Coastal Ocean Forecasting in Spanish Ports: The SAMOA Operational Service.

Marcos G. Sotillo^{a*}, P. Cerralbo^b, P. Lorente^a, M. Grifoll^b, M. Espino^b, A. Sanchez-Arcilla^b, E. Álvarez-Fanjul^a

^a *Área de Medio Físico. Puertos del Estado, Madrid, Spain.*

^b *Laboratori d'Enginyeria Marítima. Politechnic University of Catalonia (UPC), Barcelona, Spain.*

High Resolution Coastal Ocean Forecasting in Spanish Ports: The SAMOA Operational Service.

SAMOA is the latest Puertos del Estado (PdE) initiative to boost the delivery of customized operational met-ocean information to the Spanish Port Authorities to meet port needs for decision making in harbour safety, environmental management and operations. Within this initiative, an advanced design of high-resolution coastal operational systems for prediction of ocean circulation in restricted domains such as harbors and their nearby coastal waters has been performed. These systems are today fully implemented (in operations from January 2017) for 9 Spanish ports located in the Mediterranean, the Iberian Atlantic and the Canary Islands. This paper provides an end-to-end description of these SAMOA model systems, based on high resolution (up to 70 m horizontal resolution in inner port waters) ROMS model applications. At the surface, models are forced by daily updated high frequency (hourly) winds and heat and water fluxes from the Spanish Meteorological Agency (AEMET) forecast services. The SAMOA systems are CMEMS downstream services, being the coastal models nested into the regional CMEMS IBI forecast solution. A comprehensive multi-parametric validation tool is used to evaluate the downscaled SAMOA coastal solutions, using operational observational sources (both remoted sensed, including HF Radars, and in-situ observations). A summary and some highlights of the scientific validation assessments performed both within the SAMOA pre-operational model qualification phase and along the first months of operations are shown, illustrating the reasonable agreement of the SAMOA model products with observations. Finally, plans to upgrade SAMOA systems are outlined, providing a look ahead to future SAMOA developments and operational novelties.

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

Introduction

There is a growth of the ports and their activity, mainly associate to the increase of traffics. The total gross weight of goods handled in EU ports is estimated at just above 3.8 billion tonnes in 2015, resulting in an annual increase of 1.3 %. 447 million tonnes

were handled by the Spanish Port System, 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 modify water quality within the harbor and its adjacent coastal waters, so the European common policy framework to protect continental, underground and coastal waters includes harbors and their adjacent waters within the EU Water Framework Directive (2000/60/CE WFD). Consequently, European port authorities have by law a series of responsibilities in terms of environmental monitoring and fighting against pollution in harbor waters (Darbra et al. 2009, Puig et al. 2017).

Understanding the physical behavior 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 very specially by the most extreme events, to support their growing activities they need customized real-time and forecast information on environmental conditions.

For their implications in the safety of port operations and their affection in terms of ship draught allowance, wind and waves, together with sea level were traditionally the most important met-ocean parameters for the port activity, and therefore the most extensively monitored and forecasted ones. Since mid-90's, the Spanish ports counts on operational oceanographic information delivered by the PdE operational forecast and monitoring services, including regional and local wave and sea-level operational forecasts (Gómez Lahoz and Carretero-Albiach 1997; Álvarez Fanjul et al. 2001; Gómez-Lahoz and Carretero-Albiach 2005, Pérez et al. 2013).

Nevertheless, water currents are progressively becoming a more demanded parameter for port management and a detailed knowledge of the local currents is useful for the ports, not only to aid in navigation and ship maneuverability (e.g. local currents

highly affect piloting activity to get cargo ships safely into and out of the ports and the navigation through channels) but also for many other applications related to water quality management and environmental risk assessment (Grifoll et al. 2011), including those related to oil spill issues (Sotillo et al. 2008; Guo et al. 2014; Valdor et al. 2015). In that sense, it is of interest for a port to have detailed information on the physical local circulation patterns occurring in its waters (i.e. flushing patterns, residence times, as well as the associated advective and dispersive capabilities).

The implementation of numerical models in coastal areas, combined with the use of observational information, enables a better understanding and characterization of main hydrodynamic features of specific coastal zone and it is becoming a common practice all around the world (among many others, Djath et al., 2014, Kärnä et al. 2015). However, to support port activities is decisive to rely on information from services providing near-real-time and forecast information updated in operational basis.

As response to this growing demand of sustained regularly updated ocean information, physical operational oceanography has undergone a rapid maturation process and operational ocean circulation modelling systems have been emerging progressively. In a pan-European scale, the Copernicus Marine Environmental Monitoring Service (CMEMS, <http://marine.copernicus.eu/>), fully operational from May 2015, represents a noticeable upgrade of the European operational oceanography 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 (Sotillo et al. 2015).

The CMEMS IBI products cover all the Spanish waters and PdE uses them in some of its marine applications focused on Spanish ports. These IBI products are extensively validated and can be used as reference product to characterize regional ocean circulation features around the Iberian Peninsula (Aznar et al. 2016 and Capo et al. 2016). Despite its very high horizontal resolution ($1/36^\circ$), that makes them adequate to rightly characterize regional circulation features, some limitations are detected when looking at 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 of interest (mostly, the local ones) to meet end-users needs, some downstream services are using different downscaling approaches (Sotillo et al. 2008, Korres et al. 2010, Juza et al., 2016). Following this downstreaming way, PdE has developed in the recent years a series of local operational oceanography developments, and particularly ocean dynamical downscaling in harbor environments. The SAMPA ocean circulation forecast system, operationally running from 2012, is a good example of this approach. This system centered in the Gibraltar Strait area has contributed to enhance the scientific knowledge of this hot spot (Sánchez-Garrido et al., 2013), increasing the capabilities of proper knowledge-based decision making for maritime challenges, such as accidental oil spills and port operations optimization (Sotillo et al., 2016). In parallel, PdE implemented operational local circulation forecast systems for some specific ports (i.e. Barcelona, Bilbao, Tarragona) showing that this kind of operational systems for prediction of currents in seaports constitute a proved convenient instrument for risk assessment and environmental harbor management (Grifoll et al., 2012).

For the last 3 years (2014-2017), PdE has leaded and developed the SAMOA initiative: 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 very high-resolution ocean circulation forecast system, able to solve from coastal to very local scales inside the ports.

As Kourafalou et al. (2015) points in their detailed review on the science foundation of coastal modelling, the advancement of coastal ocean forecasting systems requires the support of continuous scientific progress to address, among others, issues related to primary mechanisms driving coastal circulation; methods to achieve coastal systems dynamically embedded in larger scale systems; downscaling and methods to adequately represent air-sea and land interactions, including, atmosphere-wave-ocean couplings. These primary science topics are fundamental for the successful of any coastal model application, connected to evolving operational downstream applications and have been faced in the SAMOA implementation phase.

This paper provides an end-to-end description of these new operational SAMOA circulation forecast in Spanish ports. The paper is organized 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 in 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 summarizes main conclusions and gives a look ahead to future areas of development, outlining a roadmap that summarizes 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 (*Sistema de Apoyo Meteorológico y Oceanográfico de la Autoridad Portuaria* or Meteorological and Oceanographic Support System of the Port Authority) was born, co-financed by PdE and the 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 customized ocean-meteorological information, fully adapted to their needs. The SAMOA service (Álvarez-Fanjul et al., 2017) consists of several modules: some of them, focused on enhancing near-real-time observational capabilities (improving instrumentation of the current existing PdE observational networks) and some others on implementing new local high-resolution forecast model systems for atmosphere, waves and ocean circulation. New added-value systems accompany these modules: i.e. the new CMA (*Cuadro de Mando Ambiental* or Environmental Control Panel), a tailor-made software application to allow customize access to any available met-ocean information in the ports (see snapshot in Figure 1), as well as to new advanced viewing capabilities and services, such as user alert system (through e-mail and SMS).

SAMOA is allowing a better exploitation of the available data by the ports and its services have a widespread use, going beyond the Port community, and mean potential benefits for the whole society (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).

Within the SAMOA framework, it has been developed operational ocean forecasting systems based on very high-resolution model implementations able to solve typical shelf and coastal processes at port scales. In this SAMOA circulation component, PdE is collaborating with the *Maritime Engineering Laboratory* of the Politechnic University of Catalonia (LIM/UPC) to make the required scientific research and developments to configure the local circulation model applications that later will be the core of the operational applications implemented and daily run by PdE (the SAMOA operational systems are run on daily basis, 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 today fully implemented and in operations (from January 2017) for 3 Spanish ports in the Mediterranean (Barcelona, Tarragona, Almeria), 2 in the Iberian Atlantic (Bilbao, Ferrol) and 4 in the Canaries (Las Palmas, Tenerife, La Gomera, and Santa Cruz de la Palma). All the 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 Modeling 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.

Several operational oceanography systems use ROMS (e.g. Marta-Almeida, 2012; Juza et al., 2016). These systems cover different spatial scales and uses different forcing and nesting strategies. Aside of operational oceanography, ROMS model is also

used for a widespread range of applications such as estuarine modeling (Cerralbo et al., 2015a, 2016), sediment transport (Grifoll et al., 2014), oceanic basin modelling (Malanotte-Rizoli et al. 2000), climate studies (Di Lorenzo et al. 2008) or atmosphere-wave-current interaction (Warner et al., 2010). One of the strong point of ROMS is its modularity and the use of an efficient parallelization strategy with MPI interface, which allows to develop applications with very competitive computational time (Wang et al., 2005). Early versions of PdE local high-resolution oceanographic systems for some Spanish ports, which may be considered as prototype of the here presented SAMOA systems, were developed using ROMS (Grifoll et al., 2012).

The SAMOA model applications consist of 2 nested regular grids with spatial resolution of ~350 m and ~70 m for the coastal and harbor domains, respectively (see example in Figure 3). 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 ports allowing the transference of large-scale dynamics into the nested domain. The chosen vertical discretization 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 the port domains.

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 to the IBI velocities imposed as open boundary condition. In the ports, 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 parameterized with a logarithmic profile using a characteristic bottom roughness height of 0.002m. 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 $5 \text{ m}^2\text{s}^{-1}$.

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 model: one, the HNR (0.05° resolution and a forecast horizon of +36 hours) covering the Spanish territory and the more extended regional ONR application (0.16° resolution and a forecast horizon of +72h). HNR and ONR fields are jointly used according to best available basis and pre-processed to obtain wind surface stress, surface net heat and salinity fluxes. To avoid land contamination of the atmospheric forcing on coastal areas, a prior land mask is applied to the forcing data.

Hourly barotropic water currents and sea level are provided by CMEMS-IBI and consistently accommodated to the open boundaries (OBC) with Chapman and Flather algorithms (Carter and Merrifield, 2007). The variability of currents along the water column (baroclinic component), temperature and salinity are imposed from CMEMS-IBI daily average values with clamped conditions (as used in other applications like: Penven et al. 2006, Costa et al. 2012). When 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 worthy to mention that this final model configuration used as base of the operational SAMOA systems arise from an extensive pre-operational qualification test 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 harbor operations. In that case, a model test configuration imposing meteorological sea level variation at the boundaries from the PdE NIVMAR System (Álvarez-Fanjul et al. 2001) and astronomic harmonic components from the LEGOS 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 1 cm the root-mean-square errors (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 non-detided IBI data (currently, not available in the CMEMS catalog) 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 CMEMS IBI solution. In the meantime, and waiting for the availability of de-tide IBI products that allow to apply the combined data solution to improve the sea level solution, the SAMOA systems are running operationally imposing at the OBCs

only IBI data. This nesting strategy has been verified, being proved the lack of inconsistencies or spurious mesoscale circulation patterns along the open boundaries. This continuity between the regional IBI and the finer SAMOA coastal solution along the boundaries is shown in Figure 5. Apart of illustrating such continuity between nested and parent solution, the surface current field in the Barcelona Port and vicinities also shows the effects of the port layout in 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*, understanding it as the process of checking any new model development or product against a series of metrics using available observational reference data, was performed. 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 on-line operational validation, allow us to have a better knowledge of the quality and accuracy of the SAMOA forecast products and services.

SAMOA pre-operational qualification phase

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

The 9 existing SAMOA model applications have been run to simulate oceanographic conditions in the ports for a year (from Jan 1st 2014 till 31st Dec 2014), generating hourly information on sea level, 3D salinity and water temperature values together with vertically-integrated and 3D currents. The products from each downscaling system (comprising both CST and PRT domains) have been used to validate the SAMOA model implementation on each port, comparing 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): using the first 24h of CMEMS-IBI daily forecasts as imposed data for the sea level, water currents, temperature and salinity OBCs. Related to the atmospheric forcing (winds, atmospheric pressure and heat fluxes) used in the long-runs, it was used only the AEMET HNR products of ~5 km resolution, corresponding to the same configuration used for the first 36h of the daily SAMOA forecasts in the operational design (see previous section).

The observations used to qualify the model application and to validate the operational forecast systems were: a) sea level data from the PdE REDMAR Tide Gauge Network. These observed sea level time series, available in all the harbors, 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. b) in-situ observations of surface water currents, from the PdE Mooring Network, were also available to validate the Bilbao, Tarragona and Almeria SAMOA costal 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. A summary of all the observational data sources used both for the pre-operational qualification and the on-line validation is provided in Figure 8 (upper panel).

High linear correlations are obtained from the SAMOA sea level comparisons within the harbors (with similar level of agreement, both in phase and amplitude, than the one obtained for the CMEMS IBI regional system; Sotillo et al. 2015). For instance, Atlantic ports with maximum tidal ranges between 2.5m (La Palma) and almost 5m (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 5cm (representing maximum errors of around 14%). Two factors are responsible for such differences between Mediterranean and Atlantic harbors. First, in the Atlantic harbors 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.

Surface water currents (~3m depth) from the PdE deep-water moorings are also used to validate the coastal domains. Figure 6a-b shows as an example, the subtidal water currents, filtered using a 30h low-pass band Lanczos filter (Emery and Thomson 2004), observed in the Cabo de Gata mooring, together with the currents delivered by the SAMOA ALM-CST system and the regional CMEMS-IBI used as parent solution in the downscaling. Both CMEMS-IBI and ALM-CST show similar behavior (it should be reminded that the mooring location is close to the SAMOA coastal domain boundary) indicating the good behavior of the downscaling process without the apparition of spurious structures usually related to an inadequate OBCs specification (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 (the CMEMS-IBI not shown, but it is quite like the SAMOA one) are plotted in Figure 6c-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 frequent than in the observed record), being favored in excess the modelled southeastern currents.

The lack of more observed time-series in the port regions coincident with the qualification run periods does not allow a more exhaustive direct quantitative validation of the SAMOA system. However, a qualitative comparison of circulation patterns can be addressed using to this aim information from previous studies and campaigns in port waters. For instance, in the Ria de Ferrol, deCastro et al. 2003 measured currents in the narrowest part of the ria using a Doppler current-meter, and again using current-meters at two stations (deCastro et al., 2004) to analyze the ria's hydrodynamics. The SAMOA

modelled results obtained from the Ferrol qualification run are compatible with their measured data, both in magnitude and general behavior at the observational stations. For instance, axial currents at the computational node closest to the measuring station in deCastro et al. 2003 in the Ferrol Strait, present magnitudes at mid- and bottom layers comparable to their field measurements for a period with a similar tidal range (maxima around 0.5 m/s at mid-depth, and smaller for deeper waters). The magnitudes and depth profiles of currents during a tidal phase are also reasonably replicated by the present numerical implementation (Mestres et al. 2017).

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. This HF Radar system consists in a 13.5 MHz 3-site CODAR SeaSonde radar, providing hourly averaged total current vectors on a regular 3 x 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 on 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 (Figure 7a and 7b, show the time series of rotated water surface velocity components in one point within the Radar coverage domain). The time-series shows high agreement between the modeled currents (in both along and cross-shore directions) and the observations, with a clear predominance of inertial currents (with periods around 18 hours) as stated by Salat et al. (2002) and Ràfols (2017).

The correlation between the SAMOA TAR-CST model currents and HF Radar

observations for the entire radar coverage area is shown in Figures 7a and 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 (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). Furthermore, a comparison between the correlation of CMEMS-IBI model versus observations, and SAMOA TAR-CST versus observations is shown in the Figures 7a and 7b (small images within the panel). 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 analyzing the cross-shelf component, probably more affected by local forcing like wind jets (Cerralbo et al., 2016; Ràfols et al., 2017,) or topographic influences (Cerralbo et al. 2014). Sea surface temperatures from the 1-year hindcast runs have also been validated using data from coastal moorings. However, results are not shown here (nevertheless, some examples on the SAMOA SST performances can be seen in the following section).

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 (Sotillo 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.

Since NARVAL has proved 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 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 in the range of [0.98–0.99]. Notwithstanding, in the Mediterranean basin (BCN, TAR and ALM) the statistical results are slightly worse, as it may be expected for microtidal environments. 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). Complementarily, SAMOA solution appears to reproduce reasonably well other challenging physical parameters such as the sea surface salinity (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 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 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 for the IBI system (red line) in terms of metrics and specially during the first weeks (dotted black box). 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.

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.

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* (SAMOA 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 viewing 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 customized 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 assessments performed both within the SAMOA pre-operational model qualification phase and along the first months of operations are shown. The overall behavior 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.

Apart of 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 is 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 analyzed depending on the complex phenomena under study. Certainly, the lack of observational data source in limited coastal domains is the major one. In most of the SAMOA cases,

the real-time operational oceanographic in-situ observational data source are reduced to sea-level observations from tide gauges (all the SAMOA ports count with a tide gauge) and some surface observation of surface temperature, currents and salinity from coastal buoys, moored away from the coast and outside of port waters. Satellite coverage and remote 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 are foreseen:

- *Improvement of atmospheric forcing.* This issue 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-2.5Km 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 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 of this aim a very difficult and challenging duty. Nevertheless, SAMOA will support research lines focused for instance 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 to mention 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.

Acknowledgements

Acknowledgements, avoiding identifying any of the authors prior to peer review

Autoridades portuarias. Podria ser interesnates mencionar la reuniones no solo con las autoridades porturarias sino con toda la comunidad.

References

Alvarez Fanjul E, Pérez B, Rodríguez Sanchez-Arevalo I. 2001. Nivmar: A storm-surge forecasting system for the Spanish waters. *Scientia Marina*, 65, pp. 145–154.

Alvarez Fanjul E, M G Sotillo, B Pérez, J M García-Valdecasas, S Pérez, Á Rodríguez, I Martínez-Marco, Y Luna, E Padorno, Gl Díaz, J López, R Medina, M Grifoll, M Espino, M Mestres, L Rafols, A Sánchez-Arcilla. 2017. The SAMOA initiative: Operational Oceanography at the service of the Ports. Extended proceeding. 8th EuroGOOS Conference. Bergen, 3-5 October 2017.

Aznar R., Sotillo M.G., Cailleau S., Lorente P., Levier B., Amo-Baladrón A., Reffray G., Álvarez-Fanjul E. 2016. Strengths and weaknesses of the Copernicus forecasted and reanalyzed solutions for the Iberia-Biscay-Ireland (IBI) waters. *Journal of Marine Systems*, 159, pp. 1-14.

Bell, M.J., Lefebvre, M., Le Traon, P.Y., Smith, N. and Wilmer-Becker, K. 2009. GODAE, The global ocean data experiment. *Oceanogr Magazine*. Vol. 22, Issue 3, pages 14–21.

Bell, M.J., Schiller, A., Le Traon, P.Y., Smith, N.R., Dombrowsky, E. and Wilmer-Becker, K. 2015. An introduction to GODAE OceanView. *Journal of Operational Oceanography*, Vol. 8, pages 2–11.

Capó E, A. Orfila, J.M. Sayol, M. Juza, M.G. Sotillo, D. Conti, G. Simarro, B. Mourre, L. Gómez-Pujol, J. Tintoré. 2016. Assessment of operational models in the Balearic Sea during a MEDESS-4MS experiment. *Deep Sea Research II* Vol 133, pp 118–131

Carter G. S., M. A. Merrifield. 2007. Open boundary conditions for regional tidal simulations. *Ocean Modelling* 18 (2007) 194–209. doi:10.1016/j.ocemod.2007.04.003

Cerralbo, P. Grifoll, M., Espino, M. 2015a. Hydrodynamic response in a microtidal and shallow bay under energetic wind and seiche episodes, *Journal of Marine Systems*, Volume 149, 2015, Pages 1-13, ISSN 0924-7963, <http://dx.doi.org/10.1016/j.jmarsys.2015.04.003>.

Cerralbo, P., Grifoll, M., Moré, J., Bravo, M., Afif, A.S., Espino, M. 2015b. Wind variability in a coastal area (Alfacs Bay , Ebro River delta). *Adv. Sci. Res.* 12, 11–21. doi:10.5194/asr-12-11-2015

Cerralbo, P., Espino, M., Grifoll, M. 2016. Modeling circulation patterns induced by spatial cross-shore wind variability in a small-size coastal embayment, *Ocean Modelling*, Volume 104, Pages 84-98, ISSN 1463-5003, <https://doi.org/10.1016/j.ocemod.2016.05.011>.

Costa, P., Gómez, B., Venâncio, A., Pérez, E., & Pérez-Muñuzuri, V. 2012. Using the Regional Ocean Modelling System (ROMS) to improve the sea surface temperature predictions of the MERCATOR Ocean System. *Scientia Marina*, 76(S1), 165-175.

Darbra, R. M., Pittam, N. Royston, K. A. Darbra, J. P. Journee, H., 2009. Survey on environmental monitoring requirements of European ports. *Journal of Environmental Management* 90, 1396-1403.

deCastro M, M. Gómez-Gesteira, R. Prego, R. Neves. 2003. Wind influence on water exchange between the ria of Ferrol (NW Spain) and the shelf, *Est. Coast. Shelf Sci.* 56 1055-1064.

deCastro M., M. Gómez-Gesteira, R. Prego, I. Álvarez. 2004. Ria-ocean exchange driven by tides in the Ria of Ferrol (NW Spain), *Est. Coast. Shelf Sci.* 61 15-24.

Di Lorenzo E., N. Schneider, K. M. Cobb, P. J. S. Franks, K. Chhak, A. J. Miller, J. C. McWilliams, S. J. Bograd, H. Arango, E. Curchitser, T. M. Powell, and P. Rivière. 2008. North Pacific Gyre Oscillation links ocean climate and ecosystem change, *Geophys. Res. Lett.*, 35, L08607, doi:10.1029/2007GL032838.

Djath B, A Melet, J Verron, J -M Molines, B Barnier, L Gourdeau & Laurent Debreu. 2014. A 1/36° model of the Solomon Sea embedded into a global ocean model: On the setting up of an interactive open boundary nested model system. *Journal of Operational Oceanography* Vol. 7 , Iss. 1, 34-36

EC Directive 2000/60/EC, 2000. Directive of the European Parliament and of the Council on Establish a framework for Community Actions in the Field of water Policy.

Emery, W. J., and R. E. Thomson. 2004: Data Analysis Methods in Physical Oceanography. 2nd ed. Elsevier, 638 pp.

EU EuroStat (2017). EuroStat explaining Statistics: Maritime ports freight and passenger statistics. http://ec.europa.eu/eurostat/statistics-explained/index.php/Maritime_ports_freight_and_passenger_statistics

Gómez Lahoz, M. and Carretero Albiach J C. 1997. A two-way nesting procedure for the WAM model: Application to the Spanish coast. Transactions of the American Society of Mechanical Engineers, 119, pp. 20–24.

Gómez Lahoz M and Carretero Albiach J.C. 2005. Wave forecasting at the Spanish coasts. Journal of Atmospheric and Ocean Science. Vol. 10, No. 4, December 2005, 389–405 DOI: 10.1080/17417530601127522

Gopalakrishnan G, A F Blumberg. 2012 Assimilation of HF radar-derived surface currents on tidal-timescales. Journal of Operational Oceanography Vol. 5 , Iss. 1. <http://dx.doi.org/10.1080/1755876X.2012.11020133>

Grifoll, M., Jordà, G., Romo, J., Espino, M., G.-Sotillo, M.A. 2011. A Management system for accidental water pollution risk in a harbour: the Barcelona case study. Journal of Marine Systems 88, 60-73.

Grifoll, M., Jordà, G., G.Sotillo, M., Ferrer, L., Espino, M., Sánchez-Arcilla, A.,
Álvarez-Fanjul, E. 2012. Water circulation forecasting in Spanish harbours. *Scientia
Marina*, 76S1, 45-61.

Grifoll, M., V. Gracia, A. Aretxabaleta, J. Guillén, M. Espino, and J. C. Warner. 2014.
Formation of fine sediment deposit from a flash flood river in the Mediterranean Sea, *J.
Geophys. Res. Oceans*, 119, 5837–5853, doi:10.1002/2014JC010187.

Guo, W., Hao, Y., Zhang, L., Xu, T., Ren, X., Cao, F., & Wang, S. 2014. Development
and application of an oil spill model with wave–current interactions in coastal areas.
Marine pollution bulletin, 84(1), 213-224.

Hernández, F., Blockley, E., Brassington, G.B., Davidson, F., Divakaran, P., Drévilleon,
M., Ishizaki, S., Sotillo, M.G., Hogan, P.J., Lagemaa, P., Levier, B., Martin, M.,
Mehra, A., Mooers, C., Ferry, N., Ryan, A., Regnier, C., Sellar, A., Smith, G.C.,
Sofianos, S., Spindler, T., Volpe, G., Wilkin, J., Zaron, E.D. and Zhang, A. 2015.
Recent progress in performance evaluations and near real-time assessment of
operational ocean products. *Journal of Operational Oceanography*, Vol. 8, No. S2,
pages 221-238.

Juza, M., Mourre, B., Renault, L., Gómara, S., Sebastián, K., Lora, S., , J. P.

Beltran, B. Frontera, B. Garau, C. Troupin, M. Torner, E. Heslop, B. Casas, R. Escudier,
G. Vizoso and J. Tintoré ... & Torner, M. 2016.. SOCIB operational ocean forecasting
system and multi-platform validation in the Western Mediterranean Sea. *Journal of
Operational Oceanography*, 9(sup1), s155-s166.

Kärnä T., A.M. Baptista, J.E. Lopez, P.J. Turner, C. McNeil, T.B. 2015. Sanford. Numerical modeling of circulation in high-energy estuaries: A Columbia River estuary benchmark Ocean Modelling 88 54–71

V.H. Kourafalou, P. De Mey, J. Staneva, N. Ayoub, A. Barth, Y.Chao, M. Cirano, J. Fiechter, M. Herzfeld, A. Kurapov, A.M. Moore, P. Oddo, J. Pullen, A. van der Westhuysen, R.H. Weisberg. 2015. Coastal Ocean Forecasting: science foundation and user benefits, Journal of Operational Oceanography, 8:sup1, s147-s167.

Korres G, K Nitti, L Perivoliotis, K Tsiaras, A Papadopoulos, G Triantafyllou, I Hoteit & King Abdullah. 2010. Forecasting the Aegean Sea hydrodynamics within the POSEIDON-II operational system, Journal of Operational Oceanography, 3:1, 37-49, DOI: 10.1080/1755876X.2010.11020112

Lorente, P., Piedracoba, S., Soto-Navarro, J., Alvarez-Fanjul, E. 2015a. Evaluating the surface circulation in Ebro Delta (NE Spain) with quality controlled High-Frequency radar measurements. Ocean Science, Vol. 11, pp. 921-935.

Lorente, P; Piedracoba, S; Fanjul, E Alvarez. 2015b. Validation of high-frequency radar ocean surface current observations in the NW of the Iberian Peninsula, Continental Shelf Research, 92,, 1-15

Lorente, P., S. Piedracoba, M. García Sotillo, R. Aznar, A. Amo-Baladrón, A., J. and E. Álvarez-Fanjul. 2016. Ocean model skill assessment in the NW Mediterranean using multi-sensor data Journal of Operational oceanography Vol. 9 , Iss. 2.

Lyard, F., F. Lefèvre, T. Letellier and O. Francis. Modelling the global ocean *tides*: A modern insight from *FES2004*, Ocean Dynamics, 56, 394-415, 2006. DOI : [10.1007/s10236-006-0086-x](https://doi.org/10.1007/s10236-006-0086-x)

Malanotte-Rizzoli, P., Hedstrom, K., Arango, H., & Haidvogel, D. B. 2000. Water mass pathways between the subtropical and tropical ocean in a climatological simulation of the North Atlantic Ocean circulation. Dynamics of Atmospheres and Oceans, 32(3), 331-371.

Marta-Almeida, M., Reboreda, R., Rocha, C., Dubert, J., Nolasco, R., Cordeiro, N., Peliz, A. 2012. Towards operational modeling and forecasting of the Iberian shelves ecosystem. PloS one, 7(5), e37343.

Mestres M., M. Grifoll, A. Sánchez-Arcilla. 2016. Analysis of current intensification in the Northwest Mediterranean shelf, Continental Shelf Research, Volume 114, Pages 29-40, ISSN 0278-4343, <http://dx.doi.org/10.1016/j.csr.2015.12.011>.

Penven, P., Debreu, L., Marchesiello, P., & McWilliams, J. C. 2006. Evaluation and application of the ROMS 1-way embedding procedure to the central California upwelling system. Ocean Modelling, 12(1), 157-187.

Pérez B, E Álvarez Fanjul, S Pérez, M de Alfonso & J Vela. 2013. Use of tide gauge data in operational oceanography and sea level hazard warning systems. Journal of Operational Oceanography Vol. 6 , Iss. 2. Pp 1-18.

Puig M., A Michail, C Wooldridge, R Mi Darbra. 2017. Benchmark dynamics in the environmental performance of ports. *Marine Pollution Bulletin*. Vol 121, Issues 1–2, Pages 111-119. <https://doi.org/10.1016/j.marpolbul.2017.05.021>

Ràfols, L., Pallares, E., Espino, M., Grifoll, M., Sánchez-Arcilla, A., Bravo, M., Sairouni, A. 2017. Wind-Wave Characterization in a Wind-Jet Region: The Ebro Delta Case. MDPI AG.

Salat, J., M. A. Garcia, A. Cruzado, A. Palanques, L. Arin, D. Gomis, J. Guillen, A. de Leon, J. Puigdefabregas, J. Sospedra, Z. R. Velasquez. 2002. Seasonal changes mass structure and shelf slope at the Ebre Shelf (NW Mediterranean), *Cont. Shelf Res.*, 22, 327–348.

Sánchez-Garrido, J.C., García-Lafuente, J., Alvarez-Fanjul, E., García-Sotillo, M., de los Santos, F.J. 2013. What does cause the collapse of the Western Alboran Gyre? Results of an operational ocean model. *Prog. Oceanogr.* 116, 142–153.

<http://dx.doi.org/10.1016/j.pocean.2013.07.002>

Shchepetkin, A. F., & McWilliams, J. C. 2005. The regional oceanic modeling system (ROMS): a split-explicit, free-surface, topography-following-coordinate oceanic model. *Ocean Modelling*, 9(4), 347-404.

Sotillo M G, E. Alvarez Fanjul, S. Castanedo, A.J. Abascal, J. Menendez, M.

Emelianov, R. Olivella, E. García-Ladona, M. Ruiz-Villarreal, J. Conde, M. Gómez, P.

Conde, A.D. Gutierrez, R. Medina. 2008. Towards an operational system for oil spill

forecast in Spanish coastal waters: initial development and implementation test. *Marine Pollution Bulletin*. (Doi: 10.1016/j.marpolbul.2007.12.021), 56 686-703

Sotillo M.G., S. Cailleau, P. Lorente, B. Levier, R. Aznar, G. Reffray, A. AmoBaladrón, J. Chanut, M. Benkiran & E. Alvarez-Fanjul. 2015. The MyOcean IBI Ocean Forecast and Reanalysis Systems: operational products and roadmap to the future Copernicus Service, *Journal of Operational Oceanography*, 8:1, 63-79, DOI: 10.1080/1755876X.2015.1014663

Sotillo MG, A Amo-Baladrón, E Padorno, E Garcia-Ladona, A Orfila, P Rodríguez-Rubio, D Conti, JA Jiménez Madrid, F J de los Santos, E Alvarez Fanjul. 2016. How is the surface Atlantic water inflow through the Gibraltar Strait forecasted? A lagrangian validation of operational oceanographic services in the Alboran Sea and the Western Mediterranean. *Deep Sea Research II*. Vol 133. pp 100-117

Valdor P. F., A G. Gómez, A. Puente. 2015. Environmental risk analysis of oil handling facilities in port areas. Application to Tarragona harbor (NE Spain). *Marine Pollution Bulletin*. Vol 90, Issues 1–2, Pages 78-87.

<https://doi.org/10.1016/j.marpolbul.2014.11.018>

Wang, P., Song, Y. T., Chao, Y., & Zhang, H. 2005. Parallel computation of the regional ocean modeling system. *The International Journal of High Performance Computing Applications*, 19(4), 375-385.

Warner, J. C., Sherwood, C. R., Arango, H. G., & Signell, R. P. 2005. Performance of four turbulence closure models implemented using a generic length scale method. *Ocean Modelling*, 8(1), 81-113.

Warner, J. C., Armstrong, B., He, R., & Zambon, J. B. 2010. Development of a coupled ocean–atmosphere–wave–sediment transport (COAWST) modeling system. *Ocean modelling*, 35(3), 230-244.

Figure Captions

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-customized alert thresholds at each point.

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).

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.

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 hours of forecast from the rest of the forecast horizon (until +72h), 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 Day of hindcast).

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. In the representation of the CST-BAR domain currents from the CMEMS-IBI velocities (arrows in magenta) are also depicted.

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) 30h 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.

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.

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 summarizing 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

Figure 9: Multiparameter validation of SAMOA systems. Model solution (red lines) against in situ observation (blue dots). 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.

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).

Figures.

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-customized alert thresholds at each point.

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).

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.

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 hours of forecast from the rest of the forecast horizon (until +72h), 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 Day of hindcast).

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. In the representation of the CST-BAR domain currents from the CMEMS-IBI velocities (arrows in magenta) are also depicted.

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) 30h 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.

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.

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 summarizing 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

Figure 9: Multiparameter validation of SAMOA systems. Model solution (red lines) against in situ observation (blue dots). 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.

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).