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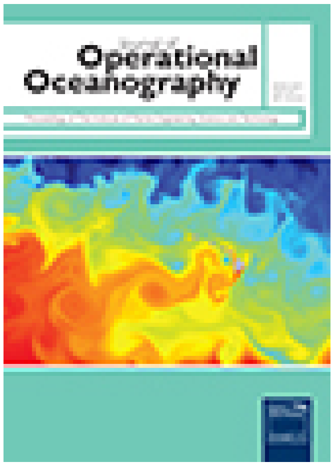

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Journal of Operational Oceanography
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tjoo20

The MyOcean IBI Ocean Forecast and Reanalysis Systems: operational products and roadmap to the future Copernicus Service

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Published online: 02 Apr 2015.

To cite this article: M. G. Sotillo, S. Cailleau, P. Lorente, B. Levier, R. Aznar, G. Reffray, A. Amo-Baladrón, 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, DOI: 10.1080/1755876X.2015.1014663

To link to this article: http://dx.doi.org/10.1080/1755876X.2015.1014663

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The MyOcean IBI-MFC (Monitoring & Forecasting Centre) has been providing continuous daily ocean model estimates and forecasts for the Iberia–Biscay–Ireland (IBI) regional seas since 2011. The operational IBI Ocean Forecast Service is based on a NEMO model application that includes high-frequency processes required to characterize regional scale marine processes. Since June 2014, a new IBI reanalysis, comprising both physical and biogeochemical components, covering the time period 2002–2012 has also been available. This paper provides an end-to-end description of these IBI model systems and presents a summary of the scientific validation assessments carried out with the derived operational products. The validation statistics suggest that the systems capture major synoptic and mesoscale ocean circulation features observed in the IBI region. Finally, an IBI roadmap towards the future EU Copernicus Service is outlined, providing a look ahead to future IBI model and data-assimilation developments and operational novelties.

Introduction

The ocean dynamics plays a major role shaping impacts of present environmental activities associated with different social-economic sectors related to the sea. There is growing interest in monitoring the marine environment, accompanied by a maximum relevance in knowing its time evolution, which is serving as a stimulus for the scientific development of models that allow marine prediction and also an understanding of the ocean dynamics. In recent times, there have been major scientific advances in the field of oceanography. More specifically, noticeable efforts have been devoted to manage the implementation of operational ocean forecasting systems (OOFSs) in order to assess the real state and dynamics of the seas and to provide predictions on various time and spatial scales. These operational oceanographic systems and products are useful not only for the scientific oceanographic community but also for other potential end users and fields (i.e. fisheries, aquaculture, navigation and ship routing, search and rescue operations, accidental oil spill preparedness and response, harbor operations and design, coastal management, tourism, etc.), thus unequivocally proving their contribution to the global societal benefit (Chassignet & Verron, 2006).

As a response to this growing demand of ocean-related information, arising from a variety of disciplines (such as scientific research on marine ecosystems, monitoring of seawater quality, and decision-making support for marine safety and coastal management), the field of physical oceanography has undergone a rapid maturation process (Martinho et al. 2012). Brasseur et al. (2005) points out that such maturation process can be feasible owing to the following factors:

- development of numerical solutions and improvement of modelling algorithms to simulate ocean circulation;
- a facilitated access to high computational resources together with significant advances in data storage leads to more ambitious, in terms of resolution and algorithms, model performance;
- a coordinated international cooperation to deploy permanent ocean observing networks that collect data in real and near-real time from different measurement platforms (e.g. moored or drifter buoys, tide gauges, satellites, or remote earth-based platforms such as coastal high-frequency radars);
- an enhanced combined use of observational data sources and modelling solutions, resulting in progress in data-assimilation techniques.

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Following these premises, the MyOcean initiative arises as a strong collaborative action to build the European Marine Core Service. The MyOcean (2009–2012), MyOcean2 (2012–2014), and MyOcean Follow-On (October 2014 to March 2015) projects, respectively, funded by the EU's Seventh Framework Programme for Research (FP7 2007–2013) and HORIZON 2020 (EU Research and Innovation Programme 2014–2020) have been designed to prepare and to lead the demonstration phases of the future Copernicus Marine Environment Monitoring Service. The latter is meant to be fully functional from 2015 onwards and aims to be a noticeable upgrade in the European operational oceanography capabilities.

MyOcean Services provide state-of-the-art generic information through different Monitoring & Forecasting Centres (MFCs) on seven areas: global ocean, Arctic, Baltic, Mediterranean, Black Sea, European northwest shelves, and the Iberia–Biscay–Ireland (IBI) region, which is the responsibility of the MyOcean IBI-MFC.

This northeast Atlantic IBI region covers areas of important economic and social activities that include fisheries, transportation of oil and gas, commercial ship traffic, coastal management, coastal protection, and energy production. The availability of validated estimates and forecasts of marine variables in this coastal region is expected to boost the ongoing development of user-driven activities and applications.

From a pure physical oceanographic point of view, the geographical domain covered by the IBI-MFC is a very complex region (Figure 1), marked by a generally steep slope separating the deep ocean from the shelf. The western, and deeper, side of the IBI domain is affected by main large-scale currents, mainly the closure of the North Atlantic Drift, here split into two major branches, the major one continuing north along the northwestern European shelves (NAC and NADC) and the other, the Azores Current, that going southeast and has continuity in the Canary Current (Mason et al. 2005). On the other hand, along the slope, a poleward slope current flows in the subsurface; it is observed as far north as Ireland (White & Bowyer, 1997). Instabilities in this slope current favour the occurrence of slope water oceanic eddies, along the northern Iberian coast (Pingree & Le Cann 1992, Caballero et al. 2014). On the continental shelves, intense tidal motions provide the dominant source of energy (Álvarez-Fanjul et al. 1997). Noticeable tidal mixing fronts occur on the most energetic tidal areas of the IBI region (i.e. English Channel, Celtic and Irish Sea). Shelf and coastal areas of the region are also affected by strong storm surges (Perez et al. 2012). Along the western Iberian and African coasts, strong summer seasonal upwelling conditions occur. Finally, contributing to this complex and variable circulation system, the IBI area has one of the most singular spots of the oceans: the Gibraltar Strait, where exchanges between the Atlantic and Mediterranean basins occur. The denser Mediterranean Intermediate Water (MIW) enters the region at the Strait, plunging to its level of neutral buoyancy, at 1000 m depth. With a characteristically high salinity and temperature signature, MIW spreads far into the North Atlantic, with a portion also forming a poleward undercurrent that flows along the slope of the Iberian Peninsula (El-Geziry & Bryden, 2010).

From a modelling point of view, this remarkable variety of processes and scales is, however, particularly challenging. The IBI area has been the subject of numerous hydrodynamic modelling studies of increasing complexity and sophistication. The MyOcean IBI-MFC has used a 3D baroclinic hydrodynamic model application evolved from previous research tools into an operational forecast system (Cailleau et al. 2010) to provide continuous daily ocean model estimates and forecasts for the IBI area since 2011. The operational IBI Ocean Forecast Service is based on a Nucleus for European Modelling of the Ocean (NEMO) model application that includes high-frequency processes required to characterize regional-scale marine processes. The current 1/36° eddy-resolving application is forced with up-to-date high-frequency meteorological forecasts from the European Centre of Medium Weather Forecast (ECMWF) and nested in the MyOcean GLOBAL system, having also an explicit representation of tidal motions. One particular aspect in the present model configuration is the relatively high (2–3 km) horizontal resolution used. This clearly pushes the model into the sub-mesoscale-permitting regime over much of the domain and allows a significant part of the internal wave spectrum to be resolved.

For a correct ocean forecasting, it is mandatory to incorporate actual sea-state information into the system via data assimilation. In global ocean and basin scale modelling, data assimilation has proved an invaluable component for operational forecasting (Bell et al. 2000; Drevillon et al. 2008). Historically, for the shelf seas, however, the necessary inclusion of shorter temporal and spatial scale processes, in particular in relation to the interaction of the tides and the shelf, discouraged the widespread use of data assimilation in operational systems (Annan & Hargreaves, 1999). However, progress in this issue has been made in recent years, and MyOcean operational regional modelling systems are progressively incorporating successfully data-assimilation schemes (O'Dea et al. 2012).

The MyOcean IBI-MFC incorporates actual sea-state information thanks to the weekly 3D restart architecture from a global analysis. Nevertheless, progress is being made towards a direct data-assimilation scheme in the IBI forecast model system in order to upgrade the system and to enhance its capabilities with the generation of regional analysis. As a first outcome of these R&D activities, a regional IBI Ocean Physical Reanalysis system was implemented. This system, described later in this paper, was used to generate a IBI reanalysis database, covering the so-called 'altimetric' decade (2002–2012). Their

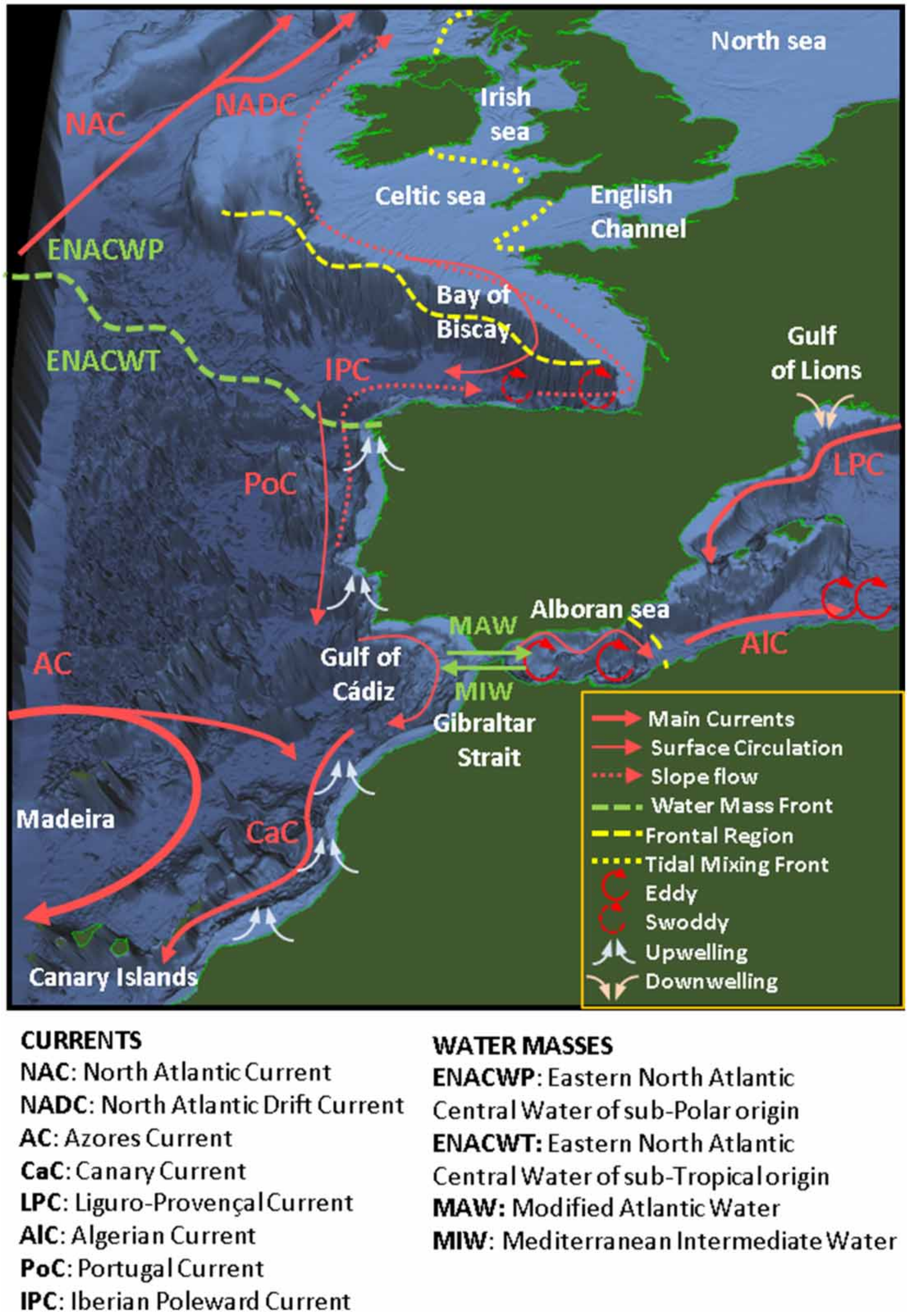


Figure 1. Bathymetry and schematic description of main oceanographic features in the IBI region.

products (IBI-PHY-REA) have been available to users through MyOcean since June 2014. Together with these physical ocean reanalysis products, a modelled biogeochemical state of the ocean for the IBI areas was generated through a Pelagic Interaction Scheme for Carbon and Ecosystem Studies (PISCES) model run coupled in the IBI-REA physical run. This IBI biogeochemical hindcast run and their derived products, also described in the paper, come to fill the gap in terms of regional biogeochemical product availability in the area, meeting end-user needs.

A complete view of currently existing IBI model systems together with the operational products generated by them and delivered to users through MyOcean interfaces is summarized in Figure 2. A detailed description of each IBI model application is presented in the paper, including IBI shelf-specific developments of the physical NEMO

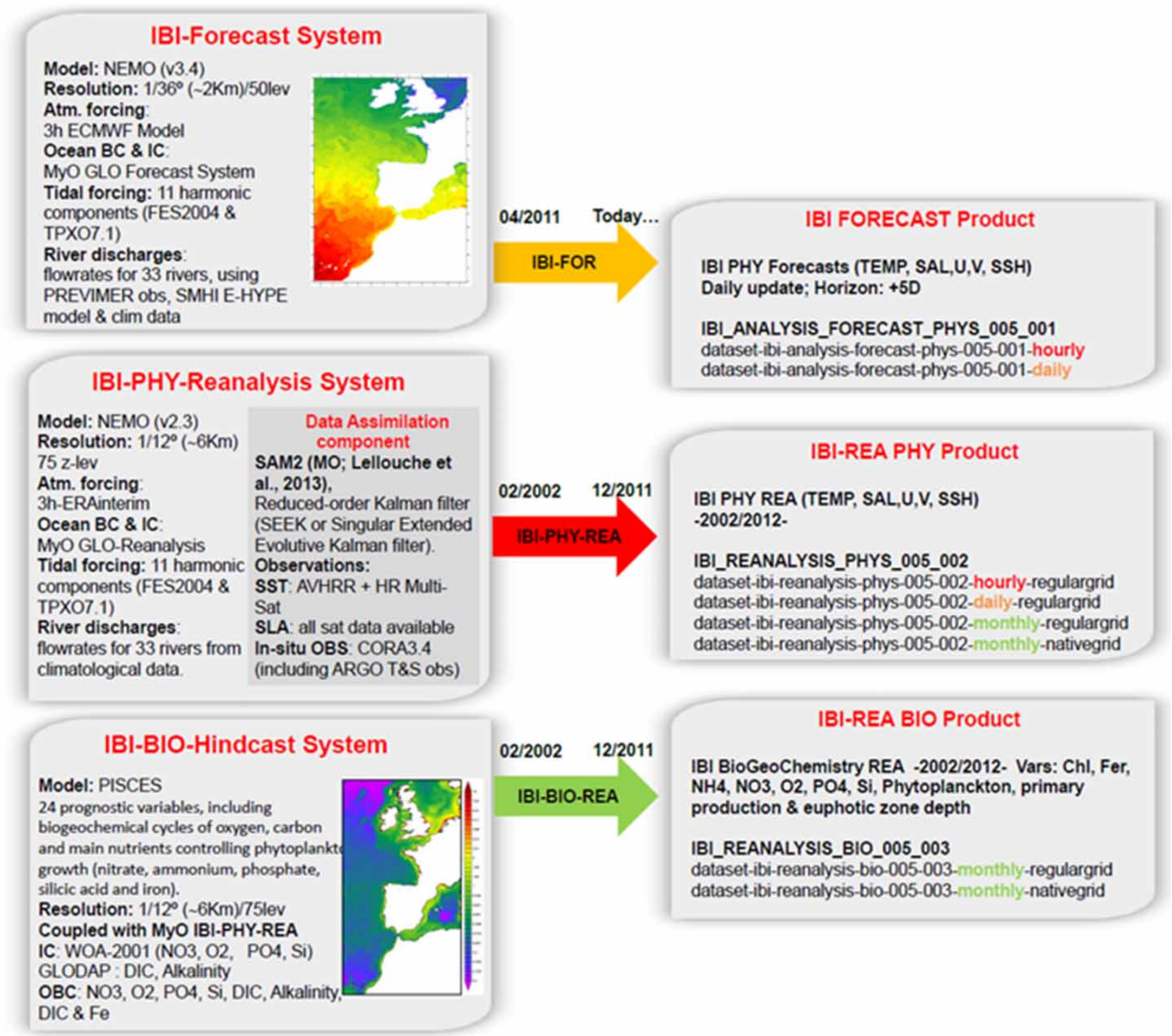


Figure 2. IBI-MFC: summary of model systems and list of operational products (and their respective datasets) generated by them and delivered through the usual MyOcean user interfaces. The main characteristics of the systems are listed. Temporal coverage and time frequency of the IBI products available through www.myocean.eu are also detailed.

model together with main characteristics of the data-assimilation scheme used in the physical ocean reanalysis and the main features of the biogeochemical model used in the long-term IBI biogeochemical hindcast run.

This paper also attempts to give a broad-brush account of the scientific validation performed on the IBI model products. Nowadays, operational oceanography delivers routine marine products to an ever-widening community of users and stakeholders, and the majority of them require reliable information, pushing forecast centres towards a more efficient evaluation of the product quality (Hernandez et al. 2014). An overview of the metrics defined to assess a wider range of ocean parameters from the IBI modelling systems is presented here. The current status of their implementation in near real-time and delayed mode through the IBI scientific validation tool, North Atlantic Regional Validation (NARVAL), is also provided.

The paper is organized as follows: first, an end-to-end description of the IBI Ocean Forecast System (IBI-FOR) is provided. Then, the systems used to generate the IBI reanalysis products are outlined together with a description of both the physical component and the biogeochemical component (IBI-REA-PHY and IBI-REA-BIO, respectively). Then, a detailed discussion is provided of the IBI product quality and ability to describe the complex dynamics of the region through their scientific validation. Finally, future areas of development are examined, with an outline of a roadmap summarizing the short- and middle-term plans to update IBI-MFC services within the framework of the future Copernicus Service.

IBI regional ocean forecast service

The objective of the service is to produce a real-time, short-term (5-day) forecast of currents and other oceanographic variables, such as temperature, salinity, and sea level, as well as to obtain a better understanding of the ocean dynamics in the IBI-region Atlantic waters.

Physical model

The IBI forecast system is based on a NEMO-v3.4 model application driven by high-frequency meteorological, oceanographical, and hydrological forcing data. The NEMO model (Madec 2008) solves the three-dimensional finite-difference primitive equations in spherical coordinates discretized on an Arakawa-C grid and, in the present implementation, 50 geopotential vertical levels (z coordinate). It assumes hydrostatic equilibrium and Boussinesq approximation, and makes use of a non-linear split explicit free surface to properly simulate fast external gravity waves such as tidal motions. Partial bottom cell representation of the bathymetry allows an accurate representation of the steep slopes characteristic of the area. The model grid is a subset of the Global 1/12° ORCA tripolar grid used by the parent system (MyOcean Global) that provides initial and lateral boundary conditions but refined at 1/36° horizontal resolution (~2 km). Vertical mixing is parameterized according to a k–ε model implemented in the generic form proposed by Umlauf and Burchard (2003) including surface wave breaking induced mixing, while tracers and momentum subgrid lateral mixing is parameterized according to bilaplacian operators.

The IBI run is forced with 3-hourly atmospheric fields (10-m wind, surface pressure, 2-m air temperature, relative humidity, precipitations, shortwave and longwave radiative fluxes) provided by ECMWF. CORE empirical bulk formulae (Large & Yeager 2004) are used to compute latent sensible heat fluxes, evaporation, and surface stress. Solar penetration is parameterized according to a two-band exponential scheme with monthly climatological attenuation coefficients built from Seawifs satellite ocean colour imagery. Lateral open boundary data (temperature, salinity, velocities, and sea level) are interpolated from the daily outputs from the MyOcean Global eddy resolving system. These are complemented by 11 tidal harmonics (M2, S2, N2, K1, O1, Q1, M4, K2, P1, Mf, Mm) built from FES2004 (Lyard et al. 2006) and TPXO7.1 (Egbert & Erofeeva 2002) tidal model solutions. Atmospheric pressure component, missing in the large-scale parent system sea-level outputs, is included assuming pure isostatic response at open boundaries (inverse barometer approximation). Freshwater river discharge inputs are implemented as a lateral open boundary condition for 33 rivers. Flow-rate data are based on a combination of daily observations, simulated data (from SMHI E-HYPE hydrological model (http://e-hypeweb.smhi.se) and climatology (monthly climatological data from GRDC (http://www.bafg.de/GRDC) and French ‘Banque Hydro’ dataset (http://www.hydro.eaufrance.fr/).

The downscaling methodology is inherited from the strategy developed for the ESEOAT system (Sotillo et al. 2007). Every week, on Thursday (D0), the regional system is initialized 14 days in the past from analysed outputs taken from the MyOcean Global system and bilinearly interpolated on the refined grid. The model is then integrated until D0 to allow the spin-up of small scales and the convergence of physical processes that are not resolved by the parent system. From the analysed output at D0 until D0 + 7 days, seven runs of 5-day forecasts plus a hindcast of the previous day with refreshed atmospheric forcing are performed.

Operational implementation

The IBI-MFC Forecast System (IBI-FOR) consists of a set of two twin applications: the nominal one, running at Puertos del Estado (PdE) and a twin backup system at Mercator Ocean (MO). The operational suites of the IBI-FOR system perform the following steps for each daily cycle:

(1) Daily acquisition and quality control of input forcing data required to run the IBI system together with those observations gathered to be used later in the online validation of the IBI products.

(2) Fluxes are processed and interpolated onto the model grid from the ECMWF inputs. Lateral boundary data produced by the MyOcean Global model are processed, together with the river freshwater input files, which are generated combining three different sources: observations, model estimates, and climatology.

(3) Once a day, the model is integrated forward, starting at T – 24 h from a re-start file generated by a previous IBI run until T + 120 h. On Wednesday afternoon, a 14-day hindcast integration (initialized and driven by 3D analysis from the MyOcean Global system) is run. This hindcast run generates a re-start file, which is used for initializing the next-day forecast run. In this way, the IBI system, with no direct data-assimilation scheme, can incorporate actual state ocean information already included in the global analysis. The 2-week spin-up process adjusts the internal dynamics of the system at short time-scales and triggers the small-scale physical processes that are not resolved by the global parent system, including tides.

(4) The best estimates (outputs from T – 24 to T + 0) together with the 5 days of forecast outputs are bilinearly interpolated onto a regular longitude/latitude 1/36° grid and post-processed to be written out in netcdf format. Both raw model outputs (together

with the inputs required to run the model) and the final IBI products files generated are stored.

(5) IBI products from the forecast bulletin of the day are made available online before 1200 UTC through the MyOcean User Interfaces.

(6) Finally, the NARVAL tool is launched to generate scientific validation metrics required to evaluate the consistency of the IBI products of the day. As will be described later, NARVAL computes, periodically, validation metrics on a monthly, seasonal, and yearly basis.

The MyOcean IBI-FOR system became fully operational in April 2011. From this time, IBI ocean forecast products are daily updated and made available to any user through the MyOcean web portal. Both visualization and downloading capabilities of IBI datasets are provided. Any user can have access to variables such as temperature, salinity, sea level, and currents on daily averages for the whole water column, as well as hourly averages for surface variables and barotropic currents. IBI best estimates from April 2011 (in the same hourly and daily average basis than is delivered in the forecast bulletin of the day) are made available as a historical view of the physical state of the ocean at the IBI region.

Regional ocean reanalysis for the IBI area

Since June 2014, the MyOcean IBI-MFC delivers a complete database of regional reanalysis products for the IBI area covering the 'altimetric' decade (2002–2012). The database provides a complete view of the ocean state including both physical and biogeochemical parameters. A brief description of the model application and the data-assimilation scheme used to generate the reanalysis of the physical component is provided. Likewise, the model set-up used to generate the biogeochemical hindcast run is described.

IBI physical ocean reanalysis system

A high-resolution 1/12° reanalysis comprising physical variables and covering the altimetric decade (2002–2012) is provided by the MyOcean IBI-MFC for the IBI region. Physical IBI-REA products were generated through an ocean reanalysis system based on a NEMO model application analogous to that currently used to produce the daily IBI ocean forecast products. The reanalysis model system (Levier et al. 2014) is also a free-surface application and includes the same tidal forcing as the IBI forecast one. Horizontal resolution decreases in the IBI-REA system (1/12° ~ 6 km), whereas the vertical one is increased up to 75 z-levels. A baroclinic time step of 450 s is used. The reanalysis run was forced with ECMWF ERA-Interim 3-h atmospheric data. Riverine inputs are implemented as lateral point sources with flow rates based on climatological values. Boundary conditions were imposed from the MyOcean GLOBAL reanalysis run. A similar data-assimilation scheme to that used in this MyO GLOBAL reanalysis was applied. The data-assimilation component SAM2 (MO assimilation system, Lellouche et al. 2013) is based on a reduced-order Kalman filter (the Singular Extended Evolutive Kalman filter). An Incremental Analysis Updates (IAU) method is used to apply the increments in the system. The error statistics are represented in a subspace spanned by a small number of dominant 3D error directions. A 3D-Var scheme corrects for the slowly evolving large-scale biases in temperature and salinity. The data-assimilation system allows the model to be constrained in a multivariate way with sea surface temperature (AVHRR + multi-satellite high resolution), together with all available satellite sea level anomalies, and with in situ observations from the CORA3.4 database, including ARGO float temperature and salinity measurements.

The first assimilated observations are altimetry tracks from satellite with a radar altimeter onboard (TOPEX, JASON, ERS, ENVISAT, GFO). Along each track, only one point over three is conserved to avoid redundant information, which yields one observation of sea-level height every 21 km. Moreover, observations along the satellite tracks are smoothed by several altimetry corrections (Le Traon et al. 2001), and there is no independent information in the non-conserved points. However, an inconsistency exists between the sea-level height computed by NEMO and altimeter data coming from SSALTO/DUACS (http://www.jason.oceanobs.com/html/donnees/duacs/welcome_uk.html). This difference comes from recent corrections applied to altimeter tracks. These corrections combine the high-frequency signal of a barotropic, non-linear, and time-stepping model (MOG2D) forced by pressure and wind, with the low-frequency solution derived from a simpler inverse barometer model. As the model is forced by atmospheric pressure, winds, and tides, generating a unique solution in the entire frequency domain, this specific method of correction must be considered when dealing with the data to be assimilated.

The Sea Surface Temperature (SST) maps assimilated result from an objective analysis of various satellite data sets. Reynolds 1/4° product is distributed on a 0.25 × 0.25° geographical grid, but the SST does not contain signals with spatial scales shorter than ~1°. As the IBI-REA model grid is 1/12°, it is required to slightly 'smooth' the IBI model SST in order to obtain an appropriate model equivalent for the AVHRR-only SST field. The observation operator in that case is a horizontal smoother applied on the model first-level temperature field. The smoother consists of an iterative method (60 iterations with a Shapiro filter $\alpha = 1/2$) applied to the model SST.

With respect to the ARGO data, the observed profiles are interpolated before being assimilated onto model levels by using a spline function. If the distance between two consecutive data depths is less than the model level thickness, the spline interpolation on the model level is not used. No extrapolation is performed either at the top or at the bottom of the profiles.

The resulting MyOcean product (IBI_REANALYSIS_PHYS_005_002) consists of 3D monthly and daily mean fields of temperature, salinity, sea surface height, zonal, and meridional velocity components. Hourly means of surface fields such as sea surface height, surface temperature, and currents, together with barotropic velocities are also provided.

Biogeochemical ocean hindcast system

IBI products from a regional high-resolution 1/12° non-assimilative biogeochemical hindcast run covering the altimetric decade (2002–2012) are provided by the MyOcean IBI-MFC for the IBI area. The biogeochemical state of the ocean was simulated through a PISCES model hindcast run online coupled with the IBI physical ocean reanalysis previously described. This PISCES Biogeochemistry model (Aumont, 2012) is a model of intermediate complexity and is part of NEMO modelling platform (Aumont & Bopp, 2006). The IBI PISCES model application (Levier et al. 2014) integrates 24 prognostic variables, simulating biogeochemical cycles of oxygen, carbon, and the main nutrients controlling phytoplankton growth (nitrate, ammonium, phosphate, silicic acid, and iron). The model distinguishes between four plankton functional types based on size: two phytoplankton groups (small nanophytoplankton and large diatoms) and two zooplankton groups (small microzooplankton and large mesozooplankton). Prognostic variables of phytoplankton are total biomass in C, Fe, Si (for diatoms) and chlorophyll, and hence the Fe/C, Si/C, and Chl/C ratios are variable. For zooplankton, all these ratios are constant, and total biomass in C is the only prognostic variable. The bacterial pool is not explicitly modelled. PISCES distinguishes between three non-living pools for organic carbon: small particulate organic carbon, large particulate organic carbon, and semi-labile dissolved organic carbon. While the C/N/P composition of dissolved and particulate matter is tied to Redfield stochiometry, the iron, silicon, and carbonate contents of the particles are computed prognostically. Next to the three organic detrital pools, carbonate and biogenic siliceous particles are modelled. Besides, the model simulates dissolved inorganic carbon and total alkalinity. In PISCES, phosphate and nitrate + ammonium are linked by a constant Redfield ratio (C/N/P = 122/16/1), but cycles of phosphorus and nitrogen are decoupled by nitrogen fixation and denitrification. The distinction of two phytoplankton size classes, along with the description of multiple nutrient co-limitations, allows the model to represent ocean productivity and biogeochemical cycles across major biogeographic ocean provinces (Longhurst, 1998).

The biogeochemical model PISCES was coupled online with the IBI NEMO run used to generate the IBI ocean physic reanalysis. The time scheme of the biogeochemistry model is Eulerian, whereas in the physical IBI run, a leap-frog scheme is applied. Thus, for numerical conservation aspects, the PISCES model was called every two time-steps of the IBI NEMO ocean physic integration, the bio model time step then being 900 s. The advection scheme is the same as those used in the physical part.

Regarding initial and boundary conditions, the IBI biogeochemical PISCES model application is initialized with data from the World Ocean Atlas 2001 for nitrate, phosphate, oxygen, and silicate (Conkright et al. 2002), with GLODAP climatology including anthropogenic CO_2 for dissolved inorganic carbon and alkalinity (Key et al. 2004) and, in the absence of corresponding data products, with model fields for dissolved iron and dissolved organic carbon. Boundary fluxes account for nutrient supply from three different sources: atmospheric deposition (Aumont et al. 2008), rivers for nutrients, dissolved inorganic carbon and alkalinity (Ludwig et al. 1996), and inputs of Fe from marine sediments.

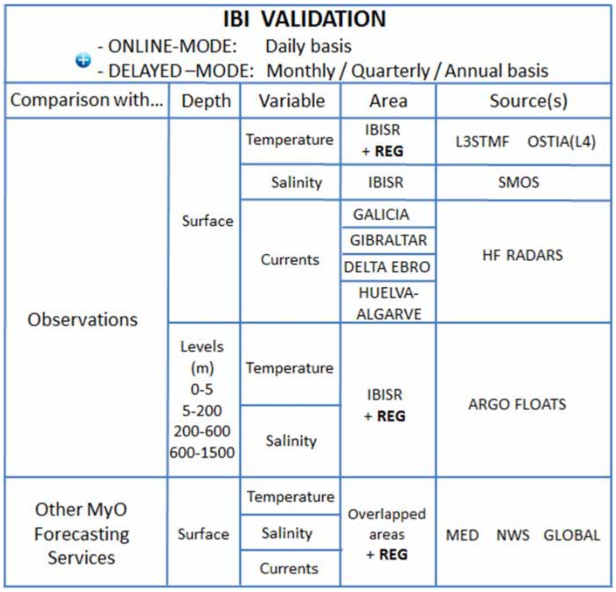
This new biogeochemical database based on model outputs comes to fill the current gap in terms of regional biogeochemical product availability in the IBI area, meeting end-user needs. The MyOcean product (IBI_REANALYSIS_BIO_005_003) resulting from the non-assimilative hindcast run described here comprises 3D monthly fields for concentration of variables such as: chlorophyll, iron, nitrate, ammonium, oxygen, phosphate, silicate, phytoplankton net primary productivity of carbon, and euphotic zone depth. The product can be seen as one of the outcomes from the IBI-MFC R&D efforts. The hindcast system was set up and run by MO, whereas PdE built the final IBI BIO REA products and disseminated them through the MyOcean User Interfaces.

Scientific validation of the IBI systems

NARVAL: a synthesis of validation metrics for the IBI Forecast Service

Evaluating the quality of OOFS performances in terms of reliability and accuracy is mandatory for this type of service in order to inform its end users about the products' confidence level. Furthermore, increasing knowledge on the model solution helps to identify areas where potential improvements in OOFSs can be achieved (Martin 2011), thus helping them to evolve to more advanced versions thanks to reliable upgrades, encouraging interoperability, and collaboration between scientist focused on R&D and the operations teams. Therefore, calibration of OOFSs and verification of their forecast products' quality constitute a core activity in operational centres (e.g. Blockley et al. 2013; Lellouche et al. 2013). An inter-institutional close collaboration to set up a common validation methodology (Crosnier et al. 2006; Crosnier & Le Provost 2007; Ferry et al. 2007; Metzger et al. 2008, 2009; De Mey and Proctor 2009) and to standardize metrics is ongoing. Such metrics are based on sets of diagnostics that compute scalar measures from ocean system outputs, providing not only objective quality indicators that can be compared (Hernandez et al. 2009; Hernandez 2011) but also error levels (Hernandez et al. 2009).

In this context, it is not surprising that one of the primary objectives of the IBI-MFC is to assess the quality of the IBI operational products delivered (Lorente et al. 2012). To this aim, a comprehensive validation tool named NARVAL has been developed to routinely evaluate IBI performance in terms of accuracy, robustness, and variability: 3D comparisons of main oceanographic variables are carried out in different times and spatial bases using all the available observational sources together with other ocean model solutions, operationally running in overlapped areas, as summarized in Figure 3. As can be seen in this figure, the observational sources used as reference include, among others: SST satellite-derived data (from both L3 and L4 type products), temperature and salinity profiles from ARGO floats, SMOS salinity fields, surface currents measured by high-frequency radars, and in situ measurements of temperature, currents, and salinity from moorings and sea level from tide gauges existing in the IBI region and collected and disseminated by the MyOcean In-SituTac.



IBI VALIDATION

- ONLINE-MODE: Daily basis
- DELAYED –MODE: Monthly / Quarterly / Annual basis

Comparison with...	Depth	Variable	Area	Source(s)
Observations	Surface	Temperature	IBISR + **REG**	L3STMF OSTIA(L4)
		Salinity	IBISR	SMOS
		Currents	GALICIA	HF RADARS
			GIBRALTAR	
			DELTA EBRO	
			HUELVA-ALGARVE	
	Levels (m) 0-5 5-200 200-600 600-1500	Temperature	IBISR + **REG**	ARGO FLOATS
		Salinity		
Other MyO Forecasting Services	Surface	Temperature	Overlapped areas + **REG**	MED NWS GLOBAL
		Salinity		
		Currents		

Figure 3. Conceptual scheme of the scientific validation made to IBI ocean model products using the NARVAL tool in online mode (near-real-time) and delayed mode. 3D comparisons with available observational sources and other MyOcean forecasting systems are carried out in overlapping areas on a regular basis.

The NARVAL tool presents two different modes according to the time frequency of the metric computation. On the one hand, the so-called 'online mode' validation focused on performing a daily verification of the IBI best estimates (from the latest available operational IBI forecast bulletin, D-1) by comparing them with independent observational measures. On the other hand, the IBI 'delayed mode' validation is used to provide an overall review of the IBI product quality over longer time periods (i.e. monthly, seasonal, and annual basis). Metrics are computed over the whole IBI spatial coverage domain but also over specific sub-regions of particular interest (i.e. Strait of Gibraltar, English Chanel, Irish Sea, Western Mediterranean Sea, Gulf of Biscay, Gulf of Cadiz, Western and Northern Iberian shelves, and the Canary Islands area), depicted in Figure 4(a). This approach provides further insight into the evaluation of spatial and temporal uncertainty levels, since it delimits areas where discrepancies are mainly located, and it also infers the strength and weaknesses of the IBI system throughout specific time periods. For instance, monthly SST comparisons between the IBI hindcast and the L4 OSTIA product (Donlon et al. 2012) reveal key details about the IBI reliability in different sub-regions. According to the daily evolution of spatial correlation and RMSE, it can be inferred from the example shown (May 2014) in Figure 4(b) and (c), respectively, that a better agreement (in terms of higher/lower correlation/RMSE values) between IBI and OSTIA is found in the Gulf of Biscay (GOBIS, light pink line) than in the Canary Islands area (ICANA, light green line). In addition, the highest IBI SST inaccuracies are detected in a very challenging area as the Strait of Gibraltar (GIBST, cyan line) shows. Looking at the temporal evolution of monthly metrics for a longer period [October 2012 – July 2014, shown in Figure 4(d)], a noticeable improvement in IBI skill on GIBST sub-region (cyan line) is observed during the autumn and winter (with correlation coefficients above 0.6), whereas a significant decrease in accuracy is evident during the spring–summer period (with RMSE values up to 2°C). By contrast, IBI system exposes a rather stable performance in terms of metrics variability at intra-annual scales in other areas like the GOBIS (light pink line).

Supplementary validation metrics with the IBI SST product are also carried out using L3 satellite products (MyOcean L3STMF). For instance, an overall marked concordance between modelled and observed SST average patterns for summer 2013 can be seen in Figure 5(a) and (b), respectively. Major discrepancies are detected in coastal areas such as the western coastline of Morocco, the Strait of Gibraltar, or the Alboran Sea [Figure 5(d) and (f)], where the influence of upwelling processes and satellite imagery limitations (in terms of cloud cover and interference in the sea–land interface) might partially explain the higher error rates in SST predictability. Time series with

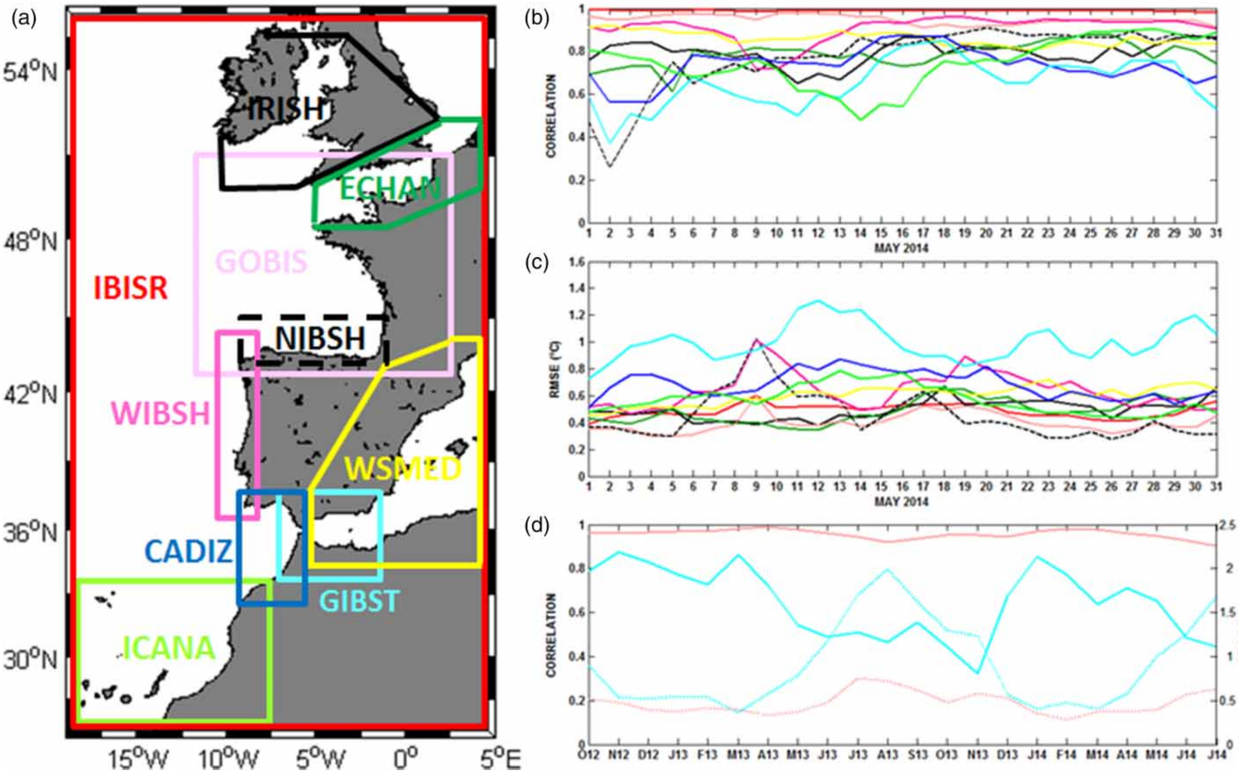


Figure 4. (a) Regionalization analysis: IBI spatial coverage domain is split into sub-regions (delimited in different colours) of special concern to study specific events. (b-c) SST comparison between IBI and OSTIA satellite-derived product: daily evolution of spatial correlation and RMSE, respectively, during May 2014 for each IBI sub-region (line colours math those selected to define sub-regions in the map). (d) Evolution of monthly metrics during the period October 2012 to July 2014 for the Strait of Gibraltar (GIBST, cyan line) and GOBIS, light pink line). Averaged time correlation and RMSE are denoted by solid and dotted lines, respectively.

the evolution of the SST spatial mean and RMSE are shown in Figure 6(a) and (b), respectively, and reveal a slight IBI SST overestimation during the central part of the summer 2013, associated with higher uncertainty rates.

In order to evaluate IBI system performance in the entire water column, salinity and temperature profiles provided by ARGO floats are automatically compared with IBI data on a monthly basis. Figure 7(a) and (b) depict the RMSE and correlation values, respectively, obtained in August 2013 from the entire temperature profiles measured by ARGO floats dropped within the IBI domain. Overall correlation values are above 0.8, whereas RMSE present a broad range of values, usually lying between 0.2 and 1°C. According to Figure 7(c) and (a), a higher concordance is found in deeper layers, since daily evolution of mean RMSE at the 0–5 m and 5–200 m levels reveals higher values. This is an expected result owing to deep ocean low variability. On the other hand, daily evolution of mean correlation values (full profile) shows that this parameter remains rather stable throughout the whole month, although punctual decreases can be detected and associated with discrepancies in the temperature profile at 5–200 m and 200–600 m depth levels.

The ability of IBI to simulate surface currents in key regions like the Strait of Gibraltar is evaluated through validation metrics using HF-Radar observations. To this aim, observational data from the growing Puertos del Estrado Coastal Ocean Radar Network [sites represented in Figure 8(a)] are automatically gathered and employed daily to routinely compare the surface current fields provided by four different HF radar systems with the product of the IBI surface currents. In this context, as a preliminary step to the application of HF radar measurements, it is worthwhile assessing their reliability and precision, and evaluating intrinsic uncertainties related to this technology (Lorente et al. 2014). As can be seen in Figure 8(c) and (d), IBI seems to properly represent basic oceanographic features and well-known circulation patterns observed with the HF radar deployed in the Ebro delta for spring 2014: a shelf-slope geostrophic jet flowing southwestwards and an anticyclonic circulation in the southern half of the Ebro shelf (Salat et al. 2001). Figure 8(e) to (h) show maps of metrics obtained for this quarterly comparison, with zonal and meridional RMSE (correlation) values in the range of 6–10 cm/s (0.4–0.8) over central areas of HF radar domain, with higher errors detected in far edges of the radar spatial coverage.

Finally, it is worthwhile mentioning that NARVAL comprises an IBI-validation dedicated website, automatically

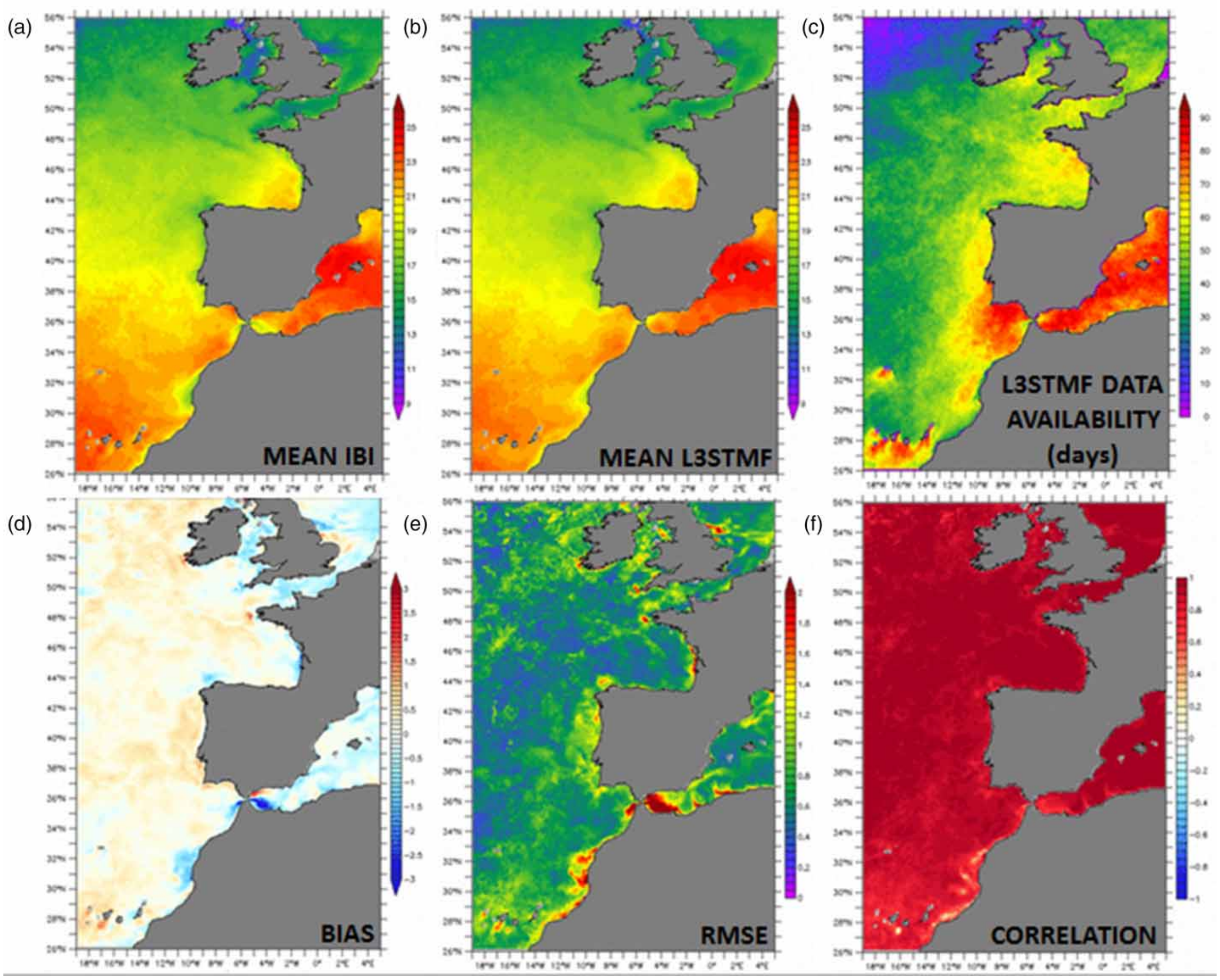


Figure 5. Quarterly validation of SST for Summer (JJA) 2013. SST mean patterns derived from (a) IBI and (b) L3STMF satellite-derived product. (c) Spatial distribution of sample size (in days) of L3STMF. (d)–(f) Spatial distribution of metrics (temporal bias, RMSE, and correlation).

updated on a daily basis to routinely monitor the involved systems accuracy and to disseminate (currently only to identified users from the IBI-MFC Team) results from the comprehensive comparative exercises performed both on a daily basis and on a delayed mode. NARVAL is a powerful tool that provides quite useful information to plan future R&D activities required to improve and to evolve the MyOcean IBI system. Indeed, before a new IBI forecast system version is transitioned into operational status, the updated system is fully tested and deemed to meet standards established by the IBI-MFC and the MyOcean community. At the present time, NARVAL is a key tool in this calibration phase performed prior to each IBI version upgrade (Sotillo et al. 2014). Furthermore, in parallel to this scientific validation performed by the IBI-MFC Team, there are many different specific validation exercises or IBI product evaluations performed locally by different users within the context of different research initiatives or projects (Maraldi et al. 2013).

Scientific validation of IBI reanalysis product

The IBI reanalysis products are generated by a model system able to deal with a large range of physical processes (from tidal to seasonal circulations). The skill of this system to reproduce main IBI oceanographical features has been evaluated. The quality of the IBI-Reanalysis has been assessed, mainly validating their monthly outputs with observational data sources. Figure 9 provides an example of the kind of metrics computed, in this case for the SST field. At the surface, the warm bias can be greater than 1°C over the shelf, and the bias is cold along all the western coasts. The mean SST is similar to the observations with a misfit less than 0.5°C, except in shelf areas: the reanalysis is warmer than the observations along the French and Spanish coasts, and in the Gulf of Lions. The reanalysis is colder than the observations in the Irish and Celtic Sea and in the English Channel. Different indicators computed from the 10-year database have also been evaluated. Figure

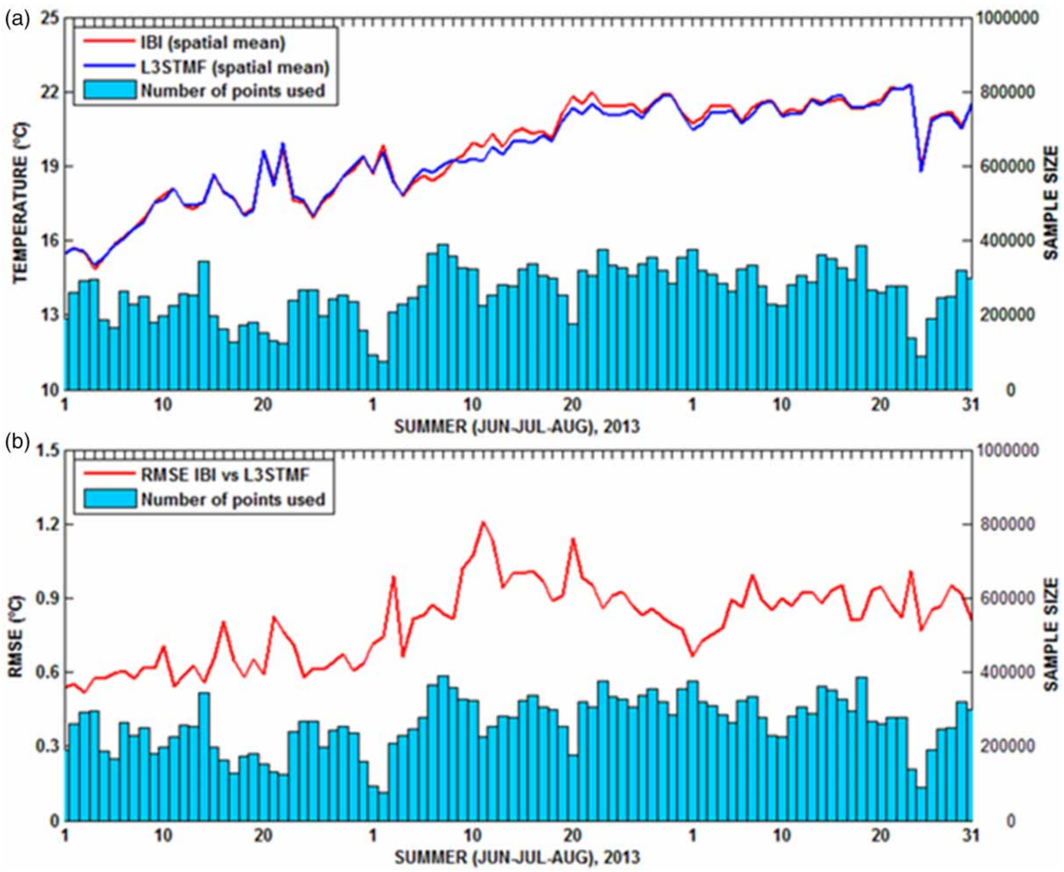


Figure 6. (a) Temporal evolution of spatial mean SST for IBI (red line) and L3STMF satellite-derived product (blue line) for summer (June to August) 2013. Blue bars denote the sample size or number of points taken into account to compute the statistics. (b) As for (a), but for the spatial RMSE between IBI hindcast and L3STMF.

9(b) and (c) show the differences in terms of SST trends over the IBI area derived from the IBI reanalysis and satellite data. The reanalysed trend is consistent with that derived from AVHRR data, negative in the northern part of the domain, and positive all around the Iberian peninsula and along the Moroccan coast.

Comparisons between the regional IBI reanalysis and other model solutions available in the area were also performed (Levier et al. 2014). In this sense, special attention was paid to the comparison of the IBI solution with the MyOcean GLOBAL reanalysis. Since IBI reanalysis is nested into this MyOcean GLOBAL reanalysis system, the comparison of both solutions is quite useful for the IBI-MFC Team to evaluate the added value generated by the regional IBI solution in comparison with the 'parent' global one. In general terms, the IBI-REA and MyOcean GLOBAL reanalysis present similar results in the IBI area. Comparisons with in situ profiles show that IBI-REA has smaller RMS error values than the GLOBAL. Likewise, IBI-REA also performs better than MyOcean GLOBAL compared with tide gauges measurements, and it seems that the IBI-REA benefits from a high resolution, which allows for a better representation of physical and biogeochemical processes. It also benefits from a fine tuning of the assimilation system adapted to regional modelization.

Furthermore, several assessments of IBI reanalysis skill have been performed using data not assimilated into the IBI-REA system. To this aim, statistics and metrics using high-frequency (hourly) in situ measured data over the 10-year period across the 16 moorings from the PdE network have been computed. Overall, IBI performance was quantified and discussed with an emphasis on surface circulation features at short time-scales (hourly to daily). Interest in this long-term high-frequency validation increases when one considers the very limiting and scarce availability of observational data remaining after discarding the observational data sources already assimilated. Figure 10 shows an example of the metrics computed from high-frequency data. The hourly model-observation comparisons extended not only to absolute values but also to anomalous ones. The figure provides a measure of the annual evolution at the Gran Canaria Buoy (in the Canary Islands) of the SST values (and its anomalies). The box-and-whisker plots of the anomalies show that the variability in SST is realistically reproduced by IBI. The quantile–

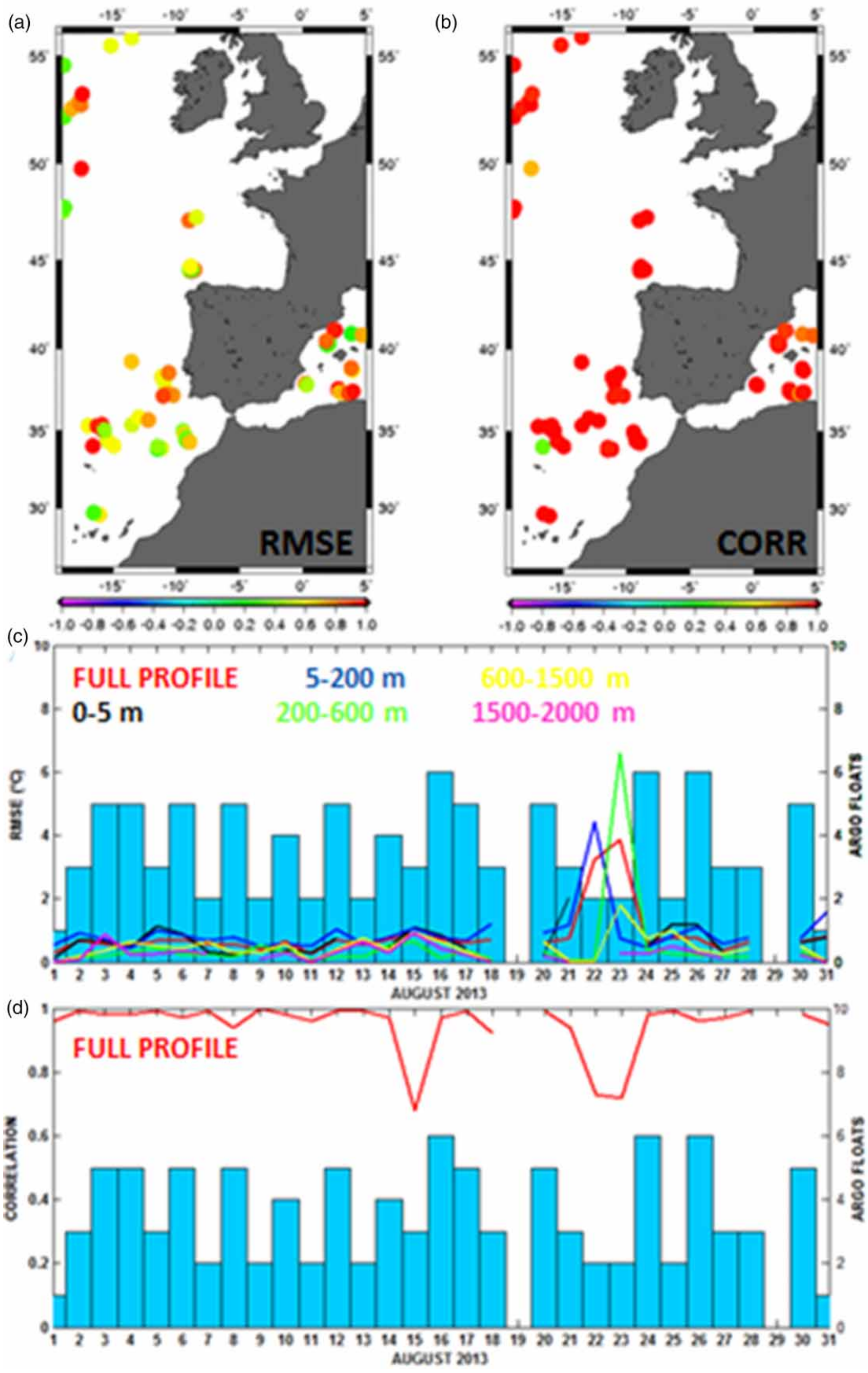


Figure 7. (a) RMSE distribution (in °C) derived from IBI-ARGO monthly comparison of temperature profiles for the whole IBI coverage domain (August 2013). (b) As for (a), but for correlation (c)–(d) temporal evolution of daily mean RMSE obtained for different depth levels and averaged for the whole IBI domain. (d) Temporal evolution of daily mean correlation (full profile) for the whole IBI domain.

quantile plot [Figure 10(c)] illustrates the good agreement between the reanalysed and observed samples over the whole range of values.

Regarding biogeochemical reanalysis, the IBI system performance and the associated product quality were assessed by comparing biogeochemical modelled fields

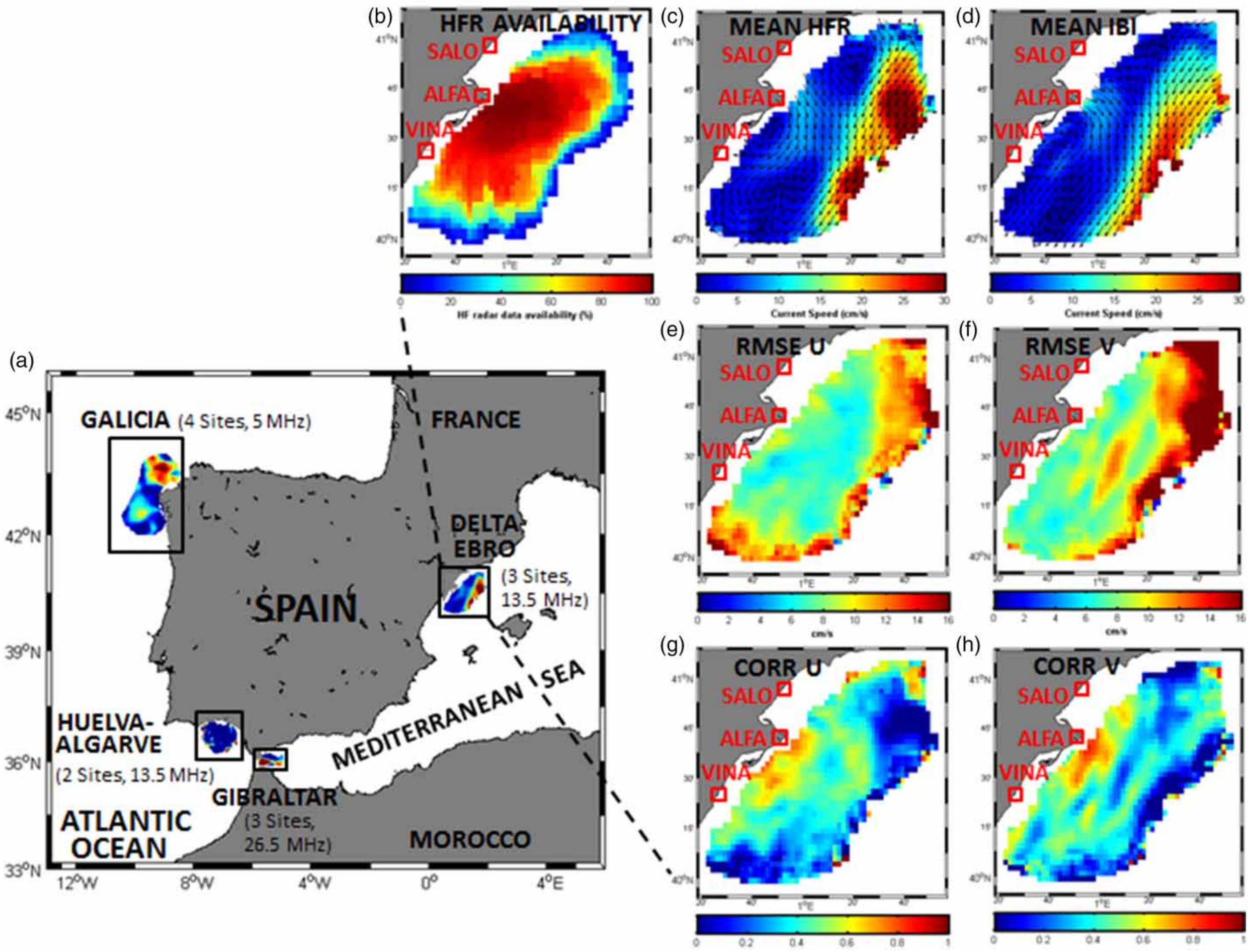


Figure 8. (a) Spanish Coastal Ocean Radar Network, composed by four different HF radar systems (from west to east: Galicia, Huelva-Algarve, Gibraltar, and Delta Ebro) operating at different radiowave frequencies. Example of validation metrics computed for the HF radar deployed in Delta Ebro, for Spring (MAM) 2014: HF-radar data availability. (b) Mean surface current patterns provided by (c) IBI and (d) the HF-Radar. Unitary vectors (coloured contours) denote current directions (velocities, in cm/s). (e)–(h) Spatial distribution of metrics: temporal RMSE and correlation, for zonal (U) and meridional (V) components.

(i.e. sections and maps of chlorophyll, nitrates, phosphates, silicates, and dissolved oxygen) with climatological products or observational data, when they are available (unfortunately, biogeochemical data to assess quality of biogeochemical models are still scarce). Comparisons (not shown here) were made using time averages of the biogeochemical fields over the years 2003–2011. Further information on the validation methodology and the metrics computed is described in Lellouche et al. (2012) and in the MyOcean IBI BIO Reanalysis QUID.

Summary and roadmap towards the future Copernicus Service for IBI

As described earlier, the MyOcean IBI-MFC currently provides, through its different model systems, a good description of the state of the ocean (temperature, salinity, currents) from the surface to the bottom of Atlantic IBI waters.

The MyOcean IBI Ocean Forecast Service, fully operational since April 2011, delivers a daily update of short-term (D + 5 days) ocean forecast products together with a historical dataset. The disseminated products are scientifically validated using the NARVAL tool. An automatic online evaluation of IBI products consisting of a validation of best estimates (D – 1 day) and consistency of forecast products (from D to D + 5) is performed on a daily basis. Additionally, a delayed mode validation is performed, computing longer-term metrics on a monthly, quarterly, and annual basis. The exhaustive validation of these IBI products allows us to enhance our knowledge of the IBI model solution and of the dynamics of the IBI waters. Some of these verification statistics against observations have been shown in this paper as examples. The overall behaviour of the present IBI forecasting system is very

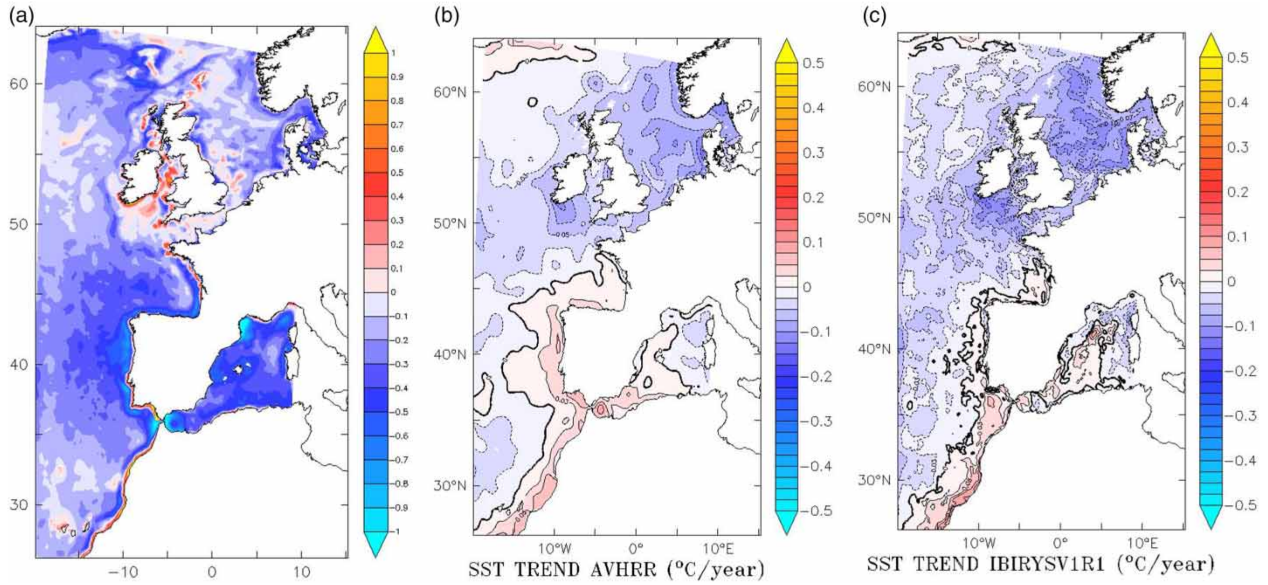


Figure 9. (a) IBI-REA vs satellite AVHRR. SST. Bias (°C) computed from monthly values, averaged over the period 2002–2011. SST trends (°C/year) computed over the same period from (b) IBI and (c) AVHRR data, respectively.

encouraging. Nevertheless, several key improvements can be implemented in the near future to enhance the system's performance. The IBI forecast system continues to evolve, and the more detailed analysis of specific dynamics and regions allows us to highlight specific features, processes, or areas that need to be addressed. All this knowledge and the scientific validation tools illustrated here play a major role in the calibration phase prior to any transitioning to a new IBI system version update.

The IBI forecast system performance is satisfactory in the IBI area, including coastal and shelves regions, but several limitations are foreseen. Among others, the lack of a data-assimilation method applied in the forecast service is one of the most significant IBI shortcomings. With the aim of enhancing IBI-MFC abilities to generate a regional analysis for the IBI waters, the IBI-MFC is making efforts to implement a data-assimilation scheme in the IBI regional system. The implementation, production, and dissemination of regional reanalysis for the IBI area can be seen as a first step towards this main objective.

Since June 2014, ocean-reanalysis products generated by means of a regional NEMO model application plus a data-assimilation scheme are available for the IBI area covering the altimetric decade 1992–2002. The IBI physical ocean reanalysis system, documented in this work, includes a data-assimilation scheme that allows the model to be constrained in a multivariate way with sea surface temperature (AVHRR, plus multi-satellite high-resolution datasets), together with all the available along-track satellite sea level anomaly data, and with in situ observations from the CORA-03 database, including ARGO float temperature and salinity measurements. The NEMO model application used for reanalysis was analogous to that currently running in the daily operational forecast service, but for changes in the resolution (1/12° instead of the operational 1/36°) and in the forcing and open boundary data (coming from atmospheric and ocean reanalysis instead of that from operational forecast systems). Monthly, daily, and even hourly (those only for surface variables) reanalysis products are delivered to users through the MyOcean service platform.

Another relevant issue is that a non-assimilative biogeochemical hindcast run was coupled to this decadal physical ocean reanalysis, a new IBI biogeochemical model database having been generated for the period 1992–2002. Monthly biogeochemical products are being delivered to users through MyOcean. The regional IBI biogeochemical database fills the existing gap in terms of homogeneous long-term biogeochemical data products available in the IBI area. Likewise, this first non-assimilative biogeochemical hindcast run opens the door in the future to exploring ways to perform online coupling of biogeochemical systems in the IBI daily forecast service to produce daily short-term forecasts of the biogeochemical state of the IBI waters.

In general terms, the MyOcean IBI-MFC service provides a good description of the state of the ocean in the IBI region through its different model products (generated by both forecast and reanalysis systems). These IBI services have been developed within the framework of MyOcean, MyOcean2, and MyOcean Follow-On EU Projects (the first two financed by the FP7 and the third by the Horizon2020 programmes). These three projects have been designed to prepare and to lead the demonstration phases of the future Copernicus Marine Environment Monitoring Service (previously known as GMES). This

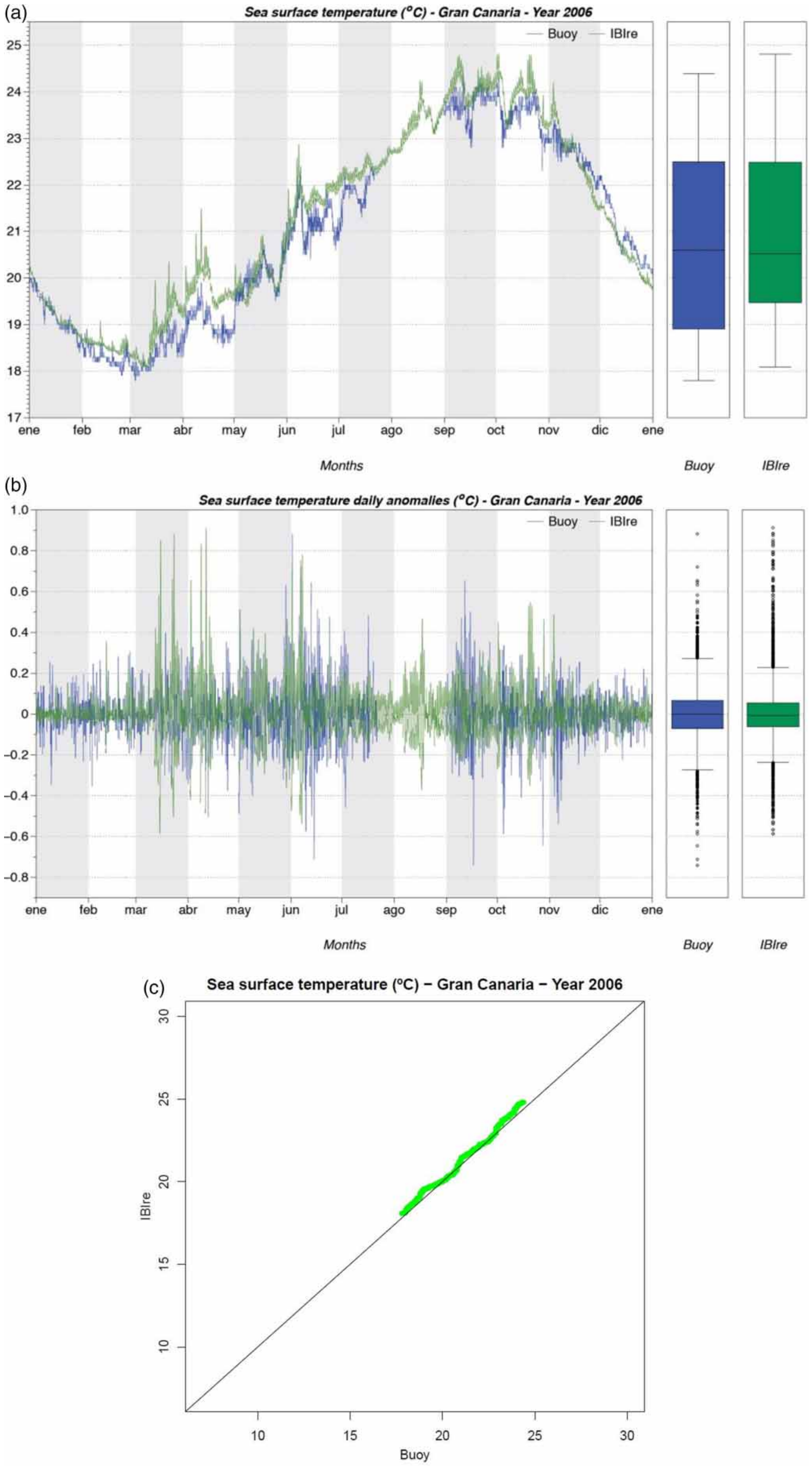


Figure 10. (a) Sea surface temperature–time series (and box plots) measured at the PdE buoy of Gran Canaria (blue) and from IBIre (green). Period shown: 2014. (b) As for (a), but for anamolous values. (c) Quantile–quantile plot of the reanalysed and observed SST at the Gran Canaria buoy location.

Copernicus Marine Service will be fully operational from 2015 onwards. In this context, an evolution of the IBI systems is expected. Currently, IBI-MFC R&D efforts are focused on including a data-assimilation scheme in the IBI operational suite to generate regional analysis at high spatial resolution (1/36°). The assimilation scheme to be tested will be based on that already used to generate physical reanalysis in the IBI area (at 1/12°). Another IBI-MFC upgrade for Copernicus will be the inclusion in the catalogue of wave products for the IBI region. Further current-wave coupling will also be investigated. All these updates are expected to be held in the first phases of the Copernicus Service (2015–2018).

Acknowledgements

This study has been conducted using MyOcean Products. Regarding observational data sources displayed in the present paper, the authors acknowledge MyOcean Services for access to SST satellite products (OSTIA & L3STMF) and for the temperature and salinity profiles from the ARGO floats. The authors also acknowledge Área de Medio Físico of PdE for access to HF-Radar data.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work has been supported by the MyOcean [grant number FP7-SPACE-2007-1], MyOcean-2 [grant number 283367], and MyOcean Follow-On Projects funded by the EU-7FP in the case of the former and Horizon-2020 for the latter.

References

Alvarez-Fanjul E, Pérez B, Rodríguez. 1997. A description of the tides in the Eastern North Atlantic. Progress in Oceanography. 40:217–244.

Annan JD, Hargreaves JC. 1999. Sea surface temperature assimilation for a three dimensional baroclinic model of shelf seas. Cont Shelf Res. 19:1507–1520.

Aumont O, Bopp L, Schulz M. 2008. What does temporal variability in aeolian dust deposition contribute to sea-surface iron and chlorophyll distributions? Geophy Res Lett. 35:L07607. doi:10.1029/2007GL031131.

Aumont O, Bopp L. 2006. Globalizing results from ocean in situ iron fertilization studies. Global Biogeochem. Cycles. Global Biogeochem Cy. 20(2):10–1029.

Aumont O. 2012. PISCES. Unpublished documentation.

Bell MJ, Forbes RM, Hines A. 2000. Assessment of the FOAM global data assimilation system for real-time operational ocean forecasting. J Marine Syst. 25(1):1–22.

Blockley EW, Martin MJ, McLaren AJ, Ryan AG, Waters J, Lea DJ, Mirouze I, Peterson KA, Sellar A, Storkey D. 2013. Recent development of the Met Office operational ocean forecasting system: an overview and assessment of the new Global FOAM forecasts. Geoscientific Model Dev Discuss. 6:6219–6278.

Brasseur P, Bahurel P, Bertino L, Birol F, Brankart JM, Ferry N, Losa S, Remy E, Schröter J, Skachko S, Testut CE, Tranchant B, Van Leeuwen PJ, Verron J. 2005. Data assimilation for marine monitoring and prediction: the MERCATOR operational assimilation systems and the MERSEA developments. Q J Roy Meteor Soc. 131:3561–3582.

Caballero A, Ferrer L, Rubio A, Charria G, Taylor BH, Grima N. 2014. Monitoring of a quasi-stationary eddy in the Bay of Biscay by means of satellite, in situ and model results. Deep Sea Res Part II. 106:23–37.

Cailleau S, Chanut J, Levier B, Maraldi C, Reffray G. 2010. The new regional generation of Mercator Ocean system in the Iberian Biscay Irish (IBI) area. Mercator Ocean Q Newslett. 39:5–15.

Chassignet EP, Verron J. eds. 2006. Ocean weather forecasting. An integrated view of oceanography. Springer. 577pp.

Conkright ME, Locarnini RA, Garcia HE, O'Brien TD, Boyer TP, Stephens C, Antonov JI. 2002. WorldOcean Atlas2001: objective analyses, data statistics, and figures, CD-ROM documentation. SilverSpring, MD: National Oceanographic DataCenter. 17 pp.

Crosnier L, Le Provost C, MERSEA Strand1 Team. 2006. Internal metrics definition for operational forecast systems inter-comparison: examples in the North Atlantic and Mediterranean Sea. Pp. 455–465 in GODAE Summer School in "Ocean Weather Forecasting: An Integrated View of Oceanography." Chassignet EP, Verron J, eds. Springer. Lallonde les Maures, France.

Crosnier L, Le Provost C. 2007. Inter-comparing five forecast operational systems in the North Atlantic and Mediterranean basins: the MERSEA-strand1 methodology. J Marine Sys. 65(1–4):354–375.

De Mey P, Proctor R. 2009. Assessing the value of GODAE products in coastal and shelf seas. Ocean Dyn. 59(1):1–2.

Donlon CJ, Martin M, Stark JD, Roberts-Jones J, Fiedler E, Wimmer W. 2012. The Operational Sea Surface Temperature and Sea Ice analysis (OSTIA). Remote Sens Environ. 116:140–158.

Drévillon M, Bourdallé-Badie R, Derval C, Drillet Y, Lellouche J-M, Rémy E, Tranchant B, Benkiran M, Greiner E, Guinehut S, Verbrugge N, Garric G, Testut C-E, Laborie M, Nouel L, Bahurel P, Bricaud C, Crosnier L, Dombrowsky E, Durand E, Ferry N, Hernandez F, Galloudec O Le, Messal F, Parent L. 2008. The GODAE/Mercator-Ocean global ocean forecasting system: results, applications and prospects. J Oper Ocean. 1(1):51–57.

Egbert GD, Erofeeva SY. 2002. Efficient inverse modeling of barotropic ocean tides. J Atmos Oceanic Technology. 19:183–204.

El-Geziry TM, Bryden IG. 2010. The circulation pattern in the Mediterranean Sea: issues for modeller consideration. J Oper Ocean. 3(2):39–46.

Ferry N, Rémy E, Brasseur P, Maes C. 2007. The Mercator global ocean operational analysis system: assessment and validation of an 11-year reanalysis. J Marine Sys. 65(1–4):540–560.

Hernandez F, Bertino L, Brassington G, Chassignet E, Cummings J, Davidson F, Drévillon M, Garric G, Kamachi M, Lellouche J-M, Mahdon R, Matthew JM, Ratsimandresy A, Regnier Ch. 2009. Validation and intercomparison studies within GODAE. Oceanography. 22(3):128–143.

Hernandez F, Blockley E, Brassington GB, Davidson F, Divakaran P, Drévillon M, Ishizaki S, Sotillo MG, Hogan PJ, Lagemaa P, Levier B, Martin M, Mehra A, Mooers C, Ferry N, Ryan A, Regnier C, Sellar A, Smith GC, Sofianos S, Spindler T, Volpe G, Wilkin J, Zaron ED, Zhang A. 2014. Performance evaluations, near real-time assessment of operational oceanography forecast products. Submitted to Journal of Operational Oceanography.

Hernandez F. 2011. Performance of Ocean Forecasting Systems-Intercomparison Projects. Operational Oceanography in the 21st century. Schiller A and Brassington GB, eds. Springer. 633–655.

Key RM, Kozyr A, Sabine CL, Lee K, Wanninkhof R, Bullister JL, Feely RA, Millero FJ, Mordy C, Peng TH. 2004. A global ocean carbon climatology: results from Global Data Analysis Project (GLODAP). Global Biogeochem Cycles. 18:GB4031.

Large WG, Yeager SG. 2004. Diurnal to decadal global forcing for ocean and sea-ice models: the data sets and flux climatologies. NCAR technical notes.

Le Traon PY, Dibarboure G, Ducet N. 2001. Use of a High-Resolution Model to Analyze the Mapping Capabilities of Multiple-Altimeter Missions. J Atmos Ocean Technol. 18:1277–1288.

Lellouche J.-M, Le Galloudec O, Drévillon M, Régnier C, Greiner E, Garric G, Ferry N, Desportes C, Testut C-E, Bricaud C, Bourdallé-Badie R, Tranchant B, Benkiran M, Drillet Y, Daudin A, De Nicola C. 2013. Evaluation of global monitoring and forecasting systems at Mercator Océan. Ocean Sci. 9 (1):57–81.

Lellouche J-M, Le Galloudec O, Drévillon M, Régnier C, Greiner E, Garric G, Ferry N, Desportes C, Testut C-E, Bricaud C, Bourdallé-Badie R, Tranchant B, Benkiran M, Drillet Y, Daudin A, De Nicola C. 2012. Evaluation of real time and future global monitoring and forecasting systems at Mercator Océan. Ocean Sci Discuss. 9:1123–1185.

Levier B, Benkiran M, Reffray G, Sotillo M. 2014. IBIRYS: a regional high resolution reanalysis (physical and biogeochemical) over the European North East Shelf. EGU 2014.

Longhurst A. 1998. Ecological geography in the sea. San Diego: Academic Press. 398 pp.

Lorente P, Levier B, Drevillon M, Regnier C, Sotillo MG. 2012. The IBI-MFC NARVAL: products, operational status and progress. MyOcean Science Days Conference, Hamburg, Germany.

Lorente P, Piedracoba S, Soto-Navarro J, Álvarez-Fanjul E. 2014. Accuracy assessment of high frequency radar current measurements in the Strait of Gibraltar. J Oper Ocean. 7 (2):59–73.

Ludwig W, Probst J-L, Kempe S. 1996. Predicting the oceanic input of organic carbon by continental erosion. Global Biogeochem Cycles. 10(1):23–41.

Lyard F, Lefevre F, Letellier T, Francis O. 2006. Modelling the global ocean tides: modern insights from FES2004. Ocean Dyn. 56:394–415.

Madec G. 2008. NEMO Ocean General Circulation Model. Reference Manual. Internal Report. LODYC/IPSL, Paris.

Maraldi C, Chanut J, Levier B, Ayoub N, De Mey P, Reffray G, Lyard F, Cailleau S, Drévillon M, Fanjul EA, Sotillo MG, Marsaleix P, and the Mercator Team. 2013. NEMO on the shelf: assessment of the Iberia–Biscay–Ireland configuration. Ocean Sci. 9:1–18.

Martin, M. 2011. Ocean forecasting systems – Product evaluation and skill. Operational Oceanography in the 21st century. Schiller A and Brassington GB, eds. Springer. 611–631.

Martinho MA, Reboreda R, Rocha C, Dubert J, Nolasco R, Cordeiro N, Luna T, Rocha A, Lencart e Silva JD, Queiroga H, Peliz A, Ruiz-Villarreal M. 2012. Towards Operational Modeling and Forecasting of the Iberian Shelves Ecosystem. PLoS ONE. 7(5):e37343. doi:10.1371/journal.pone.0037343.

Mason E, Coombs S, Oliveira PB. 2005. An overview of the literature concerning the oceanography of the eastern North Atlantic region. Relatórios Científicos e Técnicos. IPIMAR, Série digital (http://ipimart-iniap.ipimar.pt). 33. 58pp.

Metzger EJ, Hurlburt HE, Wallcraft AJ, Shriver JF, Smedstad LF, Smedstad OM, Thoppil P, Franklin DS. 2008. Validation Test Report for the Global Ocean Prediction System V3.0 - 1/12 Degree HYCOM/NCODA: Phase I. Naval Reasearch Laboratory. Memorandum report.

Metzger EJ, Smedstad OM, Carroll SN. 2009. User's Manual for the Global Ocean Forecast System (GOFS) Version 3.0. Naval Reasearch Laboratory. Memorandum report.

O'Dea EJ, Arnold AK, Edwards KP, Furner R, Hyder P, Martin MJ, Siddorn JR, Storkey D, While J, Holt JT, LiU H. 2012. An operational ocean forecast system incorporating NEMO and SST data assimilation for the tidally driven European North-West shelf. J Oper Ocean. 5(1):3–17.

Pérez B, Brouwer R, Beckers J, Paradis D, Balseiro C, Lyons K, Cure M, Sotillo MG, Hackett B, Verlaan M, Fanjul E. 2012. ENSURF: multi-model sea level forecast: implementation and validation results for the IBIROOS and Western Mediterranean regions. Ocean Sci. 8(2):211–226.

Pingree, R, Le Cann B. 1992. Three anticyclonic slope water eddies (swoddies) in the southern bay of Biscay in 1990. Deep Sea Res Part A. 39:1147–1175.

Salat J, Garcia MA, Cruzado A, Palanques A, Arín L, Gomis D, Guillén J, de León A, Puigdefàbregas J, Sospedra J, Velásques ZR. 2001. Seasonal exchanges of water mass structure and shelf slope exchanges at the Ebro shelf (NW Mediterranean). Cont Shelf Res. 22(2002):327–348.

Sotillo MG, Jordi A, Ferrer MI, Conde J, Tintoré J, Álvarez-Fanjul E. 2007. The ESEOO regional ocean forecasting system. Proceedings of the ISOPE-2007: The 17th International Offshore Ocean and Polar Engineering Conference. Lisbon, Portugal.

Sotillo MG, Lorente P, Levier B, Drevillon M, Chanut J, Amo A. 2014. MyOcean Quality Information Document for the Atlantic -Iberian Biscay Irish- Ocean Physics Analysis and Forecasting Product (IBI_ANALYSIS_FORECAST_PHYS_005_001_b). MyOcean Technical Report (www.myocean.eu)

Umlauf L, Burchard H. 2003. A generic length-scale equation for geophysical turbulence models. J Marine Res. 61(2):235–265.

White M, Bowyer P. 1997. The shelf-edge current north-west of Ireland. Ann Geophys. 15:1076–1083.