estimated at just above 3.8 billion tonnes in 2015, representing an annual increase of 1.3%. The Spanish Port System contributes to this activity, handling 447 million tonnes during 2015, with a 4.5% of annual increase and a 2010–2015 growth rate of + 18.6% (EU EuroStat 2017).

Anthropogenic pressure caused by port activities can adversely affect water quality in harbours and adjacent coastal waters. Consequently, the EU Water Framework Directive was established to protect continental, underground and coastal waters including harbours and adjacent waters (2000/60/CE WFD; http://ec.europa.eu/environment/water/water-framework/index_en.html). Through this Directive European port authorities are legally responsible for environmental monitoring and minimising pollution in harbour waters (Darbra et al. 2009; Puig et al. 2017).

Understanding the physical behaviour of coastal areas is important to manage main issues related to these anthropic impacts and resource exploitation activities. Since ports are affected by met-ocean conditions, and especially by extreme events, customised real-time and forecast information on environmental conditions is needed to support port activity growth.

Wind, waves and sea-level are traditionally the most important met-ocean parameters for port activity due to the implications for safety of port operations and the impacts on ship draught allowance. These parameters are therefore the most extensively monitored and forecasted. Since the mid-90s, Spanish ports have come to depend on operational forecast and monitoring information delivered by the Spanish Public State Port Agency: Puertos del Estado (PdE, hereafter). These PdE services included regional and local wave and sea-level operational forecasts (Gómez Lahoz and Carretero Albiach 1997; Alvarez Fanjul et al. 2001; Gómez Lahoz and Carretero Albiach 2005; Pérez et al. 2013).

More recently, port managers are requesting water current information. Detailed representations of the local currents guide navigation and aid ship maneuverability as well as support water quality management and environmental risk assessment applications (Grifoll et al. 2011). Examples of using water current information

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include adjusting cargo ship piloting to account for local currents and mitigating oil spill issues (Sotillo et al. 2008; Guo et al. 2014; Valdor et al. 2015). Detailed information on local circulation patterns (i.e. flushing patterns, residence times, as well as the associated advective and dispersive capabilities) is essential for these types of applications.

The implementation of numerical models in coastal areas, combined with the use of observational information, enables a better understanding and characterisation of the main hydrodynamic features of specific coastal zones and is becoming common practice around the world (i.e. Djath et al. 2014; Kärnä et al. 2015). However, supporting port activities demands from ocean forecast model systems timeliness and a reliable delivery of updated information on an operational basis.

In response to this growing demand of sustained regularly updated ocean information, operational physical oceanography is maturing rapidly, and ocean circulation modelling as an operational capability is emerging. Across Europe, the Copernicus Marine Environmental Monitoring Service (CMEMS, http://marine.copernicus.eu/), fully operational since May 2015, represents a noticeable upgrade of the European operational oceanographic capabilities. This European operational oceanographic service provides comprehensive regular and systematic information on the state of the global oceans and European regional seas. Focusing on the European Atlantic façade, the CMEMS IBI-MFC (Iberia-Biscay-Ireland Monitoring & Forecasting Centre) provides daily ocean model estimates and 5-days forecasts of different physical and biogeochemical parameters (Hernández et al. 2015).

The CMEMS IBI products cover all Spanish waters and PdE uses these products in several marine applications focused on Spanish ports. These IBI products are extensively validated and can be used as reference product to characterise regional ocean circulation features around the Iberian Peninsula (Aznar et al. 2016; Capó et al. 2016). In spite of very high horizontal resolution (1/36°), that adequately characterises regional circulation features, there are some limitations capturing small-scale coastal ocean processes (Sotillo et al. 2016; Lorente et al. 2016).

To overcome this gap between the scales effectively solved by the regional services and the scales to meet end-users needs (mostly local), some downstream services are using different downscaling approaches (Sotillo et al. 2008; Korres et al. 2010; Juza et al. 2016). In recent years, PdE has developed along this line a series of local operational oceanographic developments, and particularly ocean dynamical downscaling in harbour environments. The SAMPA (*Sistema Autónomo de Medición, Predicción y Alerta*) ocean circulation forecast system, operationally running from 2012, is a good example of this approach. This system, centred in the Gibraltar Strait area, has enhanced the scientific knowledge of this hot spot (Sánchez-Garrido et al. 2013) and enables knowledge-based decision making for maritime challenges, such as oil spills and port operation optimisation (Sotillo et al. 2016). In parallel, PdE implemented operational local circulation forecast systems for some specific ports (i.e. Barcelona, Bilbao, Tarragona) demonstrating that this kind of operational system for the prediction of currents is a viable tool for risk assessment and environmental management in seaports and harbours (Grifoll et al. 2012).

For the last 3 years (2014–2017), PdE has led and developed the SAMOA initiative (*Sistema de Apoyo Meteorológico y Oceanográfico de la Autoridad Portuaria* or Meteorological and Oceanographic Support System of the Port Authority): an on-going massive effort to provide operational high-resolution met-ocean data to feed Decision Support Systems of the Spanish Harbour Authorities. This SAMOA initiative combines observation, modelling and end-user service tools, and has one of its components focused on the design and implementation of a very high-resolution ocean circulation forecast system, able to resolve from coastal to very local scales inside the ports.

As Kourafalou et al. (2015) points out in their detailed review of the science foundation of coastal modelling, the advancement of coastal ocean forecasting systems requires the continuous scientific progress in several key topical areas. Among others, most necessary are: understanding the primary mechanisms driving coastal circulation; developing methods to dynamically embed coastal systems in larger scale systems; downscaling methods to adequately represent air–sea and land interactions, including, atmosphere-wave-ocean couplings. These primary science topics are fundamental for the success in the upgrade of any coastal model application into a new operational downstream service and consequently have been addressed in the SAMOA implementation phase.

This paper provides a complete description of the ocean circulation model applications in which are based the new operational SAMOA circulation forecast in Spanish ports. The paper is organised as follows: Section 2 outlines the PdE SAMOA initiative, describing its objectives, components and major benefits. Section 3 provides a description of the model application on which SAMOA ocean forecast systems are based. Section 4 presents a detailed discussion of the SAMOA products quality, with highlights from both the pre-operational scientific qualification and the operational validation phases. Finally, Section 5 summarises main conclusions and gives a look ahead to future areas of development, outlining a roadmap that summarises the short and long-term plans to update SAMOA high-resolution ocean forecast services within the framework of the future SAMOA-2 initiative.

The PdE SAMOA service: delivering coastal and local met-ocean information to the Spanish ports

The SAMOA initiative was born, co-financed by PdE and the Spanish Port Authorities, to respond to the complex port needs in terms of coastal and local met-ocean information. SAMOA is led by PdE and a total of 18 Spanish Port Authorities are participating.

The main objective of the system is to provide for each Port Authority customised ocean-meteorological information, fully adapted to their needs. The SAMOA service (Alvarez Fanjul et al. 2017) consists of several modules: some are focused on enhancing near-real-time observational capabilities (improving instrumentation of the existing PdE observational networks) and others on implementing new local high-resolution forecast model systems for atmosphere, waves and ocean circulation. New added-value systems accompany these modules such as the new CMA (*Cuadro de Mando Ambiental),* or Environmental Control Panel, a tailor-made software application that allows customised access to available met-ocean information in the ports (see snapshot in Figure 1), as well as new advanced viewing capabilities and services, such as the user alert system through e-mail and SMS.

The concept behind SAMOA was born after a 6-month collaboration with all Spanish Port Authorities to determine and define precisely the problems that their facilities suffer due to met-ocean activity. This work included the filling of several questionnaires and several visits to all the ports in order to properly understand the real problems and to generate tailored solutions. The result of this study confirmed the relevance of certain phenomena, such as those originated by waves (resulting in overtopping, internal water agitation, etc.), and raised the awareness with respect to other less known issues, as those created by extreme winds in certain operations. Circulation inside the harbours was also detected as a relevant variable to be monitored and forecasted. The importance of currents is mostly related to the legal commitment that Port Authorities have in order to ensure good water quality inside the ports. As a response to this study, and to the variety of issues detected, the SAMOA initiative was designed in a modular way, so each Port Authority was able to support economically and made use of the specific products and services that will help to manage its particular operational issues. The high-resolution model downscaling operational system described in this paper is the result of one of these modules.

SAMOA allows a better exploitation of available data by the ports. Its services have a widespread use, enabling data access to users outside of the Port community. As an example, the Bahia de Algeciras Port Authority has granted CMA access to more than 200 users, including private companies related to the port activity, but also public local and regional institutions and general users.

Operational ocean forecasting systems based on very high-resolution models able to solve typical shelf and coastal processes at port scales were developed within the SAMOA framework. PdE is collaborating with the *Maritime Engineering Laboratory* of the Politechnic University of Catalonia (LIM/UPC) to conduct the scientific research required to develop the SAMOA circulation component. Collaborative efforts include configuring the local circulation model applications for future use in the operational applications, which are implemented and run daily by PdE using the owned PdE existing supercomputing resources and capabilities. A scientific team, composed of experts from both LIM/UPC and PdE, is working on the scientific validation of the available SAMOA model solutions.

These SAMOA high-resolution coastal forecast systems are fully operational (starting January 2017) for 3 Spanish ports in the Mediterranean (Barcelona, Tarragona, and Almeria), 2 in the Iberian Atlantic (Bilbao, Ferrol) and 4 in the Canaries (Las Palmas, Tenerife, La Gomera, and Santa Cruz de la Palma). These locations are shown in Figure 2.

Description of the SAMOA coastal model application

The three-dimensional hydrodynamic model used in SAMOA is the Regional Ocean Modelling System (ROMS). Numerical details are described in Shchepetkin and McWilliams (2005), and a complete description of the model, user documentation and source code are available at the ROMS website (http://www.myroms.org/).

Several operational oceanography systems use ROMS (e.g. Marta-Almeida et al. 2012; Juza et al. 2016). These systems cover different basins at regional scales (approx. 2 km of grid resolution) and use different forcing and nesting strategies. However, not many applies at port scales. There are some examples of NOAA operational forecast systems (https://tidesandcurrents.noaa.gov/models.html) running for specific locations, such as the

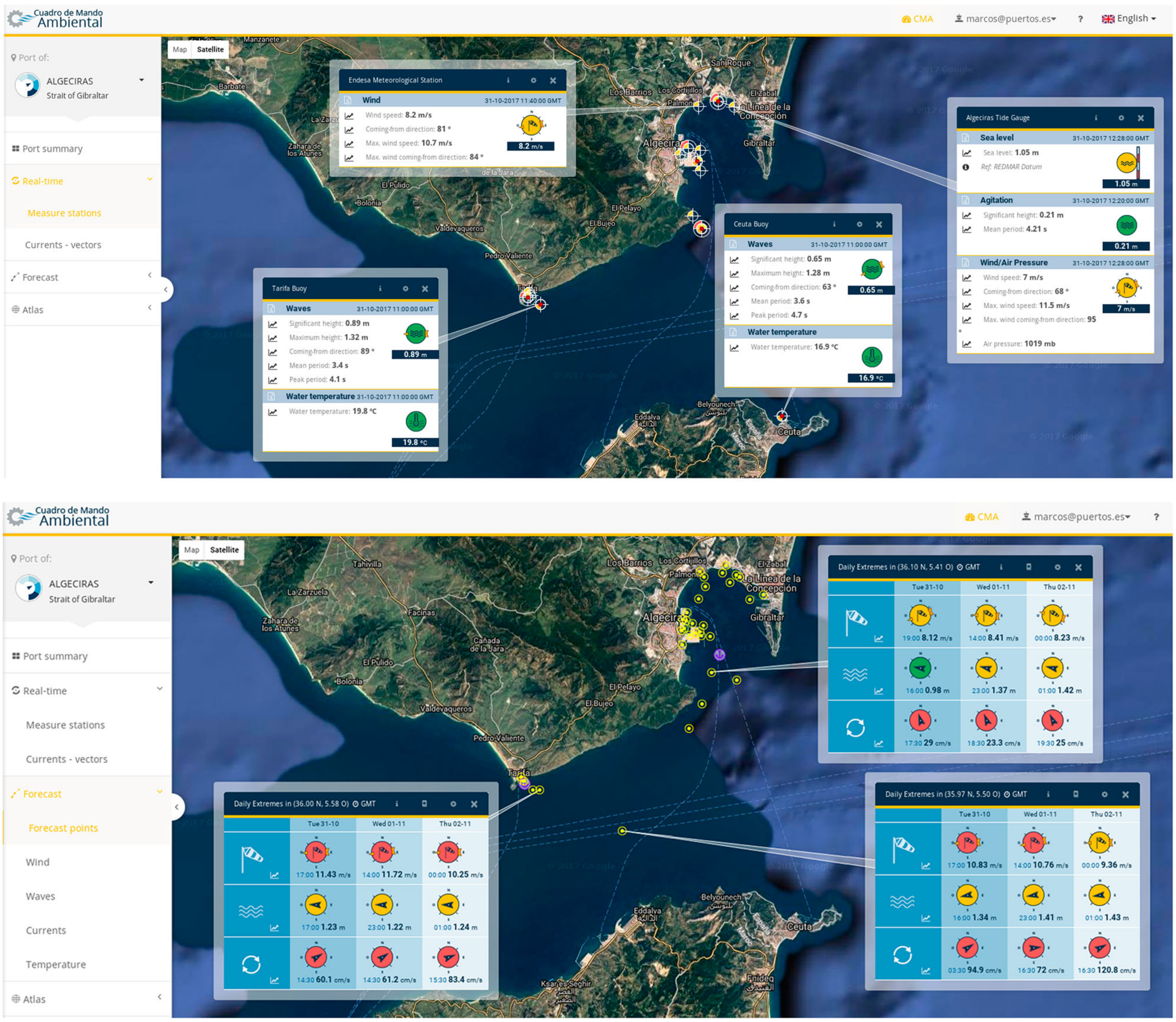

Figure 1. Example of Port user-oriented viewing capability through the CMA environmental dashboard developed within SAMOA. (Top panel) example of viewing capabilities with observations from NRT stations (including info from meteorological station, tide-gauge and mooring buoys). (bottom panel) 3-days forecast information for wind, waves and currents. Maximum forecasted values depicted and alert symbols coloured (green-yellow-red) based on specific user-customised alert thresholds at each point.

Tampa and Chesapeake Bays and the Gulf of Maine, whose products are used to support ports operations. In addition to operational oceanography, the ROMS model is also used for a widespread range of applications such as estuarine modelling (Cerralbo et al. 2015a, 2016), sediment transport (Grifoll et al. 2014), oceanic basin modelling (Malanotte-Rizzoli et al. 2000), climate studies (Di Lorenzo et al. 2008) and investigation of atmosphere-wave-current interaction (Warner et al. 2010). One of the strong points of ROMS is its modularity and the use of an efficient parallelisation strategy with MPI (Message Passing Interface), which allows development of applications with very competitive computational time (Wang et al. 2005). Early versions of PdE local high-resolution oceanographic systems were developed using ROMS for some Spanish ports (Grifoll et al. 2012). These first systems can be considered as prototypes of the SAMOA systems presented here.

The SAMOA model applications consist of 2 nested regular grids with spatial resolution of ~350 m and ~70 m for the coastal and harbour domains, respectively (see Figure 3 for example of domains and bathymetries). The nesting ratio (~5) between coastal and port domains is defined to get enough resolution to reproduce the circulation due to the inner shape of the harbour considering the mesoscale dynamics of the coastal domain. The chosen vertical discretisation consists in 20 sigma levels for the costal domains (except for the Canary implementations where, due to the deepest bathymetry, 30 levels are used) and 15 levels for all the port domains.

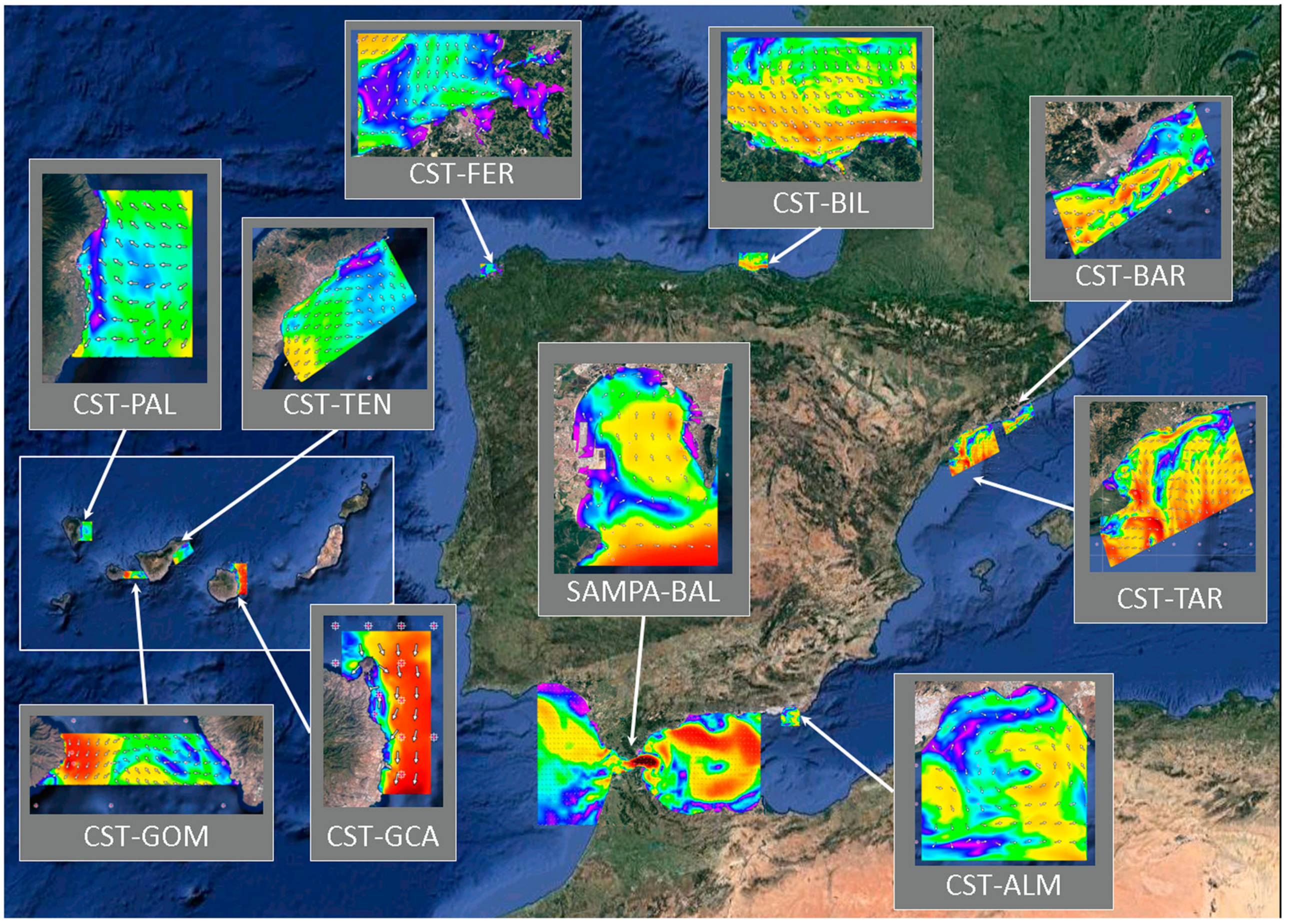

Figure 2. SAMOA Circulation Forecast Services currently in operations. Coastal domains covered by each system depicted (by means of a surface current field shown in each case, as example). SAMOA Systems in Atlantic Spanish Ports (CST-BIL and CST-FER for Bilbao and Ferrol ports), in Mediterranean ones (CST-BAR, CST-TAR and CST-ALM for the Barcelona, Tarragona and Almeria ports, respectively; here also depicted the system for the Port of Bahia de Algeciras, covered by the PdE SAMPA system for the Gibraltar Strait area), and in the Canary Islands (CST-GCA, CST-TEN, CST-GOM and CST-PAL for Las Palmas de Gran Canaria, Tenerife, Gomera and La Palma ports).

Bathymetries of the SAMOA coastal systems are built using a combination of bathymetric data from GEBCO (www.gebco.net) and from specific local high-resolution sources provided by local Port Authorities. Furthermore, within a transition region (∼2 km) along the open boundaries of the SAMOA coastal domains, the bathymetry from the CMEMS-IBI system is used to accommodate the high-resolution information and keep consistent the transports associated with IBI velocities imposed as open boundary condition. In the port domains, an updated and higher resolution bathymetry is also applied adjusting the open boundary to the coastal bathymetries. The bathymetry information interpolated at the mesh is smoothed using a Shapiro filter with an r-factor criterion below 0.25.

The bottom boundary layer was parameterised with a logarithmic profile using a characteristic bottom roughness height of 0.002 m. The turbulence closure scheme for the vertical mixing is the generic length scale (GLS) tuned to behave as k-epsilon (Warner et al. 2005). Horizontal harmonic mixing of momentum is defined with constant values of 5 $m^2\,s^{-1}$.

The SAMOA models are nested into the daily updated regional ocean forecast products delivered by CMEMS-IBI (Sotillo et al. 2015) following the scheme shown in Figure 4. At the sea surface, the SAMOA models are driven by high frequency (hourly) wind stress, atmospheric pressure and fluxes of water (evaporation minus precipitation) and surface heat derived from the Spanish Meteorological Agency (AEMET) forecast services, based on two operational applications of the HIRLAM (HIgh Resolution Limited Area Model) model: one, the HNR (0.05° resolution and a forecast horizon of + 36 h) covering the Spanish territory and the more extended regional euro-Atlantic ONR application (0.16° resolution and a forecast horizon of + 72 h). Further information on these two AEMET model applications for the Iberian and Euro-Atlantic domains can be found in Navascués et al. (2013). The HNR and ONR fields are jointly used according to best available basis and pre-processed to

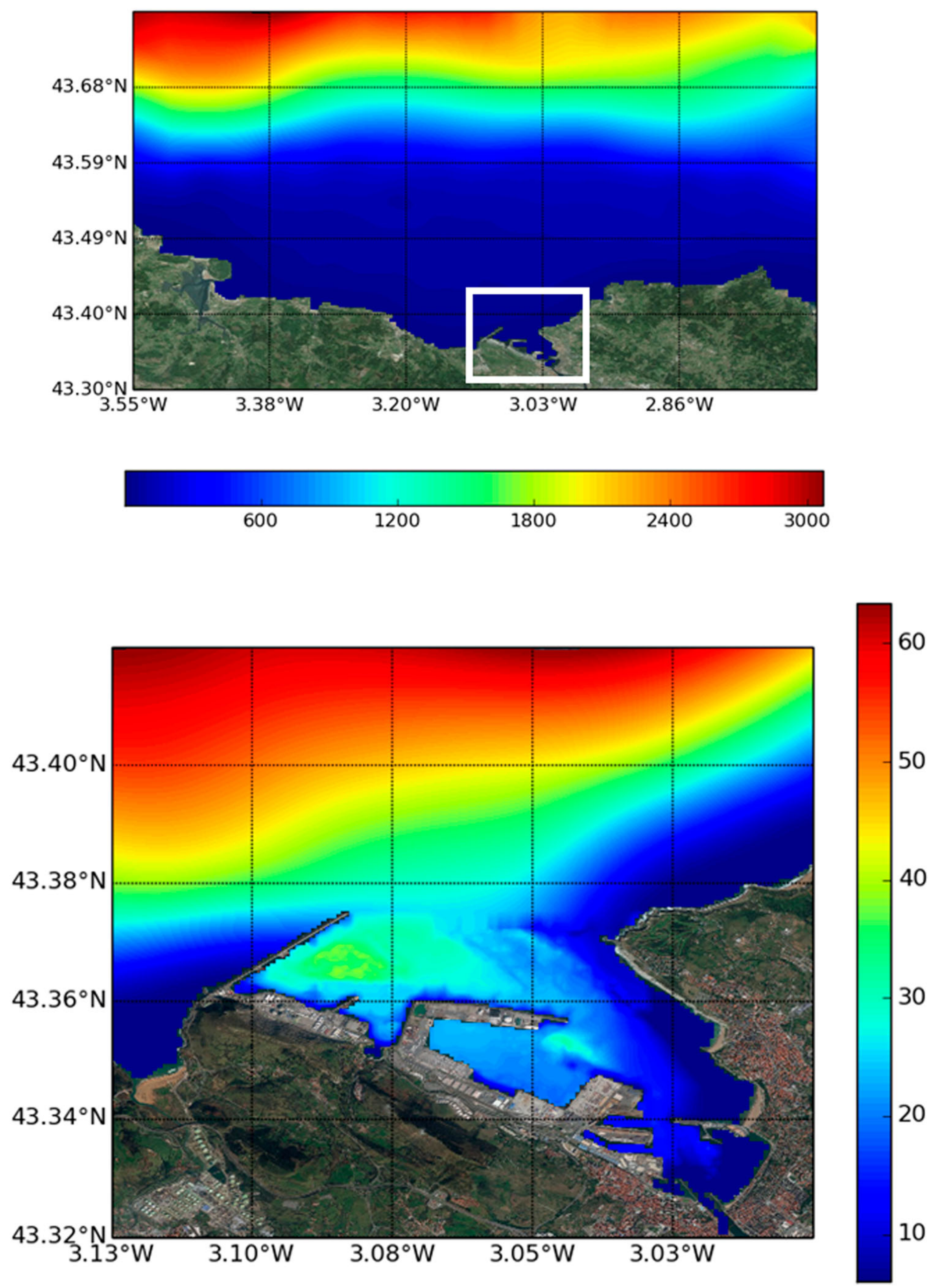

Figure 3. SAMOA System for Bilbao Port. Geographical domains covered by the coastal (CST-BIL) application (top panel) and the corresponding high-resolution port (PRT-BIL) grid (bottom panel). Bathymetry (in m) used in the model runs depicted in both cases.

obtain wind surface stress, surface net heat and salinity fluxes. To avoid land contamination of the atmospheric forcing on coastal areas, the forcing data is pre-processed with the application of a land mask before its use.

Hourly barotropic water currents and sea level are provided by CMEMS-IBI and consistently applied as Open Boundary Conditions (OBC) with Chapman and Flather algorithms (Carter and Merrifield 2007). Moreover, daily average values of CMEMS-IBI currents, temperature and salinity are imposed through the water column as clamped (Dirichlet) boundary condition (following a similar methodology as the one used in other applications: Penven et al. 2006; Costa et al. 2012). Where land freshwater discharges may be relevant (i.e. Ferrol, Bilbao, Barcelona and Tarragona), the river contribution is taken into account considering climatological run-off values and a constant salinity of 18 psu.

It is worth mentioning that this final model configuration used as the base of the operational SAMOA systems arises from an extensive pre-operational

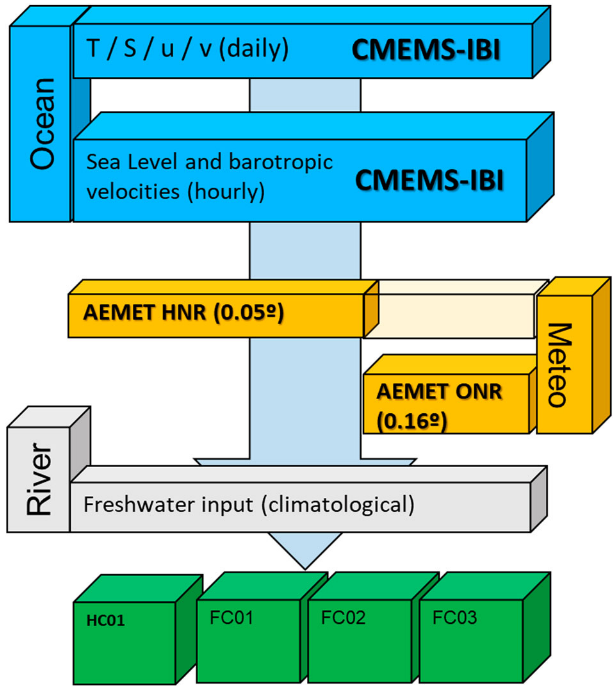

Figure 4. SAMOA Operational scheme: Open boundary conditions (OBC) from CMEMS-IBI depicted in blue; atmospheric forcing (winds, atmospheric pressure, evaporation minus precipitation and surface heat fluxes) in yellow (here it is shown the use of 2 AEMET models, differentiating the use of 4-Km HNR forcing for the first + 36 h of forecast from the rest of the forecast horizon (until + 72 h), when it is used 16-Km ONR forcing); the freshwater in grey (daily values from climatological sources); finally in green the forecast ranges used for both CST and PRT domains (consisting in + 3 Days of forecast and −1 d of hindcast).

qualification testing phase. During this pre-operational phase, several sensitivity model tests, for instance, using different OBC configurations, were performed. Among others, one of the tests consisted on using other external data sources (different from the CMEMS-IBI) to be imposed at OBCs for the sea level variable, one of the key variables in harbour operations. In that case, a model test configuration imposing meteorological sea level variation at the boundaries from the PdE sea-level forecast system NIVMAR (Alvarez Fanjul et al. 2001) and astronomic harmonic components from the LEGOS (Laboratoire d'Études en Géophysique et Océanographie Spatiales) model (Lyard et al. 2006) were used to model sea level evolution. The results of these tests (not shown) demonstrated a general improvement of sea level simulation in the Mediterranean harbours, reducing the root-mean-square errors by 1 cm, when validating against tide gauges observations available in the ports, directly related to the better accuracy of the tidal harmonics provided by the LEGOS model. However, the later use of IBI data (from a model configuration that considers the tidal dynamics) for the total barotropic velocities introduced some inconsistencies along the open boundaries that resulted in spurious mesoscale circulation. Therefore, this nested strategy, based on the combination of CMEMS IBI, LEGOS and NIVMAR data, was successful on improving the simulation of sea level in inner domain regions, but should be upgraded to avoid undesired circulation inconsistencies along the OBC. This solution may be fully appropriate when using a de-tided (model without the effects of tides) CMEMS IBI solution (currently, not available in the CMEMS catalog). In the meantime, while waiting for the availability of de-tided IBI products that allow the application of the combined data solution that improves the sea-level solution, the SAMOA systems are running operationally by imposing only IBI data at the OBCs. This nesting strategy was verified and shown to be free of inconsistencies or spurious mesoscale circulation patterns along the open boundaries; resulting in the existence of some continuity along the boundaries between the regional IBI data imposed as OBCs and the finer SAMOA coastal solution. Figure 5 shows the surface current fields from the CMEMS IBI and the CST SAMOA system for the Barcelona CST SAMOA system, illustrating this continuity between nested and parent solution at the boundaries. The surface current filed from the very high-resolution port model domain in and around the Barcelona Port is also depicted in the figure. It shows the effects of the port layout on the water circulation, as well as a current intensification near the port mouth, reported by port pilots and described in detail in Mestres et al. (2016).

Skill assessment of SAMOA forecast systems: highlights on product quality

Product quality assessment is a key issue for operational forecast systems. Before the transition into operations of any SAMOA system a *scientific qualification* is performed. This qualification process consists of checking any new model development or product update against a series of metrics using available observations as reference data. Together with this pre-operational qualification phase, an exhaustive near-real-time validation of the products operationally generated by the SAMOA forecast systems is performed. This operational validation is based on a routine monitoring of the quality of the SAMOA forecast products on a daily and monthly basis. Outcomes from both phases, off-line pre-operational qualification and online operational validation, allow us to have a better knowledge of the quality and accuracy of the SAMOA forecast products and services.

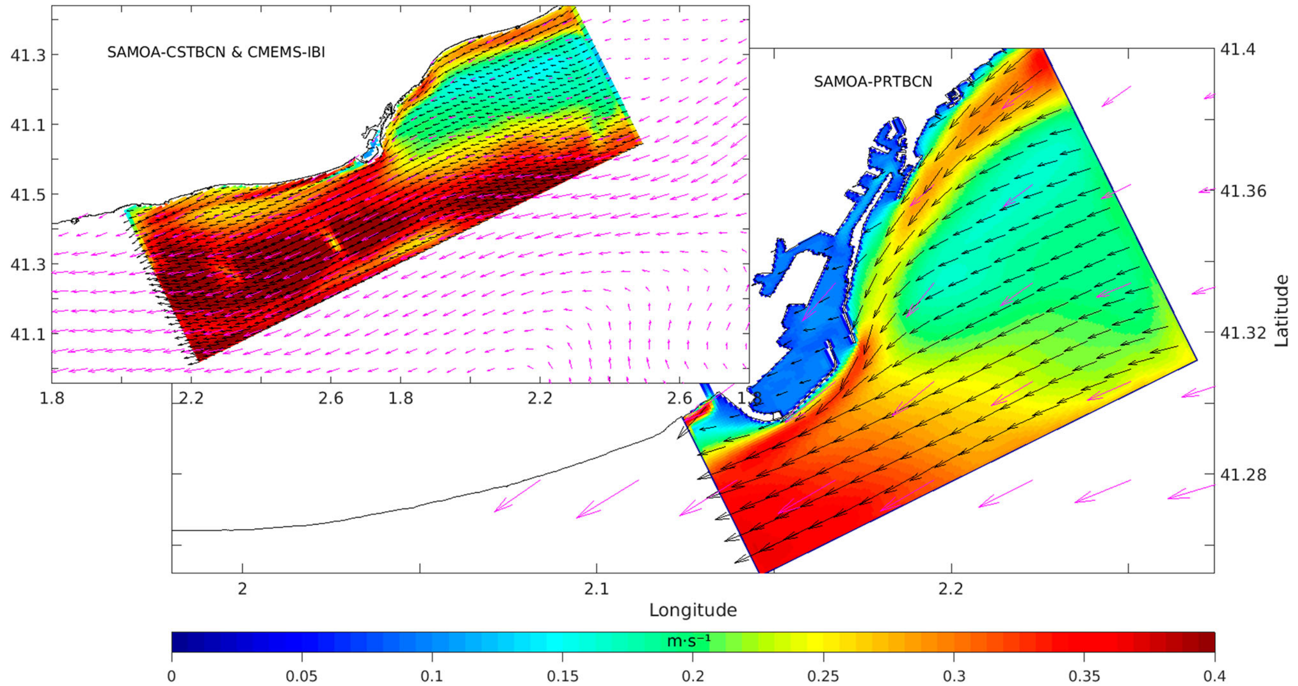

Figure 5. SAMOA Daily mean surface currents (in m/s) in the Barcelona SAMOA System (example for the date 30-03-2014). PRT (lower box) and CST (upper box) domains shown. CMEMS-IBI surface current velocities (arrows in magenta) are also depicted.

SAMOA pre-operational qualification phase

This section describes some of the issues that have arisen after the qualification of the first release of the SAMOA forecast systems (SAMOA-V1). In this first configuration and testing phase, prior to the operational launch of the SAMOA-V1 systems, the quality of 1-year of coastal (CST) and port (PRT) products (generated by means of a long hindcast run) was assessed by comparison with observations, both from in-situ moorings and remotely sensed products.

The 9 existing SAMOA model applications have been run to simulate oceanographic conditions in the ports for a year (from January 1st 2014 till 31st December 2014), generating hourly information on sea level, 3D salinity and water temperature values together with vertically-integrated and 3D currents. The SAMOA model implementations for each port have been validated. To this end, products from each downscaling system (both CST and PRT domains) were compared with available observations and the CMEMS IBI product used as regional reference solution.

In this qualification phase, the downscaling process has followed the same methodology used later in the SAMOA-V1 operations (presented in the previous section). These 1-year model runs used as open boundary conditions and atmospheric forcing the same data sources than the SAMOA operational forecast runs: the CMEMS-IBI forecasts for sea-level, water currents, temperature and salinity boundary condition and the AEMET HNR atmospheric forcing for winds, atmospheric pressure and heat fluxes. However, only the IBI and AEMET HNR data, from their first + 24 h forecast horizon, are used as forcing of these 1-year SAMOA hindcast runs for qualification purposes. The observations used to qualify the model application and to validate the operational forecast systems were:

(a) sea level data from the PdE REDMAR (after *RED de MAReografos*) Tide Gauge Network. These observed sea level time series, available in all the harbours, allowed a detailed validation of the downscaling process and were also used as reference to compare the CST and PRT model solutions with the regional one delivered by the CMEMS IBI-MFC. Model Sea Surface Height (SSH) parameter used for these comparisons.

(b) in-situ observations of surface water currents, from the PdE Mooring Network, were also available to validate the Bilbao, Tarragona and Almeria SAMOA coastal model solutions. However, these buoys are moored in deep waters, indeed far from the coast and quite close to the boundaries of the SAMOA coastal domains, where the dynamical solution is highly influenced by the OBC from the CMEMS IBI parent system.

(c) Furthermore, observed surface current fields from the PdE Tarragona High Frequency Radar (Lorente et al. 2015a) are available for almost the entire qualification period run.

(d) Sea surface temperature and salinity (SST & SSS) observations from the same PdE deep-water buoys have been used to validate these water properties evolution. In the case of the SST, it is also available for the SAMOA qualification observations from some PdE coastal moorings.

High linear correlations are obtained from the SAMOA sea level comparisons within the harbours (with similar level of agreement, both in phase and amplitude, than the one obtained for the CMEMS IBI regional system; Hernández et al. 2015). For instance, Atlantic ports with maximum tidal ranges between 2.5 m (La Palma) and almost 5 m (Bilbao) shows high correlations of 0.99 and RMSE lower than 8 cm (thus implying errors lower than 2%). On the other hand, for the Mediterranean ports, the correlation is 0.89 and the RMSE show values of 5 cm (representing maximum errors of around 14%). Two factors are responsible for such differences between Mediterranean and Atlantic harbours. First, in the Atlantic harbours the astronomical tides are the main factor controlling the sea level variability, whereas in Mediterranean Sea, a microtidal environment, the effects of storm surges and atmospheric fronts are much higher on the relative sea level variability.

Observed surface water currents (~3 m depth) from the PdE deep-water moorings are used to validate the coastal model systems. As example, Figure 6(a–b) shows the observed subtidal water currents, filtered using a 30 h low-pass band Lanczos filter (Emery and Thomson 2004) and the SAMOA ALM-CST model ones at the PdE Cabo de Gata mooring location. The currents from the regional CMEMS-IBI model, used as parent solution in the SAMOA downscaling, are also shown. It should be reminded that this mooring is located close to the SAMOA coastal domain boundary. The fact that both CMEMS-IBI and ALM-CST models show similar behaviour at this location close to the boundaries (with alongshelf currents correlations around 0.6) indicates a correct downscaling process performance, without the presence of spurious features, potentially related to inadequate OBCs specifications (Kourafalou et al. 2015). Moreover, water current roses are computed at all the available moorings. The water current roses for the Bilbao mooring derived from observations and the BIL-CST are plotted in Figure 6(c–d). Both observations and model show how the most intense currents are towards the east. However, it seems the model system shows an excess of zonality, showing a circulation pattern more concentrated on the eastern directions (more frequents than in the observed record), being favoured in excess the modelled southeastern currents.

The lack of more observed time-series of currents in the port regions coincident with the qualification run periods does not allow a more exhaustive direct quantitative validation of the SAMOA system. However, Mestres et al. (2019) present a qualitative comparison of circulation patterns in the Ria de Ferrol. In that study, the SAMOA model application for the Ria de Ferrol is compared with observations from deCastro et al. (2004). Their results show similarities in terms of tidal currents (considering different tidal phases) modelled in the gridpoint closest to the measuring station used in deCastro et al. (2003) study for the Ferrol Strait.

The water currents observations from the PdE Ebro HF Radar have allowed a spatial and temporal validation of the SAMOA coastal domain of the Tarragona Port implementation (Figure 7). This HF Radar system consists of a 13.5 MHz 3-site CODAR SeaSonde radar, providing hourly averaged total current vectors on a regular 3 × 3 km grid. Moreover, data were quality-controlled with a 6-month validation against in situ measurements from a buoy in the region (Lorente et al. 2016). Due to gaps in radar observations, only points with more than 70% of observational data have been selected to validate the models. The regional CMEMS-IBI products have already been validated in Aznar et al. 2016 and Lorente et al. 2016, in the latest using specifically the observations from this HF Radar.

Thus, following a similar methodology, the rotated along-shore and cross-shore velocities of CMEMS-IBI and SAMOA TAR-CST are compared with the observations. The correlation between the SAMOA TAR-CST model currents and HF Radar observations for the entire radar coverage area is shown in Figures 7(a,b) (along-shelf and cross-shelf, respectively). Highest correlations in both components are found in the closest region to the Ebro Delta (far from the Radar range limits) with values higher than 0.6. Lowest correlations in the along-shelf correspond to the end of the Ebro shelf, a region with high slopes in the bathymetry. The results show similar spatially average correlation of 0.52 and 0.46 for CMEMS-IBI; 0.50 and 0.50 for SAMOA TAR-CST (along and cross-shelf respectively). These results reveal how the SAMOA downscaling maintains the mesoscale information inherited from the coarser regional IBI model (mainly in the along-shelf direction), being also able to improve the parent regional solution when analysing the cross-shelf component, probably more affected by local forcing like wind jets (Grifoll et al. 2015; Ràfols et al. 2017,) or topographic influences (Cerralbo et al. 2015b, 2016).

Figure 7(c,d), show the time series of rotated water surface velocity components in one point within the

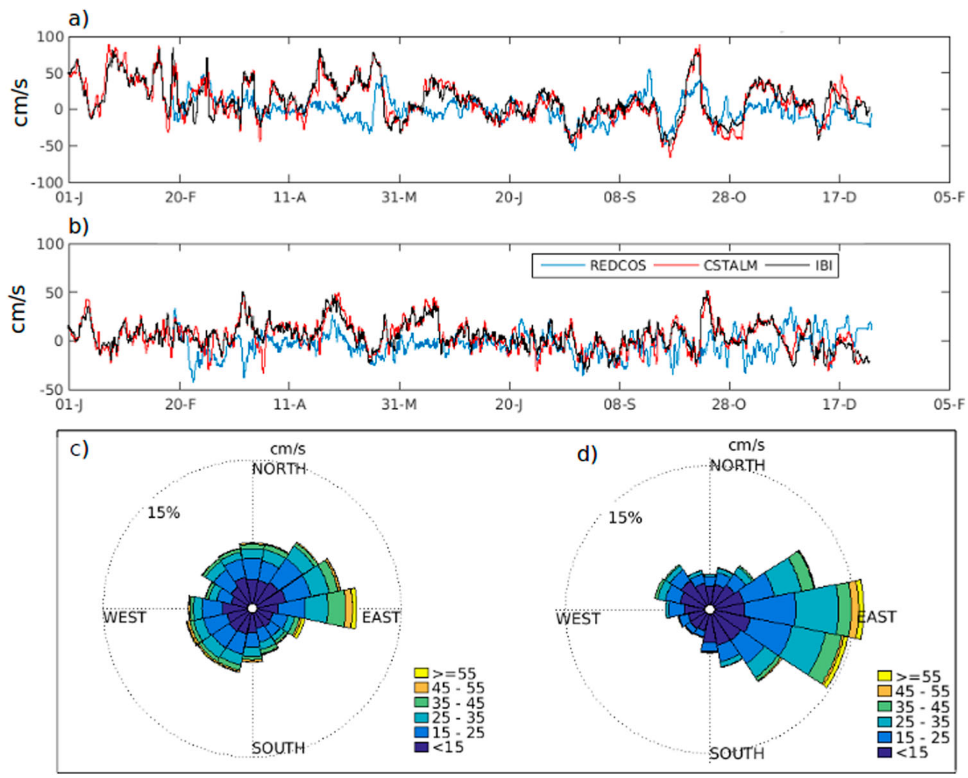

Figure 6. Validation Metrics for surface currents (in cm/s) using observations from 2 PdE moorings (REDCOS network), located within the CST-ALM domain (panels a and b) and the CST-BIL one (Panels c and d). Timeseries of observed and modelled (SAMOA & IBI solutions) 30 h filtered current components (eastward and northward components in panel a and b, respectively) at the buoy location. Water current roses derived from observations (panel c) and the coastal SAMOA solution (panel d) at the PdE mooring located within the CST-BIL domain.

Radar coverage domain. The time-series shows high agreement between the modelled currents (in both along and cross-shore directions) and the observations, with a clear predominance of inertial currents (with periods around 18 h) as stated by Salat et al. 2002 and Ràfols et al. 2017.

Sea surface temperatures from the 1-year hindcast runs have also been validated using data from coastal moorings. Correlation between SAMOA SST and observations shows values, ranging from 0.86 to 0.96 (being the minimum value obtained at Bilbao, whereas the rest of the systems exceed 0.90), with RMSE values around 0.7°C. All the SAMOA systems showed in these 1-year runs performed for pre-operational validation, SST biases bellow 0.3°C value (but in the case of Las Palmas, which shows a maximum bias value around 0.7°C). More examples on the SAMOA SST performance can be seen in the following section dedicated to illustrating the validation done during the operations of the SAMOA systems.

SAMOA operational validation

The development of skill assessment software packages and dedicated web applications is a relatively novel theme in operational oceanography. The North Atlantic Regional Validation (NARVAL) login-protected web validation tool was originally conceived and implemented to objectively evaluate CMEMS IBI regional forecast system's veracity and prognostic capabilities (Hernández et al. 2015; Hernández et al. 2015). Several physical parameters (i.e. sea surface height, temperature, salinity and current velocities) are monitored and evaluated through NARVAL on different time basis. Both real-time validation ('online mode') and regular-scheduled 'delayed-mode' validation (for longer time periods) are conducted using a wealth of independent observational sources as benchmark, encompassing in situ (i.e. tide-gauges, buoys, profilers, etc.) and remote-sensed (High-Frequency radars and satellite-derived) observations. Product quality indicators and skill metrics are automatically computed in order to infer the accuracy of IBI performance and the related spatiotemporal uncertainty levels. The statistical metrics used in the present study include, among others, the mean, model mean error (bias), bias, root mean squared error (RMSE) and scalar correlation (CORR). In order to synthesise different aspects of system performance together, Taylor diagrams were employed.

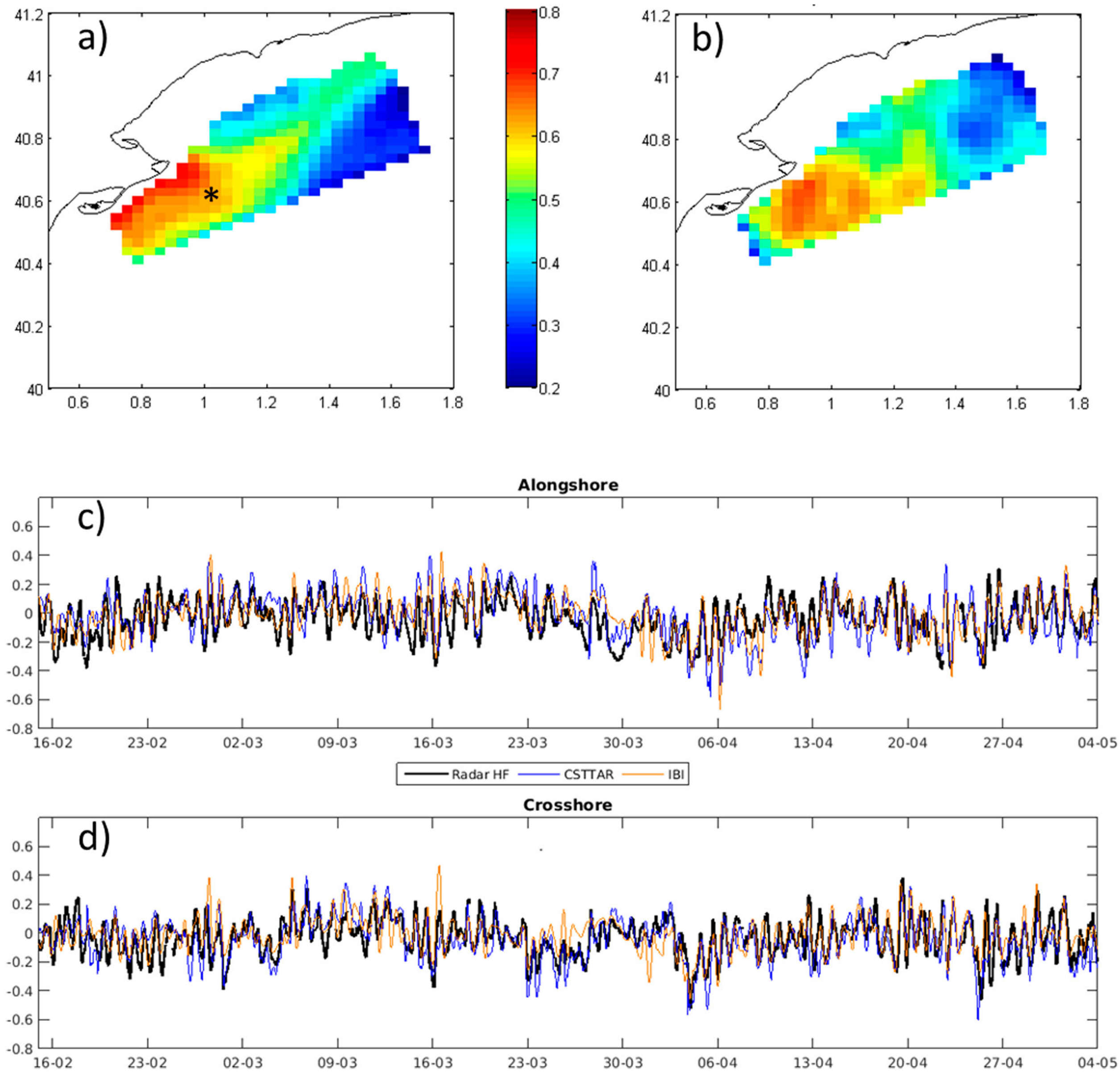

Figure 7. Validation of SAMOA (Tarragona system; TAR-CST) surface currents (in m/s) with the PdE HF-Radar observations. Correlation between HF Radar observations and CSTTAR model for alongshore (panel a) and cross-shore (panel b) current components. Surface current time-series (in m/s) of model (IBI and CSTTAR) and HF-Radar observations for alongshore (panel c) and cross-shore (panel d) components at the point indicated in panel (a) with an asterisk.

Since NARVAL has proven to be a robust and flexible web validation tool, it has been recently upgraded by PdE within the framework of SAMOA to include the in-depth evaluation of the SAMOA high-resolution coastal model solutions, dynamically embedded in the CMEMS IBI forecast system. A multi-parameter ocean model skill assessment is carried out by using all the available observational sources in the coastal SAMOA domains (see the list in the Figure 8 upper panel), primarily focusing on Class-1 (gridded model output) and Class-2 (comparison of time-series at specified locations) metrics, as defined in the Global Ocean Data Assimilation Experiment – GODAE (Bell et al. 2009).

Skill metrics derived from a 6-month comparison (the currently available SAMOA operational coverage) have been gathered in Taylor diagrams (Figure 8(a–b)), which provide a concise statistical summary of how closely hourly SST and SSH model outputs match with observations from mooring and tide-gauges, considered here as the reference points of perfect agreement (red filled squares). As it can be observed in Figure 8(a), the performance of coastal SAMOA systems appears to be rather consistent in terms of SST during the first semester of 2017, according to the skill metrics obtained: correlation values above 0.89 and RMSE usually in the range [0.2–0.4]°C, considering more than 3200 hourly

SAMOA VALIDATION: AVAILABLE OBSERVATIONAL SOURCES			
VARIABLE	**PLATFORM**	**COASTAL DOMAIN**	**PORT DOMAIN**
SSH	tide-gauge	All the domains	All the domains
SST	mooring	BCN, TAR, ALM, BIL, TEN, GCA	BCN, TEN
SSS	mooring	TAR, BIL, ALM	None
SSC	mooring	BCN, TAR, BIL	None
SSC	HF radar	TAR	None

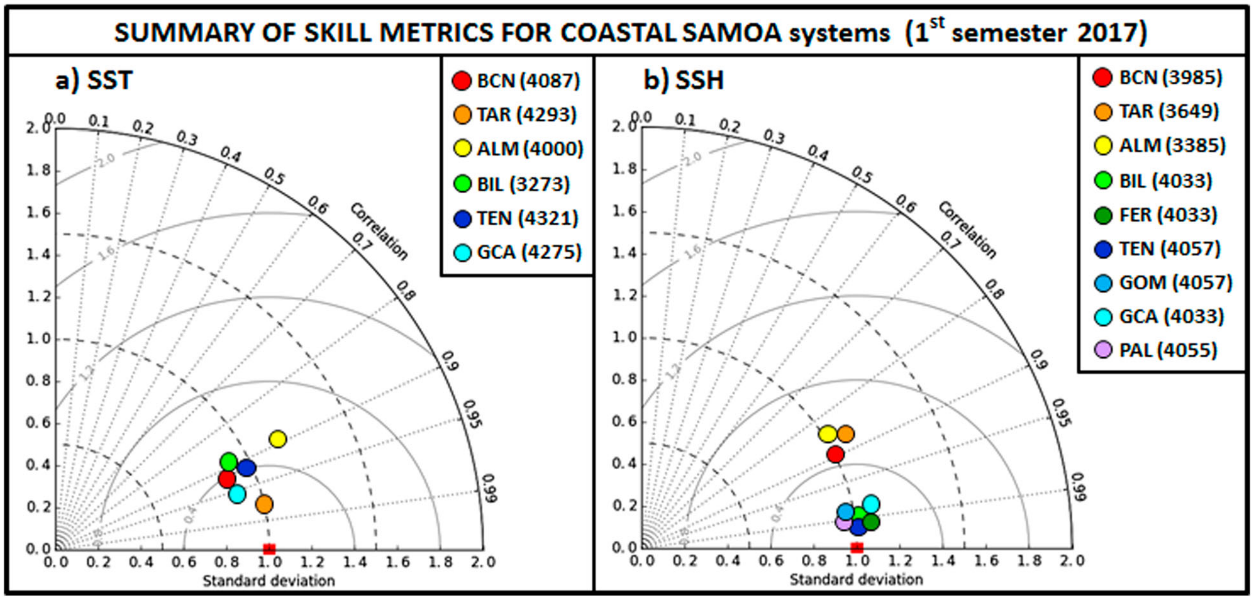

Figure 8. Top: List of platforms used to validate the SAMOA systems for the following variables: sea surface height (SSH), sea surface temperature (SST), salinity (SSS) and currents (SSC). Bottom: Taylor diagrams summarising the skill metrics derived from the operational skill assessment of each SAMOA coastal system for the SST (a) and SSH (b) during a 6-month period (January-June 2017). The number of available hourly observations is provided between brackets for each case.

observations for each case. On the other hand, some basin differences in terms of sea level solution are found.

The SAMOA systems that show the best agreement for SSH (Figure 8(b)) are those located in the Canary Islands (TEN, PAL, GOM and GCA) and the Atlantic (FER and BIL) basins, with reported correlation coefficients and RMSE in the ranges of [0.98–0.99] and [0.07–0.16] m, respectively. Notwithstanding, in the Mediterranean basin (BCN, TAR and ALM) the statistical results do not perform as well, as it may be expected for microtidal environments: correlation coefficients and RMSE emerge in the ranges [0.84–0.89] and [0.42–0.55] m, respectively. Moreover, some of these differences according to the basin may be linked and conditioned by the parent regional solution in which the local SAMOA systems are nested (indeed, a similar basin pattern is also detected in the IBI solution).

Figure 9 shows a variety of Class-2 multi-parameter SAMOA validation examples performed by NARVAL with in-situ observations. According to the Class-2 metrics obtained (grey shaded boxes), SAMOA performances seem to be very consistent for the SST (Figure 9(a)) and SSH (Figure 9(b)), with significantly high correlation values (above 0.95) and moderate RMSE around 0.15° and 0.04 m, respectively. Complementarily, the SAMOA solution appears to reproduce reasonably well other challenging physical parameters such as the sea surface salinity, as reflected by correlation and RMSE values of 0.71 and 0.16 PSU, respectively (Figure 9(c)). This approach is particularly useful to monitor SAMOA operational performances, allowing to detect in near-real-time anomalous features in the delivered SAMOA products.

Apart of validating the SAMOA systems, specific intercomparison exercises between the SAMOA solutions and the regional parent IBI solution are regularly conducted through a dedicated NARVAL web section (Figure 10(a)). These comparisons are performed on

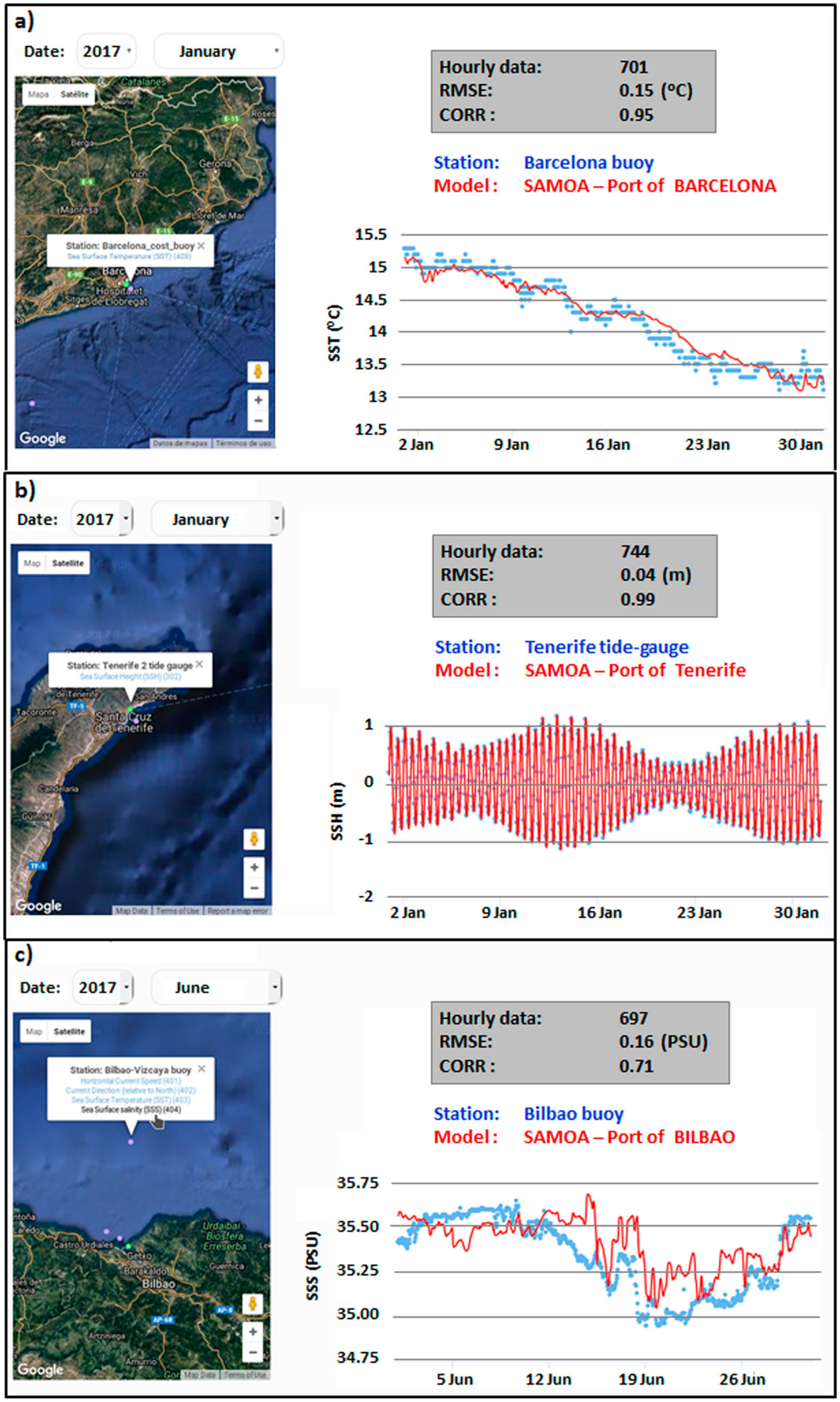

Figure 9. Multiparameter validation of SAMOA systems. Model solution (red lines) against in situ observation (blue dotes). SAMOA surface temperature, sea surface height and surface salinity solutions for Barcelona, Tenerife and Bilbao are shown in panels a, b and c, respectively. Class-2 metrics (root mean square error and time correlation) gathered in grey boxes along with the number of available observations.

overlapping areas and at diverse timescales to verify the model solution consistency and to evaluate the ability of the downscaled solution to outperform the parent model solution (Bell et al. 2015). The main goal is therefore to verify the effectiveness of the dynamical downscaling methodology and quantify its added value in local downstream approaches.

Two brief examples of Class-2 metrics are presented in order to illustrate the intercomparison of SAMOA solution with its parent system (CMEMS IBI) one (Figure 10(b–c)). The first study-case is focused on the sea surface temperature modelled by both operational forecasting systems during October–December 2016 and those registered in-situ in the PdE buoy moored in front of Barcelona (Figure 10(b)). As it can be seen the resemblance of SAMOA simulation (green dots) with observational data (blue dots) is better than the one obtained by the IBI system (red line) in terms of metrics and specially during the first weeks (dotted black box): the SAMOA correlation coefficient is higher (0.85 versus 0.81) and the RMSE is lower (0.68° versus 0.79°) than in the case of the IBI regional solution. Later on, both model solutions seem to converge, but do not satisfactorily reproduce the two temperature peaks (indicated with the solid red boxes). The second study-case reveals how the SAMOA system better replicates the maximum and minimum values of sea surface height in Bilbao (Figure 10(c)), although both model performances are significantly accurate, as reflected by the skill metrics: significantly high correlation values (above 0.96) and rather moderate RMSE (around 0.06–0.07 m).

Conclusions and future SAMOA prospective

In recent years, PdE has boosted its local operational oceanographic service capacities through the SAMOA initiative. After 3-years of scientific developments and operational model implementations, SAMOA is certainly a revolution in the way that PdE is providing operational ocean forecast services to meet the Spanish Port Authority's needs. The availability of local products delivered through SAMOA will support Port Authorities to make strategic decision in the field of port management (i.e. water quality issues) and ship navigation.

PdE and LIM/UPC has performed an advanced design of high-resolution coastal operational systems for prediction of ocean circulation in ports and their nearby coastal waters. The scientific progress made within the SAMOA implementation phase has addressed the following issues, identified in the Kourafalou et al. (2015) detailed review on science foundation of coastal modelling as fundamental primary scientific topics needed for the success of any coastal model application:

(i) *use of a model able to reproduce coastal processes* (SAMOAs systems based on ROMS model application with specific fine tuning configurations);
(ii) a *sufficiently detailed representation of bathymetric features* (SAMOA bathymetries are the result of the combination of global and specific local data sources in the port; being the last one to be regularly updated)
(iii) *best representation of air–sea interactions* (inclusion of Wind stress and surface heat and fresh water fluxes from Spanish Met Office hourly 4-km operational atmospheric forecasts)
(iv) *best method to achieve coastal model systems rightly embedded in larger regional scale solutions;* SAMOA systems are operationally nested into the CMEMS IBI regional solution; however, different sensitivity tests, focused not only on getting the most adequate nesting methodology but also to identify the best available larger scale solution to be imposed at the open boundaries were performed, and
(v) *inclusion of land-sea interactions* (river fresh water discharges inputs from climatological sources are used).

Based on these scientific developments, today there are 9 operational forecast applications fully implemented for different Spanish ports located in the Mediterranean, the Iberian Atlantic and the Canaries. This first set of SAMOA local circulation forecast systems are in operations from January 2017 and they produce daily short term (+3 Days) forecasts of 3-D currents and other oceanographic variables, such as temperature, salinity, together with sea level. The SAMOA forecast products for each of the coastal and local domains currently in operations (including hourly surface data and daily averages for 3D fields) are open and freely accessible through the PdE catalogue (http://opendap.puertos.es/thredds/catalog.html). Daily SAMOA forecasts for sea surface temperature, salinity and currents can be viewed through the PdE Portus web interface (http://portus.puertos.es). Furthermore, a subset of SAMOA circulation products for specific port sites are inserted in the PdE database and later used to build customised information, including alerts and warning systems, available for Port Authorities through the PdE SAMOA CMA Tool.

A comprehensive multi-parametric validation tool, based on the NARVAL tool is implemented to evaluate the downscaled SAMOA coastal solutions, using available operational observational sources (both remoted sensed, including HF Radars, and in-situ). A summary and some highlights of the scientific validation

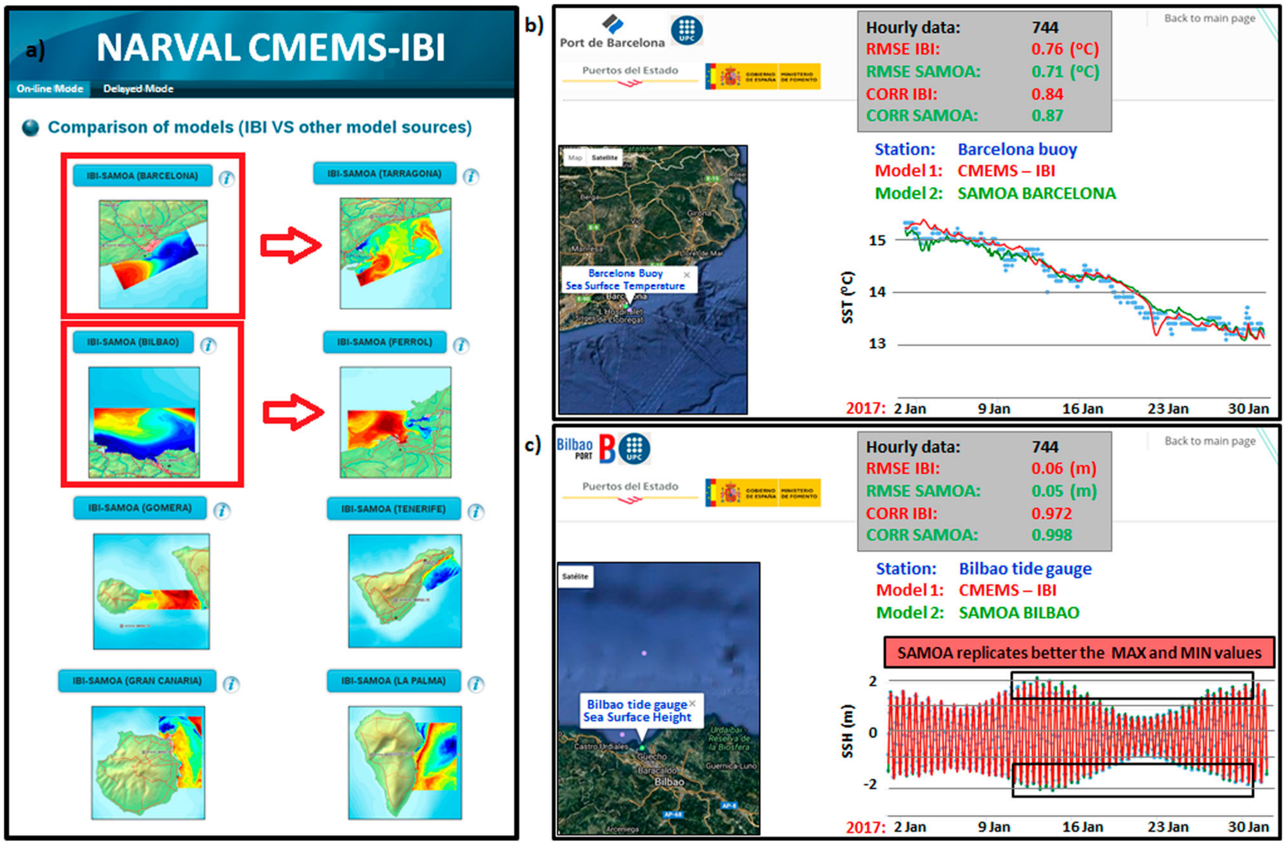

Figure 10. (#a) Snapshot of the NARVAL web section devoted to the model solution intercomparison performed between the IBI regional solution and the SAMOA high resolution coastal systems (nested into the former). Examples of SST and SSH comparisons with the Barcelona mooring and the Bilbao tide gauge (panels b and c, respectively).

assessments performed both within the SAMOA pre-operational model qualification phase and along the first months of operations are shown in this paper. The overall behaviour of the present SAMOA operational forecasting systems is very encouraging and the available validation statistics suggest that SAMOA systems generally capture major synoptic and mesoscale features (skill at these scales, mainly inherited from the forecasting capabilities of the regional solution in which SAMOA systems are embedded) together with some specific local features, more related or influenced by coastal topographies. The validation statistics obtained from the first semester of SAMOA operations, when compare during the first semester of 2017 with more than 3200 hourly observations for SST and SSH, illustrate this point: SAMOA presents errors in the range of [0.2–0.4]°C and [0.07–0.16] m and correlation values above 0.89 and 0.83 for each parameter respectively.

Apart from validating the SAMOA systems, specific intercomparison exercises between the SAMOA solutions and the regional 'parent' IBI solution are regularly conducted. These comparisons are performed on overlapping areas and at diverse timescales to verify the model solution consistency and to evaluate, through objective measures, the ability of the downscaled solution to outperform the parent model solution.

Regarding SAMOA coastal model skill assessment, there are a variety of challenges to face, mostly related to the sparseness of coastal observations (and the corresponding quality control issues) and the variety of time scales to be analysed depending on the complex phenomena under study. Certainly, the lack of observational data sources in limited coastal domains is the major one. In most of the SAMOA cases, the real-time operational oceanographic in-situ observational data sources are reduced to sea-level observations from tide gauges (all the SAMOA ports count with a tide gauge) and some surface observations of surface temperature, currents and salinity from coastal buoys, moored away from the coast and outside of port waters. Satellite coverage and remotely sensed measurement availability, as well as their representability in areas so close to the coast is certainly another issue when trying to use satellite products in validating coastal and local solutions as the ones provided with the SAMOA systems.

Future evolution of SAMOA coastal circulation model systems is currently being planned. This evolution will be done in the framework of the SAMOA-2 Project (initiative, currently approved by PdE and the Spanish Port Authorities to be undertaken for the 2018–2021 period). To evolve the present SAMOA systems, it is needed to sustain the research effort, and research activities on the following topics:

- *Improvement of atmospheric forcing*. This issue is to be faced in two ways: firstly, a general substitution of present AEMET HNR + ONR forcing by the use of a new atmospheric forcing based on the recently released AEMET Harmonie-2.5 km forecast service. Secondly, testing the use of operational atmospheric forecast inputs delivered by the new local SAMOA 1Km atmospheric forecast systems (to be tested in those ports with SAMOA atmospheric and ocean forecast systems in place).
- *Update of coastal fresh water forcing*. To be investigated using the upgrade of local river fresh water forcing, currently limited to the use of climatological river fresh water inputs at river mouth, to use near-real-time river discharge observations (where available). Together with outputs from operational hydrological forecast model applications, extending thus the forcing from single river input source to an extended run-off rate specified at every coastal grid point.
- *Other long-term scientific evolution*. Some local coupling between circulation and waves is desirable. Currently, the CMEMS IBI MFC is making progress on this matter, and it is expected that in the short-term the regional IBI solution, in which SAMOA systems are nested, will include wave contribution. Likewise, the coupling of SAMOA high-resolution wave and circulation local systems is seen as a research line of interest. Also, to increase our understanding on the complex local dynamics, it would be useful to develop some data assimilation scheme to make possible the combination of observations and models. The generation of ocean analysis has been done successfully at global scales and it is being currently undertaken at regional scales (in our region, the CMEMS IBI is expecting to produce regional analysis for 2018). However, the aforementioned lack of operational near-real-time ocean observations in coastal areas may make this aim a very difficult and challenging duty. Nevertheless, SAMOA will support research lines focused on assimilating in coastal model system observational information on surface currents provided by HF Radars sites (in the same line that currently on-going experiences, such as the one performed by Gopalakrishnan and Blumberg (2012) in the New Jersey Bay).

Finally, it is worth mentioning that along the next 3 years it is expected that the number of SAMOA high resolution operational forecast services will be significantly increased (already approved the implementation of 13 new systems, what results in a total of 22 Spanish Ports with SAMOA circulation forecast system in 2021). This noticeable increase in the number of SAMOA Port systems will result in an almost complete coverage of the Spanish coasts by means of the coastal SAMOA domains.

Disclosure statement

No potential conflict of interest was reported by the authors.

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